URBAN CLIMATE CHANGE GUIDELINES

HOW TO ACHIEVE SUSTAINABLE ADAPTATION IN URBAN AREAS.

2016

DHI

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APPENDICES

1 Introduction

1.1 Background

This document describes how Danish municipalities can respond to flooding problems expected as impact of climate change. The report provides an overview of information available about climate change in Denmark, which impacts the urban drainage systems. The most significant factors are the increase in extreme rainfall and rise in sea level. Examples of how floods can be prevented and avoided describe available methods for analysing existing urban drainage networks and evaluating the impact from various flood mitigation augmentations.

After developing The Climate Cookbook in 2007 several areas in Denmark were affected by very long-term extreme rainfall which showed limitations in the urban drainage in combination with the remaining water cycle (groundwater and streams). These rainfall events emphasise the need for municipalities to focus on flood management within urban drainage systems and the entire water cycle. This update of The Climate Cookbook is extended with descriptions of response to flooding from the sea. The described methods are limited to storm water systems, streams and seas.

The update contains guidelines for municipalities with respect to:

- Perform analysis and augmentation work of drainage systems in urbanised areas
- Undertake the principles described in The Climate Cookbook based on the latest figures from the IPCC
- Incorporate updated climate-related maximum sea levels in Danish waters by including principles for calculating wind induced increase in sea level as a supplement to the IPCC's mean sea levels
- Identify areas at risk of flooding due to climate change from rivers and seas
- Perform analysis and regulation of rivers in urbanised areas.

The report is financed by DANVA and the project partners. The report is prepared by Greve Forsyning A/S, VandCenter Syd, PH-Consult and DHI.

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The project was undertaken during the period November 2008 to June 2010 and the report was translated from Danish to English in 2012.

The report provides detailed descriptions of methods for analysis of flooding from simple "surface depression maps" or "blue spots" to the advanced hydraulic computer models. The methods can be used by both municipalities and wastewater utilities for their detailed action against floods as well as in implementation of the flood directive.

This version of the report (The Climate Cookbook) represents the translated version of the original Danish version under the title: "En kogebog for analyser af klimaændringers effekter på oversvømmelser i byer".

1.2 Purpose

Design of urban drainage systems through time has been undertaken using multiple methods such as hand calculated methods: Constant rain intensity, time-area method, runoff diagrams, rain images or the rational method. In recent decades, these methods have been supplemented with computer-based methods to support the dimensioning and analysis of the urban drainage system. In Denmark it is common practice to use hydraulic models (such as MIKE 1D or MIKE+) for analysing the function of the urban drainage system and to calculate the effect of proposed augmentations.

Along with developments in the calculation methods, the requirements for the dimensions of urban drainage system have evolved. For many years the common practice was that in combined systems conduits were only allowed to reach full running capacity every second year, and in storm water systems only once a year. National rainfall series or some older gauged rainfall data have been used. The national rainfall series are statistically derived from a series of rain gauges geographically installed at different locations in Denmark. Most of the Danish urban drainage network is probably dimensioned from the above requirement. With the release of Guide 27 (SVK Skrift 27) the dimension requirements were revised to a maximum frequency of damaging flood events occurring from the systems. The urban drainage system will now be dimensioned based on a selected return period of damaging flood events. Additionally, it is recommended that the impact on the urban drainage systems from even more extreme rainfall events than the urban drainage system is designed for, are analysed in order to minimise damage to infrastructure and the environment.

Climate change leads to on-going changes in dimension standards because of increased rainfall intensities and sea level rises. This implies that any dimension of infrastructure must be assessed for a given time horizon, adapted life span and economy. The infrastructure must at any time meet the desired standard of services for the system listed in Guide 27.

When the rain fall exceeds the design rainfall of the systems, then there is no legislation or Danish standards that describe which actions are required for the different entities in charge of the urban drainage systems. Currently, there is no requirement for assessments of when and where a city might be inundated caused by extreme rainfall. Nevertheless, a real demand is present for these assessments in the light of recent years' flood inundation events in Denmark. In this report the technical procedures to undertake the flood assessments are described. It is not considered “who you are”, but a general urge is given to consider responsibilities so that these types of assessments are undertaken in the future. In this way it is ensured that conscious choices are taken in assessing flood inundation risks in Denmark.

1.3 Definition of the problem

This project is specifically focused towards the impacts of climate change on urban drainage systems, in particular the impact from more frequent and extreme rainfall. It also focuses on methods describing the impact of sea level rise and increased groundwater table. The primary problem being considered is flooding of urbanised areas.

Urban drainage systems are loaded directly by precipitation, and the hydraulic capacity must be sufficient to convey water volumes to the receiving waters, otherwise when the hydraulic capacity is met the network may discharge to the surface resulting in flooding. The receiving waters may also be affected by climate change in terms of higher water levels which can have significant back water effects and reduced outlet discharge capacity in the urban drainage system. Rivers may also be affected by increased runoff from other sources - including groundwater – which can lead to damages caused by flooding because of the reduced hydraulic capacity. There are many contexts that should be assessed and taken into account when looking at the function of urban drainage systems influenced by climate change.

At this stage there is no solid knowledge about the correlation between the various key inputs. Preliminary estimates of water levels in Køge Bay does not indicate any correlation with extreme rainfall, but on the other hand it does not state that it is meteorologically unlikely. In many coastal settings with low-lying built-up areas and locations with low elevated overflow structures it is important to analyse these elements in conjunction. If an overflow structure is not able to function as intended because of the water level in the receiving waters, the risk of flooding increases significantly. Similarly, if the seawater rises above quayside or dike crowns, larger areas may be flooded with seawater and the urban drainage system may not be able to function. The urban drainage system may in this situation have a negative effect by transporting water to otherwise protected areas of the catchments.

Climate change is expected in some places and at certain times of the year to give rise to increased groundwater levels which affects the urban drainage system since it can lead to increased groundwater infiltration. The increased groundwater infiltration may lead to reductions in the hydraulic capacity of drainage system and increasing the load to the WWTP. Rising groundwater tables may also affect the local percolation and infiltration systems which may lead to both local flooding and flooding due to reduce hydraulic capacity in the urban drainage system. It is likely that extreme rainfall will occur in the summer period, while maximum groundwater levels will occur during winter, but local assessments should be undertaken to ensure that the effect is limited to local conditions.

It should always be assessed whether a local solution in one place may cause problems elsewhere. The risk of this can be significant in situations where the drainage network is operated at full capacity or is overloaded. In those cases it is recommended that the total water cycle in the watershed is evaluated and combined with other climate-dependent effects such as wind and seawater currents and levels. Any calculations of the urban drainage systems should ideally be undertaken with boundary conditions that are determined from the same expectations of climate change as rainfall. If possible, an integrated model simulation analysis of all factors affecting runoff should be undertaken. This integrated analysis is quite extensive and requires many details to obtain a better result than what can be achieved by more simplified analysis supplemented with sensitive analyses. Additionally, other analyses are required to provide the likelihood of i.e. high water level in the receiving waters combined with extreme rainfall runoff.

Flooding assessments can be undertaken at different levels depending on the available information that exists on the watershed being evaluated and the type of problems to be assessed. In the case of floods in well-defined areas, frequency and distribution of flood may be calculated and assessed quite easily.

If the terrain and drainage system is more complex then modelling of drainage system operation can be necessary to provide an overview of the situation. It may be an advantage to include a runoff calculation on the surface of the watershed.

A comprehensive hydrological modelling approach may be required if the system gets even more complicated where the water level in the receiving waters is included as a boundary condition.

The choice of calculation level must always be adapted to the current problem and available input and boundary conditions. It should be noted that this is the calculation of future extreme situations based on forecasts of changes in load. There is considerable uncertainty in all results and level of detail in the calculations, and the detail in the model approach should be adapted to this uncertainty.

1.4 Legislation

Any work on climate change impacts on urban drainage systems should be interdisciplinary and will influence the dimensioning, operation and maintenance of urban drainage networks and wastewater treatment plants. Work on climate effects can/should influence the following official documents:

1.4.1 Sewerage plan

All municipalities are required by legislation to develop a sewerage plan. The sewerage plan describes the status and approach for managing the sewerage in the municipality.

The infrastructure of the urban drainage system, connected industries etc. must be described. In the sewerage plan, the municipality or wastewater utility must address relevant land use planning objectives (including river basin management objectives) and other local planning schemes. The sewerage plan must include measures to ensure that wastewater discharges from wastewater treatment plants and storm water discharges do not exceed water quantity and quality objectives for the receiving waters.

As a result of desired standards of services described in Wastewater Committee, Guide No. 27, it is recommended that municipalities incorporate operational practices in their respective sewerage plans. By doing this the municipalities produce a legal document in terms of desired standards of services. When determining the desired standards of services the practices should be examined for possible climate change effects which are then incorporated into the sewerage plan.

1.4.2 Sewer renewal plan

In relation to the sewerage plan, the municipality is liable to develop a sewer renewal plan (also called sewer maintenance plan, or sewer improvement plan). The sewer renewal plan must include: An assessment of existing sewers' condition, inspection methods and frequency, target settings, a statement of sewer renewal needs and finally a plan for renewal. Sewer renewal should be performed to meet the desired standards of services specified in the sewerage plan in which the climate change effects should be accounted for. There should be close coordination of sewer renewal plan and a possible adaptation of urban drainage systems.

1.4.3 Contingency plan

All municipalities must, as part of the overall civilian preparedness, create an emergency plan. There is no requirement for a specific contingency for the operation of sewers and treatment plants. Some municipalities have, however, made such plans. A contingency plan for sewers and treatment plants will usually take a number of factors into account that are critical to the operation of the sewage plant, i.e. power failure, flood damage in exposed locations, staff readiness for emergencies in order to maintain a minimum service.

Following a risk assessment of flooding event it may be desirable to have:

- Actual physical measures to reduce the effects of a flood situation.
- Preparedness for emergency ad hoc response.
- Information / alerts both internally within the municipality's operations and externally.

There is not necessarily a requirement for a full emergency plan, but only to assess the significance of flood situations, as input to an emergency plan.

1.4.4 Additional municipal planning, local plans, plans for water quality, etc.

Climate change effects may affect other planning, particularly municipal, local plans, plans for water quality, water levels, etc. It is important to incorporate the effects of climate change and extreme rainfall in the work of sewerage plans. In the preparation of sewerage and storm water plans, the municipalities are obliged to deal with the other planning and ensure compliance. Thus, municipal plans and local plans could be controlling the sanitation, particularly in terms of allowable imperviousness and minimum allowable foundation elevations. Likewise, the municipality must deal with the impact on water quality in the recipients by more extreme rainfall events.

The municipal plan represents the municipality’s plan for the area, and in this plan guidelines should be incorporated for allocation of areas where flooded water can be stored such as wet meadows, basins etc. Guidelines for foundation levels can be written in the municipality plan for preventing flooding.

It should be noted that the horizon in the climate scenarios of 50 - 100 years is far beyond time schedules in both sewerage plans and future water plans under the Water Act directives, which operate with time horizons of 15 to 30 years.

In the draft Water Act directives there is no obligation to account for climate change. The sewerage plan should be coordinated with the Water Act directives and policies in order to reduce the risk of flooding due to climate change. The municipal plans can have impact on the boundary conditions for the urban drainage system, such as options diversion of water to the receiving waters. If the requirements of water plans become very restrictive regarding the diversion of rainwater, it may have significant impact on the handling of rainwater in the urban drainage system. In addition practices for maintenance of watercourses, such as altered weed clearance, can have a major impact on flood risk from rivers and can reduce the option of discharging water to the river.

Work on climate change will require a coordinated planning effort by the municipality.

Climate change takes place over a long time horizon. Despite this the magnitude of the potential impacts and the consequent need for investment requires analysis of the impacts on drainage systems now. This is required in order to prioritise, manage and implement measures that reduce potential future damage to society as a result of climate changes.

1.4.5 Risk assessment and analysis of extreme rain

Urban drainage networks are currently designed to overflow with a return period of either 1 or 2 years. According to Guide 27 overflows once every 5 or every 10 years, respectively for combined and separate sewer drainage systems. In addition, it is recommended to establish contingency plans for incidents where sizing criteria is exceeded. There is no formal legal requirement to assess extreme rainfall events beyond return periods of 5 or 10 years, e.g. extreme rainfall events with frequencies of 50 years or 100 years. Municipalities and their consultants have often in practice depending on the area being sewered, undertaken more qualitative assessments of extreme rainfall in model simulations, however, a formalised requirement for assessing the impact from extreme rainfall in model simulations does not exist.

Since it is commonly expected that climate changes will lead to more extreme rainfall and increased rise in sea level, it would be appropriate to assess the impact of extreme rainfall for the drainage system - including assessment of any damage caused by surcharged water. The methods described in Chapters 4 and 5 can be used for this work.

The Guide 27 is used by almost all Danish municipalities to design and maintain urban drainage systems for conditions where there is no water on the ground. There are no guidelines in Denmark for analysis and handling of the situation when there is water on the terrain / flooding. This results in situations where important infrastructures are flooded, e.g. as it happened in 2007 and 2010 with damages of more 1 billion dollars.

1.5 Flood Directive

The Flood Directive is given by the European Parliaments and Councils Directive 2007/60/EC of 23rd October 2007 for assessment and management of flood risks. A bill to implement the Directive was adopted by the Danish Parliament on 15th December 2009. The law is called "Act on assessment and management of flood risk from rivers and lakes".

Flooding originating from the sea is covered by "Assessment and risk of flooding from the sea, bay or other parts of the territorial sea". Ministry of Environment and the Coastal Directorate have identified (April 2011) nine risk areas based on a preliminary assessment of flood risk from rivers, lakes, oceans and estuaries. This is currently in public hearing.

The background for the Flood Directive is the major floods that occurred in Central Europe. The objective of the Flood Directive is to establish a framework for measures for reducing the risk of flood damages. The Flood Directive starts with article no. 1 by defining what type of floods is covered by the Flood Directive:

1. Flooding:
   A temporary coverage with water from rivers and lakes is applied to land areas which are normally not covered by water.

2. Flood Risk:
   The combination of the probability of a flood event and the potential adverse consequences for human health, environment, heritage and economic activity associated with floods.

1.5.1 Preliminary flood risk assessment

The first step is to undertake a preliminary flood risk assessments based on existing studies and data. The assessment must include at least:

a. Topographic map of appropriate scale which includes land use coverage.

b. A description of the historic flooding that has caused extensive damage and are likely to be repeated in the future. The description must include the extent of the flood, flow routes and an assessment of damages.

European Member States shall complete the preliminary flood risk assessment by **22 December 2011**.

1.5.2 Flood hazard and flood risk maps

European Member States shall compile flood hazard maps and flood risk maps. The flood hazard maps shall cover geographical areas which may be flooded according to the following scenarios:

a. low probability of flooding or extreme events.
b. medium probability of flooding (probably once every 100 years).
c. high probability of flooding, where appropriate.

For each scenario, the following information is shown:

a. flood level.
b. water depth or water level, whichever is applicable.
c. flow rate or the appropriate water quantities when appropriate.

Flood risk maps shall show:

a. the estimated number of inhabitants potentially affected.
b. the nature of economic activity in the area potentially affected.
c. infrastructure or installations which might cause accidental pollution in case of flooding.

European Member States shall ensure that the maps of flood hazard and flood risk are completed by **22 December 2013**.

1.5.3 Flood risk management plans

Based on the maps of flood hazard and flood risk, flood risk management plans will be developed. These plans will focus on: Prevention, protection and preparedness. Climate change must be included in the plans when appropriate.

European Member States must set "suitable targets" for the management of flood risks, with emphasis on reducing the potential negative impacts of floods on public health, environment, heritage and economic activity. If this is relevant emphasis should be laid on non-structural initiatives and /or reducing the likelihood of flooding.

Flood risk management plans must include relevant aspects such as costs and benefits, flood extent, flow paths and areas which have the potential to retain flood water.

Flood risk management plans must include all aspects of risk management with special emphasis on prevention, protection and preparedness, including flood forecasting and warning systems. The flood risk management plans may also include the promotion of sustainable land use practices and improve water retention as well as the controlled flooding of certain areas in cases where flooding is avoidable.

European Member States shall ensure that flood risk management plans are completed and published by **22 December 2015**.

1.5.4 Publication of maps, plans, etc.

European Member States shall prepare preliminary assessment of flood risk available to the public in terms of flood hazard maps, flood risk maps and flood risk management plans. Review of maps, plans, etc. must be done every 6. years and as part of the revisions include the climate change impact on the occurrence of floods.

1.5.5 Summary

Timeline for implementation of the directive is:

1. Preliminary flood risk assessment – deadline **2 December 2011**
2. The maps of flood hazard and flood risk – deadline **22 December 2013**
3. Flood risk management plans – deadline **22 December 2015**

Revisions and updates of the issues mentioned in the plans listed in section 1-3 above start in 2018 and are then updated every six years. From this date the likely climate change impacts on the occurrence of floods must be added to the plans etc.

The methods described in this report may be used in the work of implementing the Flood Directive. It also provides an opportunity to consider the entire water cycle and apply a holistic approach in the effort against floods.

Flood risks from urban drainage systems are not included in the implementation of the Floods Directive in Denmark, but it is recommended that it will be included in the calculations of the risk of flooding, because drainage system in many cases may convey water into the critical areas of the city from both the sea and streams. In addition, flooding due to the capacity of the urban drainage system should be known by the local authorities in order to produce comprehensive solutions to flooding problems and prepare contingency plans.

2 Status of knowledge on climate change

Climate change may result in changes to the intensity, frequency, and duration of extreme rainfall events, with impacts on urban drainage systems. It is also possible that climate change will affect average sea levels and extreme sea level rise events. Projected changes vary in different parts of the world, and sections 2.3 and 2.4 give a brief overview of likely changes.

In Denmark, it is likely that climate change will result in increases in the intensity of rainfall events, as well as changes in the intensity of storm surge events. Projected changes are also outlined in sections 2.3 and 2.4.

2.1 Projections of future climate change

The Intergovernmental Panel on Climate Change (IPCC) coordinates the activities of scientists and other researchers around the world to prepare projections of future climate changes and associated impacts. The IPCC was formed in 1988 by joint action of the United Nations Environment Programme and the World Meteorological Organization. The panel’s mandate is to prepare assessments of climate change, with the intention of informing realistic response strategies to human-induced climate change. The IPCC releases assessment reports periodically that describe the current state of science regarding projections of future climate and its impacts. The first four assessment reports were released in 1990, 1995, 2001, and 2007, respectively. The fifth assessment report (AR5) was released in stages between September 2013 and November 2014. Projections described in this chapter are based on AR5. For a technical summary of the AR5 projections, see Stocker et al. (2013).

Climate change projections presented in AR5 are based on the outputs of computer simulations that project how the climate might evolve given different assumptions about greenhouse gas concentrations in the atmosphere. AR5 also reviews evidence suggesting that significant climate change is already happening, both to check climate model projections and to provide advice about climate change in the near-term future.

The computer models used to make projections of climate changes have evolved significantly. At the time of publication of the fourth assessment report in 2007, the standard model was the Atmosphere-Ocean General Circulation Model (AOGCM), which simulates the physical components of the climate system, including the atmosphere, oceans, sea ice, and some characteristics of the land surface. Although many AOGCMs are also used to support AR5, they have been complemented by a new generation of so-called “Earth System Models” that couple the physical process modelling of AOGCMs with modelling various biochemical cycles, including the carbon cycle. More than 100 models were used to support AR5.

Because of computational limitations, global climate models use a grid size that is too large to simulate some physical processes that are important for rainfall and other variables at local scales, including orographic and convective processes. Therefore, global climate models should be coupled with regional climate models to project changes in the characteristics of local weather phenomena. A regional climate model simulates an area smaller than the entire globe (usually about the size of a continent), using a smaller grid size than is feasible in a global climate model, with global climate model results used as boundary conditions. Regional climate models simulate some processes that are not included in global climate models, using a refined grid to simulate more local processes.

Climate models simulate how the climate might respond to projected concentrations of greenhouse gases, aerosol particles, and other drivers such as land use change. These drivers result from human activities and depend on socio-economic factors, as well as political agreements about how to control greenhouse gas emissions. The IPCC has developed scenarios describing how greenhouse gas emissions and other drivers might evolve in the future, which are then used as inputs to climate models. The third and fourth assessment reports used scenarios developed as part of the Special Report on Emissions Scenarios (SRES). The SRES scenarios (Nakicenovic, 2000) were developed by projecting socio-economic conditions into the future and then estimating how this might affect greenhouse gas concentrations, as well as other drivers. For AR5, the SRES scenarios are replaced by the so-called “Representative Concentration Pathways” (RCPs). Instead of estimating changes in greenhouse gas and aerosol concentrations from projections of socio-economic conditions, the RCPs simply describe a plausible range of variation in the concentrations of these drivers (although the plausible range is based on a survey of socio-economic projections made by others). Because some regional climate results use global climate model results from the fourth assessment report as boundary conditions (and therefore use the SRES scenarios), readers should be familiar with both the SRES and RCP approaches. A comparison of RCP scenarios is presented in Figure 2.1.

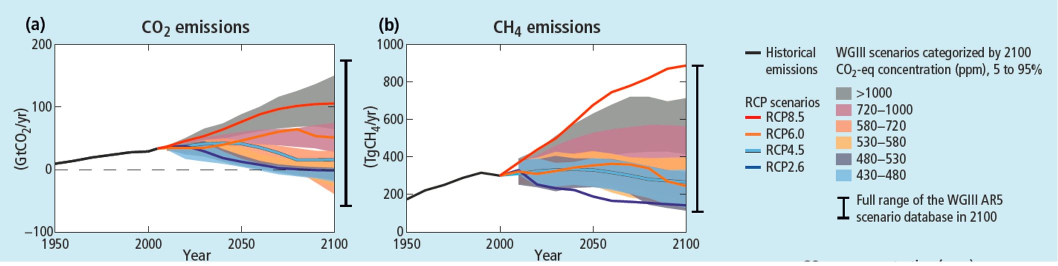


Figure 2.1 RCP projections for CO2 and methane. The coloured lines show concentrations associated with each of the four RCP scenarios: 8.5, 6.0, 4.5, and 2.6. The shaded areas show the range of concentration projections identified in a survey on which the RCP projections are based. Source: IPCC, 2014

RCM outputs require additional statistical post-processing before these data can be used in hydrological models. Although the smaller grid size used in RCM simulations improves the simulation of precipitation and other hydrologic variables, important local scale processes are not represented, even at the RCM grid scale. In addition, processes affecting the formation of precipitation are not completely understood and therefore cannot be represented in simulation models. As a result, statistical bias correction methods are used to remove biases resulting from the incomplete model representation. A number of bias correction methods are commonly used in climate studies, including methods that are based on mean bias as well as other methods that adjust bias differently depending on the likelihood of the value being corrected (in other words, methods that correct means and extremes differently).

2.1.1 Projections of future climate change in Denmark

The Water Pollution Committee of the Society of Danish Engineers, in collaboration with DHI and DTU, have recently published updated guidelines for developing projections of extreme rainfall in urban drainage design (Gregersen et al., 2014). Both DMI and the Danish Environment Agency have also published recent guidance on projecting extreme sea level rise events that may be useful for urban drainage engineers.

Future rainfall in Denmark

The new guidelines on extreme rainfall from the Water Pollution Committee of the Society of Danish Engineers use statistical procedures to downscale regional climate model output and make projections about extreme rainfall. In addition, statistical analysis is used to analyse recent trends in extreme rainfall and estimate whether these trends can be explained by climate change.

The regional climate model results use model results generated as part of ENSEMBLES, an EU research project investigating the use of regional models in Europe (van der Linden and Mitchell, 2009). A total of 13 regional model results are used, including models from research teams in Denmark, Germany, the Netherlands, Sweden, Switzerland, the United Kingdom, and Ireland. All of the models have a spatial resolution of 25 km and run on an hourly time step.

The RCMs use boundary conditions from the fourth assessment report generation of GCMs, which means that assumptions about greenhouse gas concentrations and other drivers are based on the SRES scenarios. All of the RCM results are based on the SRES A1B scenario, which assumes rapid economic growth, convergence in standards of living between the developed and developing worlds, fast diffusion of new technologies, and a mix of fossil fuel and renewable resources.

To accommodate the new RCP scenarios, two additional RCM results are used that are based on the new generation of GCMs associated with AR5. The purpose of including the two additional RCM results is to include more conservative assumptions than those used in the A1B scenario, which has received criticism for being overly optimistic about future emissions. The two additional RCM results use the RCP 8.5 and 6.0 scenarios, respectively, both of which are considered more conservative than the SRES A1B scenario. The two additional model runs are compared to equivalent runs using the RCP 4.5 scenario, which is more similar to the SRES A1B scenario.

A regional approach was used to construct extreme value distributions for historical and simulation data. The approach assumes that the annual number of extreme events follows a Poisson distribution and the magnitude of extreme events follows a generalised Pareto distribution. Some parameters of the distribution are estimated using regionalisation procedures. Some details of the distribution are provided in Gregersen et al. (2014).

Statistical post-processing procedures were used to project changes in the intensity of extreme events from RCM results. A number of procedures were used, ranging from the so-called “delta change” approach to more complex approaches. In the delta change approach, intensity-duration-frequency curves are developed for future rainfall and for a baseline period, both using simulation output. In this case, the baseline period used was 1961-1990. Intensity-duration-frequency curves are developed for each RCM grid cell, although some parameters of the extreme value distribution are estimated using regionalisation procedures, as discussed above. Regionalisation procedures were used because of significant variability in results across the different members of the simulation ensemble; because of the size of these differences, it was decided that it would be inappropriate to parameterise different distributions for different parts of Denmark. After extreme value distributions were developed, the intensities of different events are then compared and the ratio of intensities is used to recommend a “change factor” for adjusting design storms.

The delta-change approach uses RCM results directly to estimate changes in extreme precipitation intensities, and does not account for limitations imposed by the spatial grid size of RCMs, the time step used in RCMs, or limitations in the abilities of RCMs to simulate extreme events. To investigate whether these limitations might have a significant impact on estimated changes in extreme precipitation intensities, two other downscaling approaches were also used to downscale RCM results in both space and time. Details of the comparison are provided in Gregersen et al. (2014). It was found that the choice of downscaling method did not have a significant impact on resulting change factor estimates.

2.2 Obtaining climate change projections

2.2.1 Global climate model projections

Some of the climate model output used to support AR5 and previous IPCC assessment reports is available to the public, although restrictions apply for commercial use. The IPCC Data Distribution Centre provides information about data availability and instructions for downloading data. Some post-processed summary data are also available.

2.2.2 Regional climate model projections

The Coordinated Regional Climate Downscaling Experiment (CORDEX) is an effort to coordinate regional climate modelling studies and disseminate outputs to practitioners. CORDEX provides regional climate model outputs for the following regions:

- South America
- Central America
- North America
- Europe
- Africa
- South Asia
- East Asia
- Central Asia
- Australasia
- Antarctica
- Arctic region
- Mediterranean region
- Middle East and North Africa

Information about the different models and data access is available at the CORDEX website.

Regional climate model projections for Denmark

Regional simulations of Europe based on the latest generation of global climate models and RCP scenarios are available from the European CORDEX website, EURO-CORDEX. The older ENSEMBLES simulations that were used to support the new Danish guidelines for extreme rainfall are still available from DMI.

2.3 Estimates of future rainfall

IPCC provide estimates of future rainfall changes in AR5, for both averages and extremes. AR5 also provides an assessment of whether climate change can be observed in the recent historical record and a comparison of projected climate changes at different time scales.

The observed historical record and future simulations indicate that it is certain that temperatures have increased and are likely to continue increasing. Increasing temperatures increase the moisture-holding capacity of the atmosphere, and historical observations indicate that atmospheric moisture storage has also increased significantly since 1950. Increased atmospheric moisture storage is likely to lead to increased precipitation and more frequent and intense precipitation events, although it is less certain that this outcome has already been observed in the historical record.

Precipitation is affected by atmospheric circulation patterns, so changes in the atmospheric circulation will also affect rainfall. One of the most prominent features of the atmospheric circulation is the pattern generated by the thermal expansion of air near the tropics. This expansion causes air to rise, and the resulting cooling results in precipitation. The dry air then moves northward and southward, descending in the lower latitude regions that are associated with dry climates. It is likely that climate change will increase the size of the tropical zone, pushing the drier zones further north and south. In mid-latitude regions, on the other hand, it is likely that precipitation will increase. Figure 2.2 presents projections of changes in future rainfall for the four RCP scenarios.

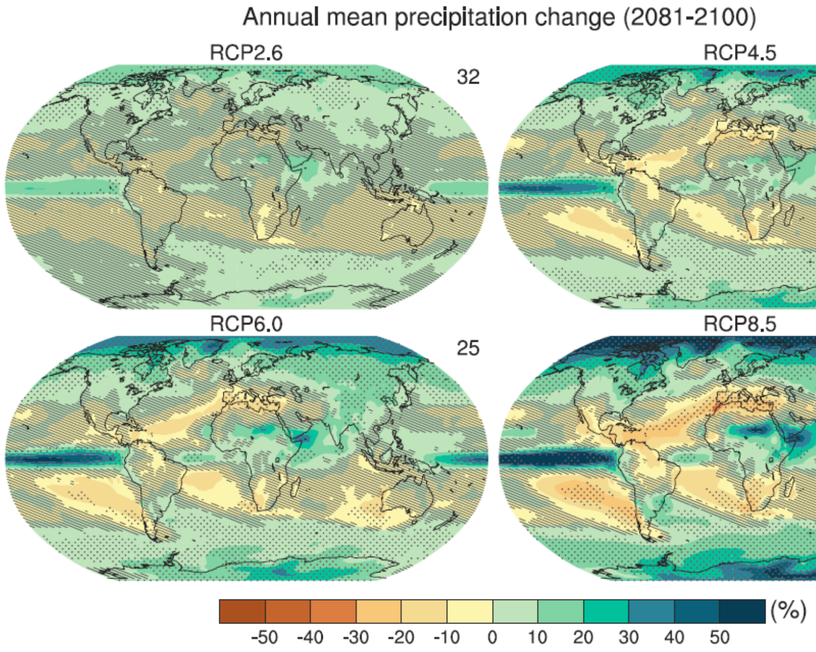


Figure 2.2 Percent changes in annual average precipitation relative to a 1986-2005 baseline. Titles at the top of each map give the RCP scenario associated with each estimate (for more information about the RCP scenarios, see below).The number at top right of each map gives the number of models used to simulate the average. Areas shaded by dashed lines are areas where projected changes are not significantly greater than might be expected given the natural variability of the climate system. Areas shaded by dots are regions where projected changes are significantly greater than natural variability. The maps suggest that precipitation will increase at higher latitudes and near the equator, with decreases in the lower latitudes. Source: Stocker et al., 2013

There is also evidence that changes in mean precipitation will be accompanied by changes in the intensity and frequency of extreme events. Although it is difficult to make conclusions about extreme events from the historical record, it appears likely that there have been increases in the frequency and intensity of extreme events in North America and Europe since 1950. In the future, climate models suggest that the intensity and duration of extreme events will increase. Figure 2.3 presents changes in projected extreme events. The figure suggests that changes in extremes will be greater in the tropics and mid-latitude regions than in lower-latitude regions.

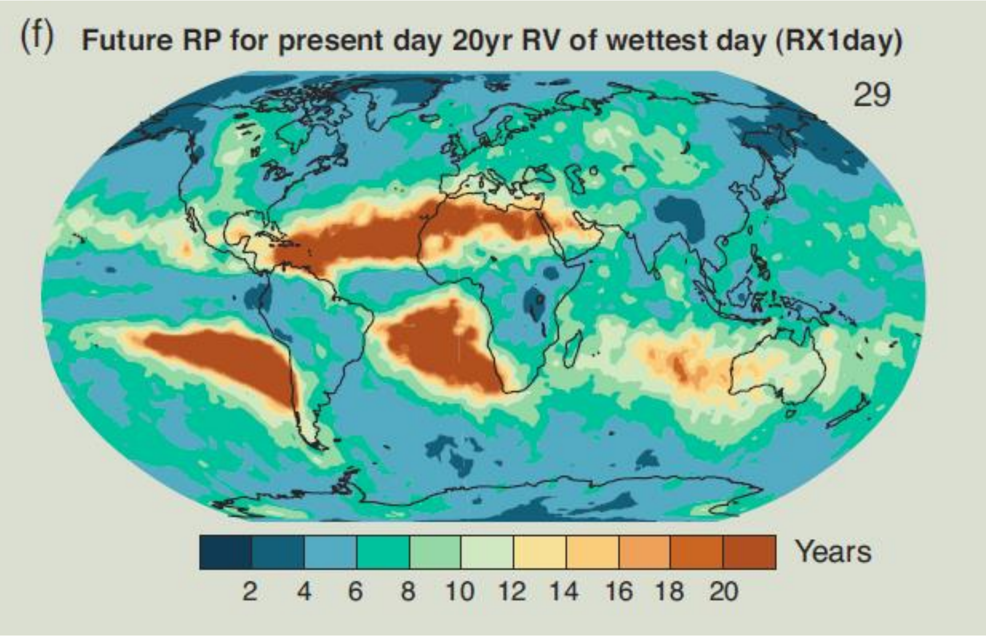


Figure 2.3 Projected return period in years for the period 2081-2100 of a daily rainfall event with a 20-year return period during the period 1986-2005. The figure suggests that intense rainfall events will become more frequent in many parts of the world. The number in the top right corner gives the number of simulation models used to develop the estimates shown in the figure. Source: IPCC 2014

Although the two figures presented above give projections for the period 2081-2100, AR5 also provides estimates of changes in precipitation and extremes for the near term. The report states that it is likely that mean precipitation will increase in medium and high latitudes in the near term, and that the frequency and intensity of extreme events will increase due to increases in atmospheric water vapor.

2.3.1 Estimates of future rainfall in Denmark

The new guidelines on extreme rainfall from the Water Pollution Committee of the Society of Danish Engineers (Gregersen et al., 2014) make projections about extreme rainfall. In addition, the guidelines provide an analysis of recent trends in extreme rainfall and estimate whether these trends can be explained by climate change.

As outlined in Section 2.1.1, change factors were estimated to apply to design storms for urban drainage design under climate change conditions. The change factors were estimated by comparing future simulation results for the period 2071-2100 to simulation results covering a 1961-1990 base period. Extreme value distributions were constructed for the future and baseline periods, and precipitation intensities were compared for different return periods and durations.

To provide recommendations for change factors, average values of the change factors computed using each of the ENSEMBLES simulations were computed and compared to change factors used in previous Danish design guidelines, which were based on outputs associated with the third IPCC assessment report. It was found that the average values from the ENSEMBLES simulations were comparable to previous change factors, so it was concluded that it was not necessary to adjust the previous change factors.

Recommendations were also provided for a higher set of change factors that may be more robust if future emissions and other drivers are not consistent with the SRES A1B assumptions underlying the ENSEMBLES simulations. The upper change factor estimate is based on the 84% quantile of the ENSEMBLES simulations. To assess whether the upper change factor estimate is reasonable, the difference between the ENSEMBLES average and 84$^{\%}$ quantile was compared to the difference between change factors developed using the RCP 4.5 and RCP 8.5 scenarios. It was found that the difference in the value of change factors was comparable, which suggests that change factors based on the 84% quantile of the ENSEMBLES simulations are reasonable for approximating conservative assumptions about future emissions. A comparison of change factors for hourly precipitation estimated using different methods is presented in Figure 2.4.

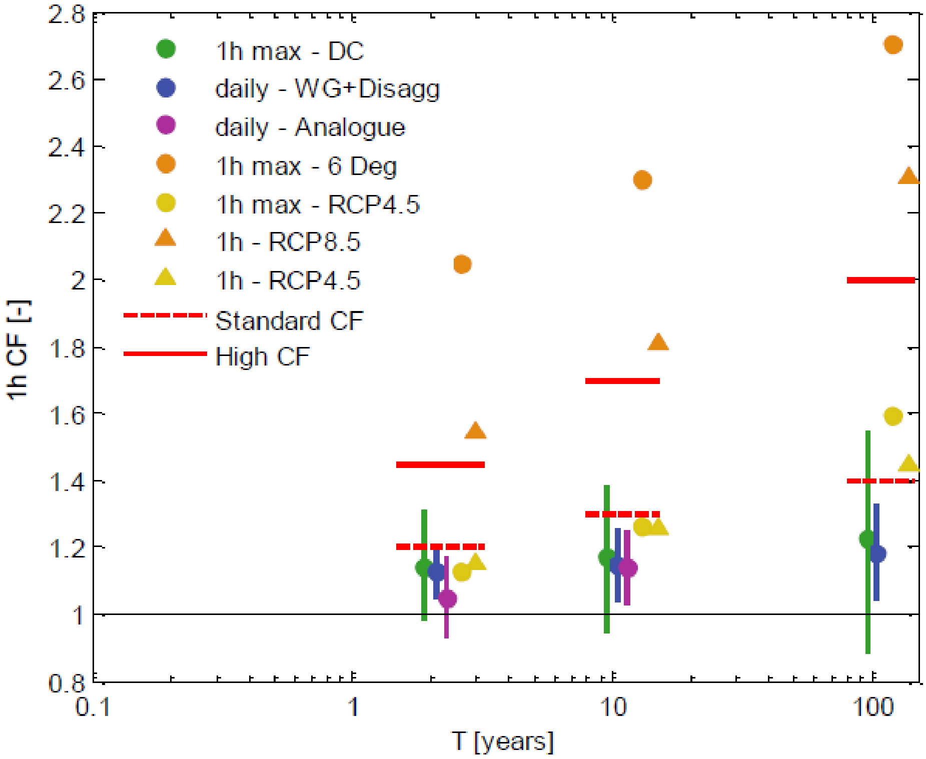


Figure 2.4 Comparison of change factors for hourly precipitation. The green, blue, and purple dots are average change factors for the ENSEMBLES simulations, computed using different downscaling methods. The associated vertical lines represent the 68% confidence interval for each downscaling method. The dotted red lines are the change factors from the previous Danish guidelines, while the solid red lines are change factors based on the 84% quantile from the ENSEMBLES simulations. The orange and red circles compare the RCP 4.5 and 6 scenarios, while the orange and red triangles compare the RCP 4.5 and 8.5 scenarios. The comparison suggests that the previous Danish guideline estimates are within the 68% confidence interval of the ENSEMBLES simulations, and that the difference between the average and 84% quantile of the ENSEMBLES simulations is comparable to the difference between the RCP 4.5 and 8.5 scenarios. Source: Gregersen et al. 2014

Change factors were also estimated for daily precipitation, but the difference between hourly and daily change factors was not found to be significant, except for the high-end change factors associated with the 84% quantile of the ENSEMBLES simulations. For simplicity, the new guidelines recommend using the same change factors for all durations. The final change factors recommended for use in Denmark are given in Table 2.1.

Table 2.1 Recommended change factors for urban drainage design in Denmark. Source: Gregersen et al. 2014

Return period (years)	Standard	High
2	1.2	1.45
10	1.3	1.7
100	1.4	2

The new guidelines also provide change factors for periods less distant in the future than the 2071-2100 period used to estimate the change factors shown in Table 2.1. Change factors are estimated for the periods 2021-2050 and 2041-2070. Because the midpoints of these periods are 50 and 70 years, respectively, from the midpoint of the 1961-1990 base period, these are considered projections of conditions 50 and 70 years in the future, even though the start dates of the simulation period are fewer than 10 and 30 years from the present. (The 2071-2100 period is considered a projection of conditions 100 years in the future even though the midpoint of this period is 110 years from the base period midpoint.) Change factors for the nearer-term are estimated by linear interpolation from the 2071-2100 estimates, and are presented in Table 2.2 and

Table 2.3.

Table 2.2 Change factors for a projection period of 50 years Source: Gregersen et al. 2014

Return period (years)	Standard	High
2	1.1	1.23
10	1.15	1.35
100	1.2	1.5

Table 2.3 Change factors for a projection period of 70 years Source: Gregersen et al. 2014

Return period (years)	Standard	High
2	1.14	1.32
10	1.21	1.49
100	1.28	1.7

The new Danish guidelines also present a statistical analysis of observed rainfall in the recent historical record to estimate whether evidence of climate change can be observed. Figure 2.5 suggests that the number of extreme events has increased in recent years. However, the figure also presents evidence of cycles of long-term variation; the authors of the guidelines conclude that it is not yet possible to determine whether recently observed changes can be separated from natural cycles of variability observed in the historical record. Figure 2.6 indicates that the average intensity of extreme events has not increased significantly in comparison to the historical record.

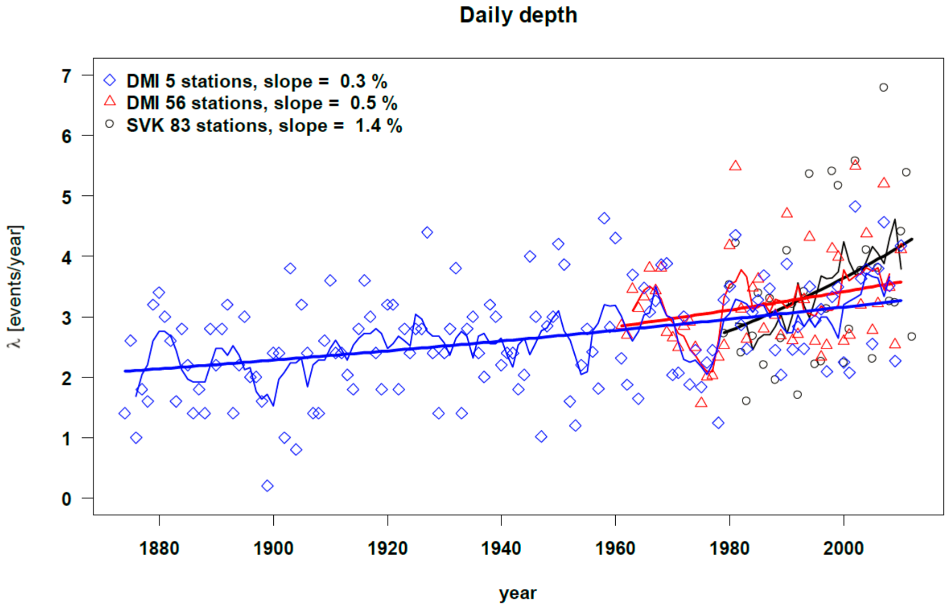


Figure 2.5 Number of extreme events observed per year for different historical records. The thin lines represent five-year moving averages, while the bold lines show a Poisson regression. Source: Gregersen et al., 2014

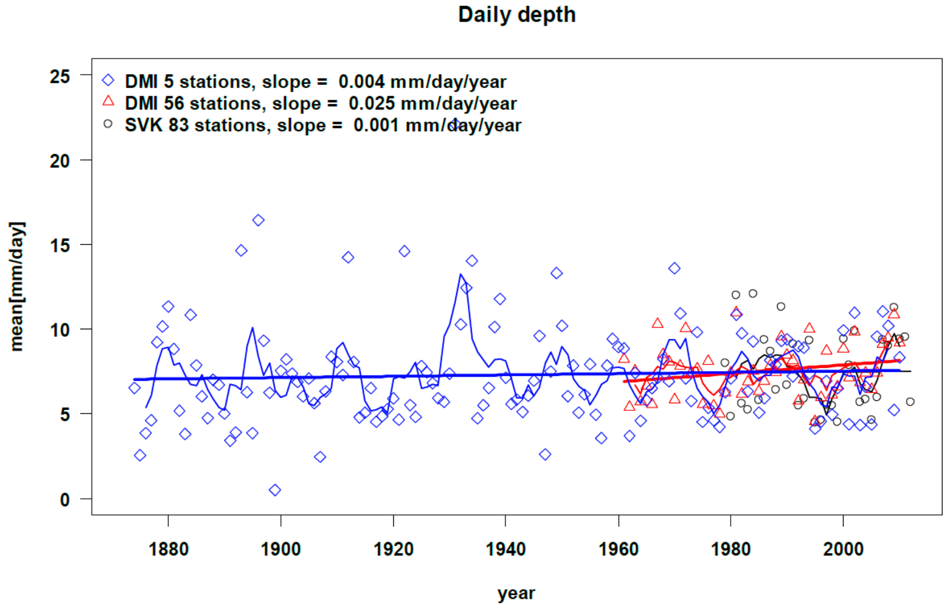


Figure 2.6 Average annual intensity of extreme events for different historical records. The thin lines represent five-year moving averages, while the bold lines show a Poisson regression. Source: Gregersen et al., 2014

2.4 Future water levels in marine waters

Future water levels in marine waters are of concern to urban drainage planners in coastal regions where maritime receiving waters are a boundary to the drainage system. In addition, changes in marine water levels can affect groundwater levels, with impacts on urban drainage.

In AR5, IPCC conclude that it is virtually certain that sea level rise accelerated in the 20th century to a rate that can be measured in mm/year. The dominant contributors to sea level rise are ocean thermal expansion and glacier mass loss (from Greenland and Antarctica). IPCC project that, mainly as a result of these processes, sea levels are certain to continue rising throughout the 21st century and beyond. Historical and projected sea levels are compared in Figure 2.7.

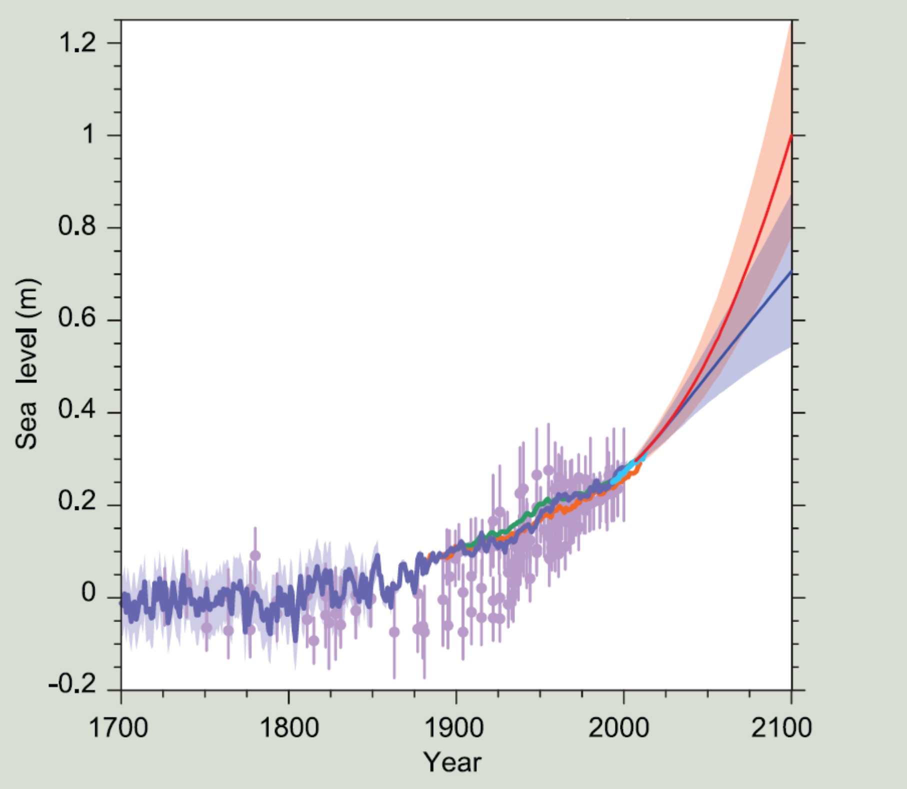


Figure 2.7 Comparison of sea levels from paleo records (purple), tide gauge data (blue, red, and green), altimeter data (light blue), and average estimates and ranges for the RCP 2.6 (blue) and 8.5 (red) scenarios. Source: Stocker, 2014

Estimated mean sea level rise projections are presented in Table 2.4.

Table 2.4 Estimated mean sea level rise (metres) relative to 1986-2005 reference period for RCP emissions scenarios. The range is estimated from different climate models used to support AR5. Source: Stocker et al., 2014

	2046-2065		**2081-2100**	
Scenario	**Mean**	**Likely range**	**Mean**	**Likely range**
RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

IPCC project that sea level changes will vary regionally. It is likely that 95% of the ocean will experience sea level rise by the end of the 21st century, with the regions experiencing declines projected to be those located near current and former glaciers and ice sheets (this effect occurs because the large mass of glaciers and mass exerts a gravitational force on ocean water, which is reduced by melting). For areas where sea level rise is expected, local sea level changes may deviate by approximately 25% from the mean projection for as much as 9% of the ocean area. About 70% of coastal areas are expected to experience a sea level rise within 20% of the global mean projection. A comparison of projected mean sea level changes is presented in Figure 2.8.

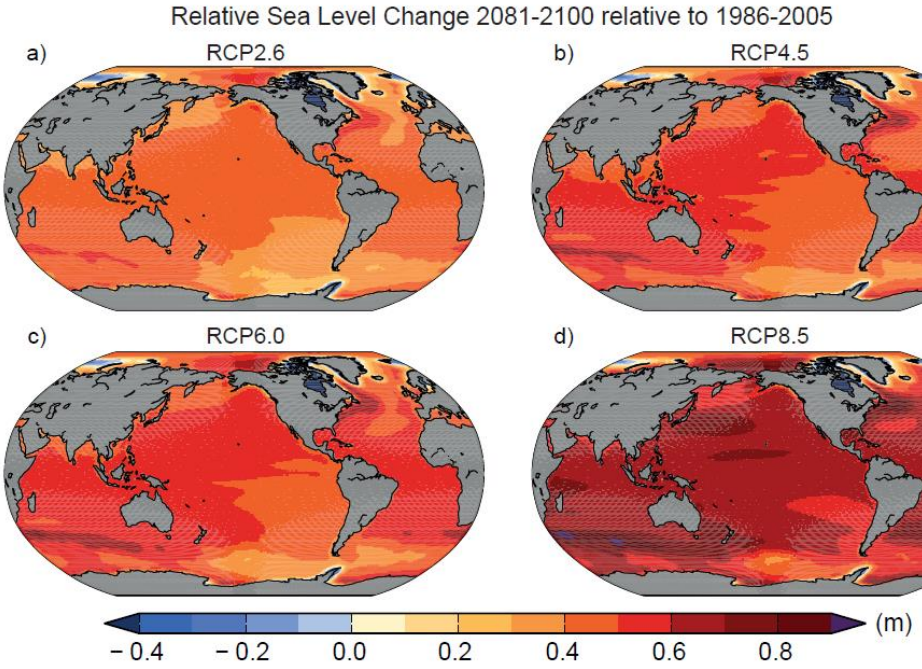


Figure 2.8 Comparison of mean regional sea level change for different emissions scenarios. Source: Stocker et al., 2014

Extreme sea level rise events are also of concern to urban drainage planners, particularly when these events take place at the same time as extreme rainfall events, as the capacity of the drainage system is then compromised at the time when it is needed most.

IPCC project that it is very likely that the frequency of extreme sea level rise events will increase by as much as an order of magnitude by the end of the 21st century. While most of this increase will be driven by changes in mean sea level rise, some will be due to increased wind speeds. IPCC do not make projections about the regional distribution of extreme sea level rise events because of uncertainty related to downscaling wind outputs from global climate models.

In coastal regions where there is a risk that an extreme sea level rise event could occur at the same time as an extreme precipitation event, a joint probability analysis should be considered so that the risk of both events occurring at the same time can be better understood. An example of a joint probability analysis in the Danish context is provided by Sunyer et al. (2009).

2.4.1 Future water levels in marine waters in Denmark

In the future, the mean sea level along the Danish coast will increase due to climate-related sea level rise. In addition to this, new climate-related extreme wind fields will lead to backwater or increases in near shore sea level, impacting boundary conditions for drainage systems that discharge by gravity to the sea.

Both DMI (Olesen et al., 2014) and the Danish Ministry of Environment (Christensen et al., 2014) provide information about climate change in Denmark that includes projections of mean sea level rise. There are some differences between the projections presented by the two agencies.

DMI compare projected mean sea level rise in Denmark with the projected global mean. The comparison uses local differences in projections developed as part of the AR5 projections. The comparison is presented in Table 2.5.

Table 2.5 Comparison of global mean sea level rise projections to projections for Denmark. All figures give the projected change in metres for 2081-2100 relative to a 1986-2005 baseline. Source: Olesen et al., 2014

	Global		**Denmark**	
Scenario	**Mean**	**Likely range**	**Mean**	**Likely range**
RCP2.6	0.40	0.26 to 0.55	0.34	0.10 to 0.60
RCP4.5	0.47	0.32 to 0.63	0.43	0.20 to 0.70
RCP6.0	0.48	0.33 to 0.63	0.44	0.20 to 0.70
RCP8.5	0.63	0.45 to 0.82	0.61	0.30 to 0.90

DMI also provide an upper limit estimate on projected sea level rise in Denmark and compare the change in this value over time to projections from IPCC. The comparison is presented in Figure 2.9.

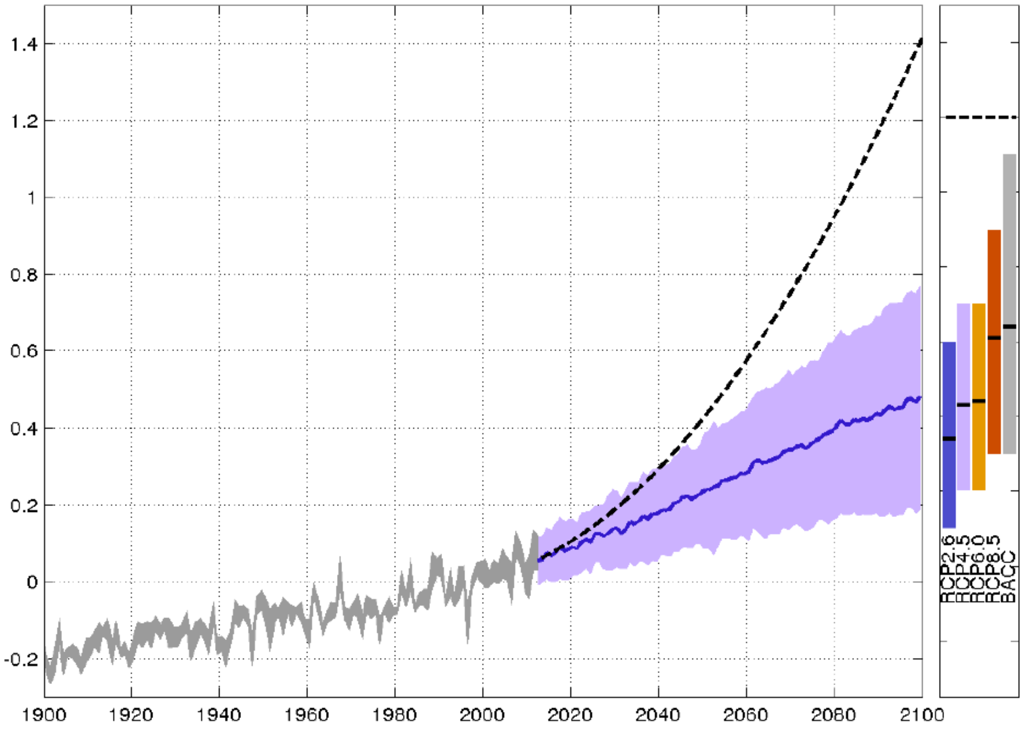


Figure 2.9 Comparison of observations and projections of mean sea level rise. The grey line represents observations of Danish mean sea level. The blue line represents the multi-model mean of IPCC projections for the North Sea assuming the RCP4.5 scenario, and the shaded area surrounding the line gives the range of projections from the different models. The dotted line is the upper limit of DMI's projection of mean sea level for Denmark. Mean projections and the associated range of projections from the multi-model ensemble are compared for different emissions scenarios for the 2081-2100 period in the box to the right. The grey area gives the range average and range for a simulation of conditions in the Baltic Sea that was based on the SRES A1B scenario. Source: Olesen et al., 2014

The Danish Environment Agency has also published estimates of mean level rise around Denmark (Christensen et al., 2014). These estimates are also based on AR5. The Environment Agency's presentation suggests a mean sea level rise of 0.7 m by 2100. A map showing the agency's projections is presented in Figure 2.10.

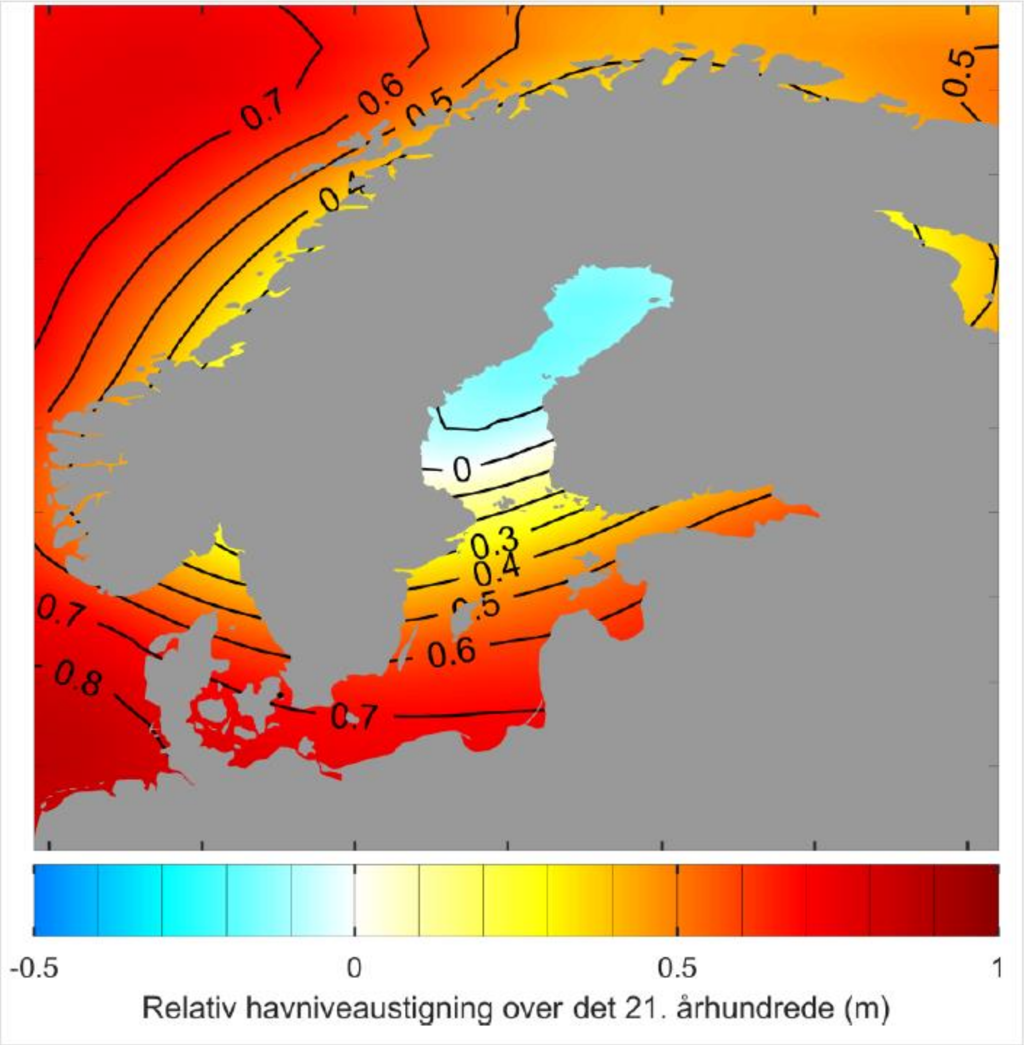


Figure 2.10 A map presenting projections changes in mean sea level rise between the present and 2100. Projections are taken from global estimates developed as a part of AR5. Source: Christensen et al., 2014

The Danish Environment Agency have also estimated probability density functions that estimate the probabilities that average sea level rise will be less than or equal to different values at different locations around Denmark. The probability density functions were estimated by the agency considering uncertainty associated with the different RCP emissions scenarios, as well uncertainty regarding conditions surrounding the large ice caps. A probability density function for Copenhagen is presented in Figure 2.11.

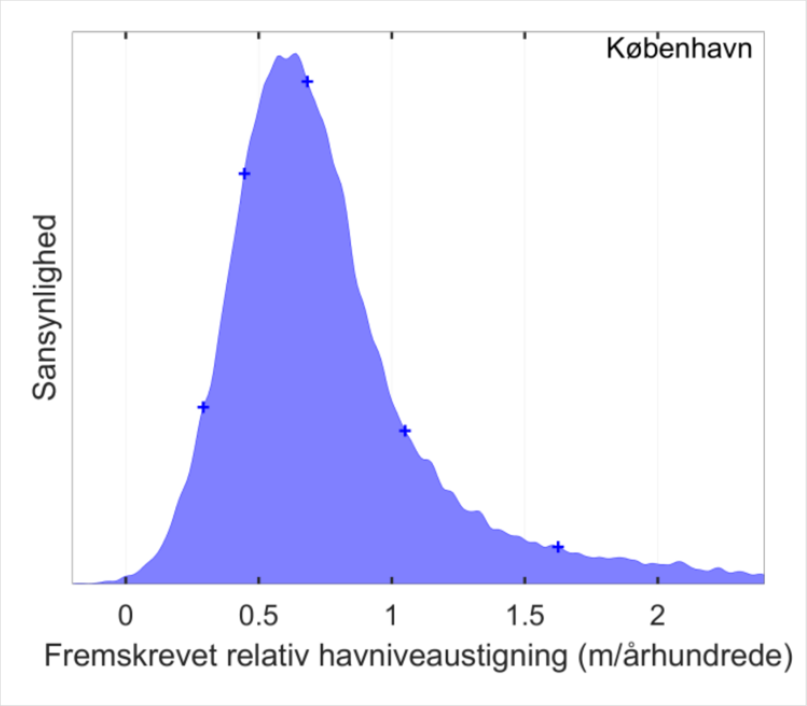


Figure 2.11 Probability density function describing likelihood of mean sea level rise per century for Copenhagen. Source: Christensen et al., 2013

The impact of mean sea level rise will be partially offset by uplift, particularly in Northern Jutland. Therefore, estimates of mean sea level rise should be adjusted accordingly. Land subsidence can have the opposite effect, amplifying the impact of sea level rise, and should also be included in mean sea level change estimates where information on subsidence is available. Guidelines for adjusting estimates of mean sea level rise are provided by the Danish Coastal Authority (Sørensen et al., 2013).

The magnitude of extreme sea level rise events is expected to increase significantly as a result of both mean sea level rise and also because of climate change impacts on factors affecting storm intensities, such as wind speeds. However, there is currently no guidance in Denmark on how to estimate how changes in factors apart from mean sea level rise might affect the frequency of storm surge events. It is recommended that existing duration curves simply be scaled by the magnitude of expected mean sea level rise changes.

Examples of how existing duration curves should be scaled by changes in mean sea level are presented in Figure 2.12. The impact is projected to be strongest on the west coast of Jutland. In Esbjerg, the current 500-year event, a rise of 4.4 m, is projected to become a 10-year event by 2100. In Copenhagen, the current 500-year event, a rise of 1.7 m, is projected to have a return period of less than one year by 2100.

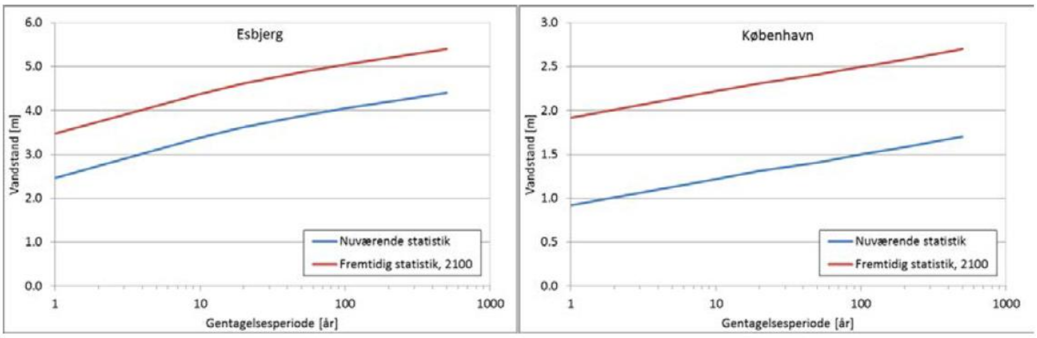


Figure 2.12 Comparison of projected changes in the magnitude of extreme events for Esbjerg and Copenhagen. Both projections assume a mean sea level rise of 1m. Source: Christensen et al., 2014

The use of scaled duration curves for storm surge events in urban drainage planning would require carrying out a joint probability analysis to estimate the probability that a storm surge would occur at the same time as an extreme rainfall event. Although these types of analysis are common in the research literature (for a Danish example, see Sunyer et al., 2009) and have been carried out in professional practice in some jurisdictions, there is currently no formal guidance in Denmark on how to carry out joint probability analyses. Therefore, it is recommended that only mean sea level changes be considered in urban drainage studies in Denmark.

2.5 Future water levels in lakes and rivers

Climate impacts on water levels in lakes and rivers are of concern for urban drainage planners where these water bodies act as boundary conditions to the urban drainage system. In the future, it is expected that rivers will also be affected by climate changes. Sea level rise will create backwater effects in coastal areas and reduce drainage capacity, particularly during extreme events. Where rivers and lakes are boundaries to the urban drainage system, it is recommended that river hydraulics be described together with the drainage network in urban drainage modelling.

In AR5, IPCC provide an overview of existing studies of climate change impacts on catchment runoff (Jimenez Cisneros et al., 2014). As with precipitation, average annual catchment runoff is projected to increase at higher latitudes and in the tropics, and decrease at lower latitudes. The most significant change to runoff patterns resulting from climate change is expected to occur in catchments where snowmelt has historically made a significant contribution to runoff. Because of warming temperatures, it is likely that more winter precipitation will fall as rain rather than snow in the future, increasing winter runoff and reducing spring and summer flows. Indeed, there is robust evidence that this impact is observable in the historical record since the 1970s. In glacier-fed rivers, there is also evidence that meltwater yields from stored glacial ice will increase during the next decades but decrease thereafter.

2.5.1 Future water levels in lakes and rivers in Denmark

Danish rivers have large differences in water flow patterns. Some creeks have a relatively constant water flow with small differences between winter and summer flow. They can have a little sensitivity to extreme rainfall events, while other streams have large differences between winter and summer flow, and can show a strong response to extreme rainfall events. This type of stream may have a tendency to dry out in summer.

In rivers located in West Jutland, a fine balance exists between rainfall intensity and the risk of flooding. In the winter of 2006/2007, Storåen went over its banks in the area of Holstebro because of the high precipitation in autumn and winter months which lead to increased surface runoff to the receiving water. Flooding from the river reoccurred in 2011 because of a combination of frozen soil and fast snowmelt in connection with rainfall.

2.6 Future water levels / pressures in groundwater

The groundwater table is also an important boundary condition for urban drainage planning. Changes to the groundwater table might impact infiltration to or from the urban drainage system, with impacts on storm water and combined systems.

The expected increase in high-intensity precipitation events may have local impacts on the groundwater conditions. Especially in areas with coarse, sandy sediments a rapid rise in groundwater table may occur under very intense rainfall with potential infiltration into sewers, basements and other underground structures. On the other hand, high-intensity precipitation events can also reduce groundwater recharge when rainfall intensities exceed soil infiltration capacity.

In lower latitude regions, the combination of increased evaporation and reduced rainfall could reduce groundwater recharge, with impacts on streamflows in areas where groundwater baseflow makes an important contribution to overall river flow.

The projected sea level rise in coastal areas could also cause a rise in groundwater levels, altering the drainage of coastal catchment areas. In many cases the sea level rise will only have very local impact on groundwater conditions. However, it may have significant impact on runoff conditions in coastal rivers, where gradients are small, especially combined with the anticipated increased intensity of rainfall.

2.6.1 Future water levels/pressures in groundwater in Denmark

In Denmark, changes in groundwater levels resulting from extreme events have been observed to have an impact on the performance of urban drainage systems. Extreme rainfall events have resulted in a higher groundwater table, reducing surface runoff from permeable areas to the urban drainage system.

2.7 Determination of input time series data and boundary conditions - Recommendations

Modelling of urban drainage systems over longer time series can be useful for estimating the frequency and magnitude of overflow events. When coupled to models of rivers, groundwater, and/or coastal waters, time series modelling can also be useful for understanding the impact of changing boundary conditions on drainage system performance. The following section provides advice on how to develop estimates of precipitation time series under climate change conditions, along with other boundary condition values.

2.7.1 Developing precipitation time series

To develop time series estimates of precipitation under climate change conditions, statistical downscaling and bias correction procedures are used to post-process output from climate models. These procedures are similar to procedures used to develop estimates of changes in extreme values.

Statistical post-processing of projections of future rainfall may be required for one or more of the following reasons:

1. Spatial downscaling of climate model output from the climate model grid to an appropriate spatial scale.
2. Temporal downscaling of climate model output from the climate model time step to a time step appropriate for drainage system analysis.
3. Bias correction to reduce biases resulting from incomplete representation of precipitation in climate models, resulting from lack of data, lack of understanding, or computational limitations.

Even if spatial and temporal downscaling are not required, a bias correction step is always necessary when developing climate projections.

The most common method of downscaling and bias correction is the so-called delta change method, which accomplishes spatial downscaling and bias correction (and sometimes temporal downscaling) in a single time step. In the delta-change method, an observed time series is scaled by the difference between a control-period climate simulation and a simulation of future conditions. A number of approaches can be used to develop scaling factors, ranging from a simple ratio of mean values to more complex approaches that account for seasonal variation and differences between ratios of averages and extremes. When a delta-change approach is applied to an observed point time series, bias removal and spatial downscaling are accomplished in a single step.

A mathematically similar, but conceptually different, alternative to the delta-change approach is the so-called “direct approach”. In the direct approach, a simulation of future conditions is scaled by the difference between a control-period simulation and observed time series. The direct approach corrects bias but does not accomplish spatial downscaling, as the resulting time series is representative of rainfall over a climate model grid cell.

Both the delta change and direct approaches have limitations when used to develop precipitation time series for urban drainage planning. The principal limitation with the delta-change approach is that this approach assumes that the frequency of rain events in the future is the same as in the historical record, as the approach simply scales the historical record. The direct approach uses the rainfall event frequency from the simulation of future climate, and there is evidence that climate models overestimate the frequency of wet days; however, approaches have been developed for correcting wet-day frequencies in climate model outputs. For reviews of different post-processing approaches, see Maraun et al. (2010) and Sunyer et al. (2015).

Developing precipitation time series for applications in Denmark

These guidelines do not provide recommendations for developing projections of precipitation time series for urban drainage analysis applications in Denmark. However, if climate change projection of precipitation time series is needed, the following approach that is used by DHI Sweden could be considered. The DHI Sweden approach is a variant of the direct approach described above that includes a simple correction of the wet-day frequency.

In the DHI Sweden method, correction of precipitation data is performed in two steps: (1) the number of wet days simulated by an RCM control-period simulation is adjusted in order to obtain the same number of wet days as in the observed record, and (2) a set of correction factors are estimated that map the control period frequency distribution to the observed distribution. In the first step, control-period output from the RCM and observed values are sorted in descending order. For each season, a cut-off value is identified in order to obtain the correct number of wet days. Values below this threshold are considered dry days and precipitation is set to zero on these days. The result is an equal number of wet and dry days in the observed and modelled time series.

The remaining wet days in the RCM output are adjusted to match the observed values by introducing a set of correction factors covering the entire range of intensity levels (i.e., a set of correction factors, specific for each percentile in the frequency distribution, is derived, Figure 2.13). The correction factors are partitioned into two groups, separated by the 95th percentile, and a polynomial function is fitted to each group, with the functions estimated a correction factor as a function of location in the frequency distribution. The polynomial functions are used to correct RCM output for future climate, using location in the RCM output distribution as the argument to the fucntions. The correction is preceded by removal of low intensity precipitation values in the same way as for the baseline period, using the same cut-off value. The correction is performed seasonally (i.e.< specific cut-off values and polynomial correction functions are derived for each season; Dec- Feb, Mar-May, Jun-Aug and Sep-Nov).

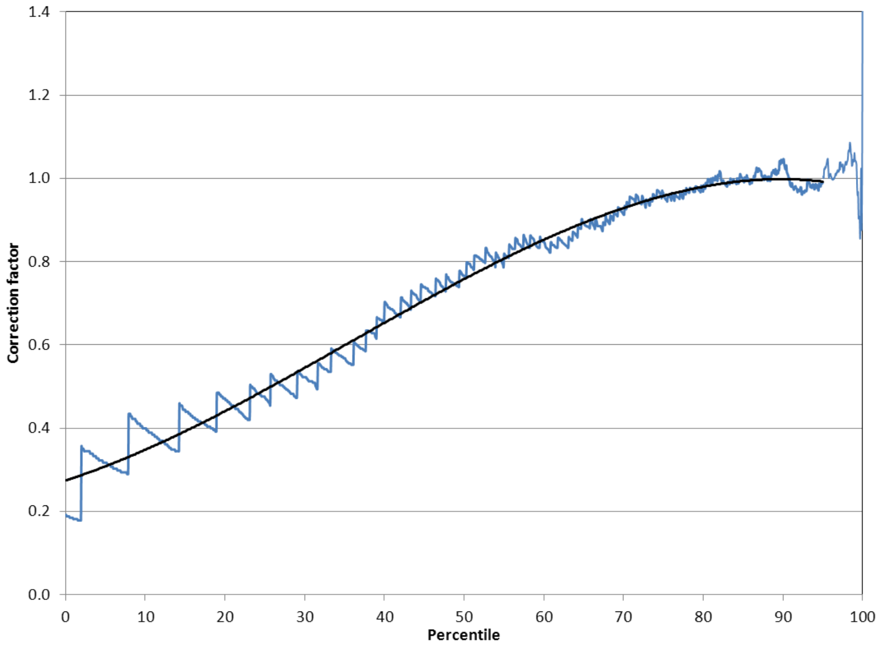


Figure 2.13 Percentile dependent correction factors (blue line), Sep-Nov for the reference period. The black line show a third degree polynomial function fitted to the correction factors <95th percentile

2.7.2 Coupled rainfall

The floodings that have taken place in recent years, have been due largely to the fact that large amounts of rain have fallen in a very short time, but in several cases the flooding has also occurred because the rain has fallen at times when the drainage systems (canals, streams, lakes, reservoirs and the groundwater zone) have not been emptied after a previous rainfall. This is referred to as coupled rain.

The impacts of such coupled rainfall events are not usually taken into consideration in the standard design of urban drainage systems. The potential impact of coupled rainfall can be estimated using long-term simulations of long rainfall time series measured in the local area. The simulations of the drainage system focus on a dynamic modelling of the relationship between streams, lakes, groundwater and water levels. A simple multiplication of a climate change factor to an existing rainfall series does not take into consideration that the interval between different rainfall events may become shorter in the future, which will increase the risk of coupled rainfalls. Projections of climate change precipitation, which include coupled rainfalls, should therefore be developed as described in the previous section.

Coupled rainfall in Denmark

Flooding resulting from coupled rainfall events has occurred in Denmark. However, there are currently no recommendations for how to take coupled rainfall into account in urban drainage design.

2.7.3 Other boundary conditions

The water levels in lakes, streams, coastal marine areas, and groundwater are boundary conditions for runoff from storm water system. In each area to be analysed, it should therefore initially be assessed whether it is likely that the boundary conditions will change significantly as a result of climate change.

The water level of a river or stream depends on runoff intensity and volumes from urban and rural hinterlands. If rainfall intensity increases in the future, it is expected that the maximum flow of the rivers increases as well. River base flows may also be affected by changes in groundwater levels resulting from climate change. If boundary conditions for an urban drainage system include rivers or streams, the impact of climate change effects on river and stream hydraulics should be investigated, either by using projected average values in urban design calculations or by simulating river hydraulics together with the drainage system in a long time series simulation.

For urban drainage systems that discharge to marine waters, it is recommended to use a sea level projection as a new downstream boundary condition. The new boundary can be a mean sea level, an extreme estimate, or a time series (if a long time series simulation of the drainage system is being considered).

Future water levels in lakes will depend on the future river flows, infiltration/recharge of groundwater and the amount of evaporation which according to DMI will increase as a result of increased temperatures. Lake boundary conditions can also be represented as means, extremes, or time series.

The water level in the groundwater zone affects river and lake levels, the extent of infiltration to the drainage system. In addition, groundwater levels are affected by sea levels. Infiltration to groundwater is affected by the amount and intensity of precipitation, evaporation, and land use. Because of the complexity of feedbacks between the groundwater system, drainage system, and other boundary conditions, it can be challenging to develop reasonable projections of groundwater conditions under climate change without undertaking a complex modelling exercise.

Other boundary conditions in Denmark

To include all of the above effects of climate change that could influence the future drainage system, it is necessary to establish a complete hydrological model which includes ocean, groundwater, lakes, streams and storm water system. This is currently beyond the scope of most municipalities and it is considered sufficient to use existing boundary condition data, with the exception of mean sea level values, which should be adjusted using IPCC or local projections.

Description of desired standard of services

Construction of urban drainage systems must comply with Danish practice (Guides from Wastewater Committee) specifying how much rainfall the urban drainage system is required to convey. This is the dimension criteria. If an extreme rainfall event occurs, then the urban drainage system is not required to have capacity to convey the water. Figure 2.14 shows an illustration of the principles of dimensioning of urban drainage systems. The figure shows the overall existing conditions in a municipality. Note that service levels can be described similarly for increased groundwater potential or seawater level.

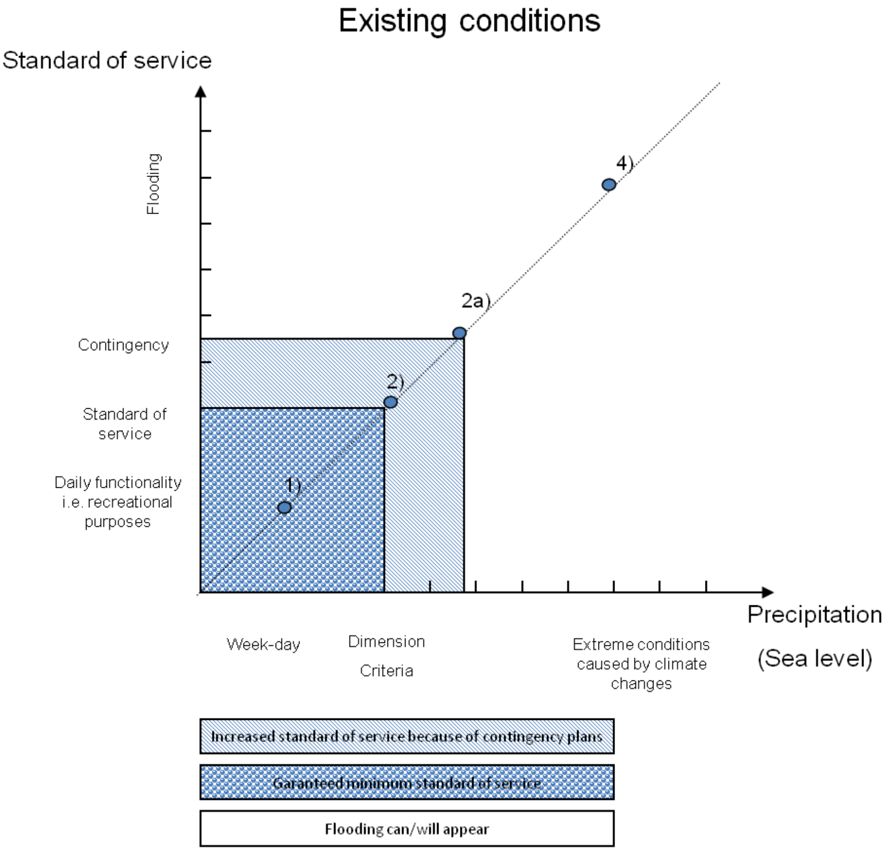


Figure 2.14 Existing conditions in the drainage systems

The amount of precipitation (the further to the right the greater precipitation) is given on the horizontal axis, and the probability of flooding is displayed on the vertical axis. The entry on line 1) represents a normal rainfall, i.e. between 10 and 20 mm. In this situation flooding due to rainfall should never happen. Additionally, it is appropriate that artificial lakes, canals, streams etc. fit into the city and appear as realistic recreational elements (i.e. there is a minimum and clean water flow in rivers, relatively clean water in the lakes, and channels are designed so that they appear "nice" in the city / landscape, etc.).

Along the line to the right the flood risk limit is reached for the current dimensioned urban drainage systems. For existing urban drainage systems this situation corresponds to a rainfall with an intensity of 8-9 mm over 10 minutes, which could previously be expected to occur every second year (averaged over many years). In this situation the capacity of the storm water systems will be reached, but there will be no flooding. This is under the condition that urban drainage systems are sufficiently maintained.

If there is an increase in precipitation (higher up on the line), the risk of flooding (as shown on the vertical axis) will increase. Within the existing network flooding can be reduced by putting a contingency plan in operation as illustrated by 2) -> 3) in the figure: Before the rain falls, the lakes and channels can be drained in order to have available storage capacity, pumping water with mobile pumps, dig out additional appropriate storage locations, cleaning grates, dam rivers, etc. In addition, if a flood incident is forecasted in a specific area, fences can be put up to avoid accidents due to flooding.

Point 4 in the figure illustrates the situation when flooding will occur. The rainfall is so extreme in this situation that it will not be possible from an economic point of view to avoid flooding.

In Figure 2.15 a vision for the development of urban drainage system and implementation of climate adaptation is given.

Based on the increasing rainfall, there is a need to revise the current dimensioning standard so that the urban drainage systems can handle the increased amount of rainfall. Point 3 in Figure 2.15 illustrates this.

The effect of Guide 27 is that the guaranteed minimum standard of services is now at point 3 when new construction is planned. The rainfall needs to be more extreme in order to cause flooding – which effectively means that minimum standard of service level is raised for current rainfall but that the population will experience the same occurrence of flooding as today when the full climate effect has been reached (approx. year 2100).

A rainfall event corresponding to point 3) represents now the guaranteed limit against flooding. Further along the horizontal line towards the right (increased precipitation) there will be a risk of flooding. Contingency plans can reduce the damages illustrated by moving from 3) to 4) in Figure 2.15.

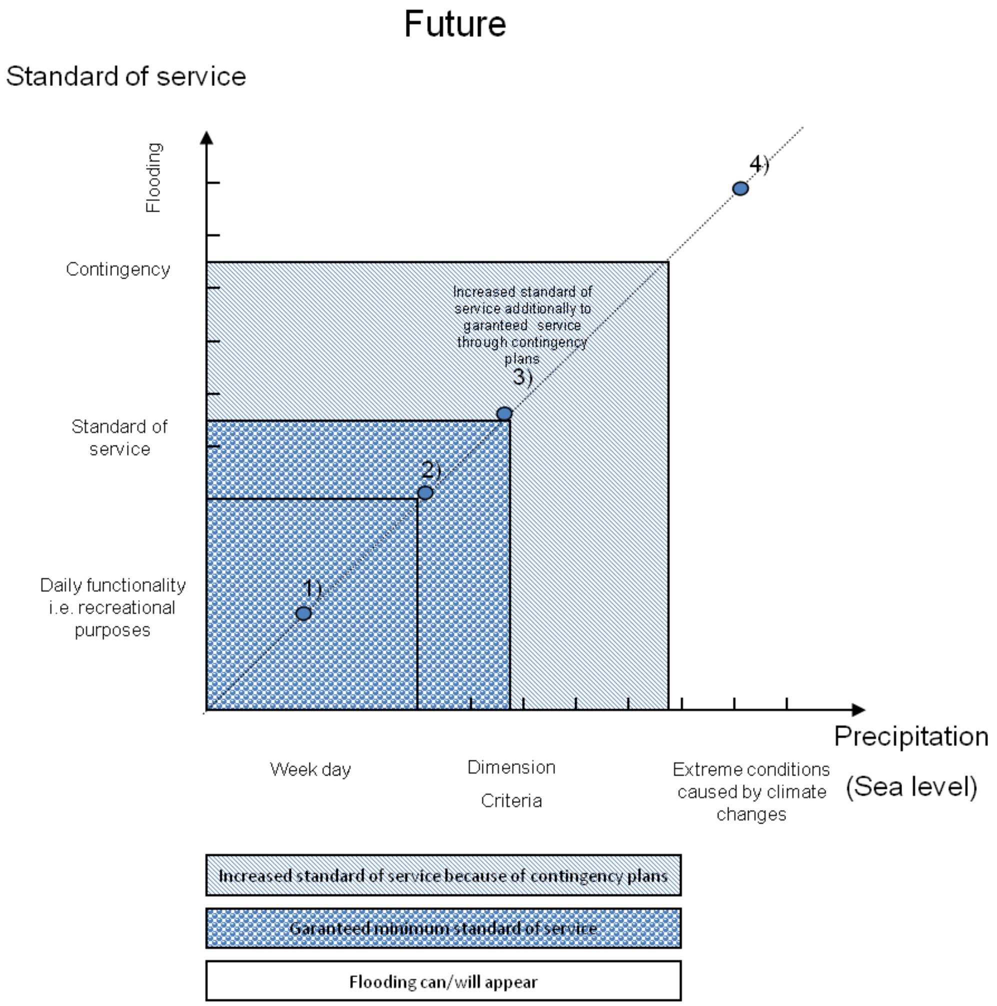


Figure 2.15 Vision for the conditions in drainage systems in Greve Kommune (colour explanation similar to that in Figure 3.1)

The last item on line 4) indicates the conditions of the extreme rainfall, as seen in recent years in many municipalities such as Greve in August 2002 with 100 mm in three hours and in July 2007 with 250 mm within a period of three weeks (and approx. 60 mm in one day). In these situations (4) there are no guarantees against flooding. Contingency plans might reduce flooding and damage, but it is likely that flooding will occur.

Making a city resilient against such precipitation conditions the guaranteed minimum service levels must be moved towards Point 4) with extensive investments as a result.

It is a political question if the minimum guaranteed service level should be raised through expansion of existing system. It is a question of what is acceptable and willingness to pay.

Water Utilities are responsible for fulfilling the national requirements as described by Land Commission Guides for old systems and in the Wastewater Committee Guides in recent years, (point 2) in Figure 2.15. These requirements may be considered as Danish practice in this area for constructions undertaken before 2005. Constructions established after 2005 must comply with the new requirements described in Guide 27, corresponding to point 3 in Figure 2.15.

If a municipality wants to establish a higher level of service than point 2 for constructions undertaken before 2005, or possibly also for point 3 constructions after 2005, it is a local political issue.

As it is today, municipalities are not responsible for flooding in the cases where precipitation is above point 2, and there is no legislation requiring authorities to take into account these precipitation events.

2.7.4 Service level and compliance with operational requirements under the influence of climate change

The changes in rainfall over Denmark as described in section 2.3 result in an altered response in urban drainage systems in the future.

Work to reduce the negative impact from climate changes on drainage systems will have the overall aim of reducing potential damage to community values - either by reducing the flood level, or by reducing damage through efficient management of potential flooding.

Danish urban drainage systems constructed after 2005, must comply with functional requirements formulated by the Wastewater Committee in Guide 27:

- In combined sewered areas surcharges to terrain is only allowed once every 10 years
- In separate sewered areas surcharges to terrain is only allowed once every 5 years.

These are minimum requirements, and municipalities are allowed to set higher standards to meet additional and / or more stringent requirements. In Guide 27 it is stated that it is the actual situation in the catchments that is decisive based on e.g. the actual frequency of surcharges. It is pointed out that when sizing and analysing urban drainage systems, future changes in climate must be taken into account, particularly changes in rainfall conditions and water level in receiving waters in order to ensure that the system meets the required functional requirements throughout the life expectancy.

In order to check if service levels are maintained, calculations (corresponding to precipitation described in Section 2.3) can be undertaken to analyse the response in urban drainage system to changes in climate with return periods of 10, 25, 50 and 100 years. This analysis will reveal locations and timing in the urban drainage system where function requirement is exceeded. This information can be included in plans for maintenance and expansion. It is recommended by the Environmental Protection Agency report, Environmental Project No. 1123 (2006) that a problem identification and prioritisation of the effects of climate change on three levels must be undertaken:

Level 1. Analysis of whether climate change will result in a violation of current operational requirements.

Level 2. Mapping of the level of flooding as a result of the new design rainfall based on forecasts of future climate changes. The water depth and spatial distribution of the flooding is assessed as well as the potential damage.

Level 3. If significant flood water is surcharged to terrain, an assessment of any damage and management of water on the ground must be undertaken. This assessment is part of the planning when a drainage system should be adapted so it can handle the extra rainfall due to climate change.

When the problems are identification they are prioritised using the risk analysis procedure described in Chapter 6.

An example of such a projection of a 10-year design rainfall including calculations of functional specifications to the urban drainage network is provided in Appendix A and Appendix B. Municipalities can use this method to prioritise measures against floods. These calculations will show the trend in the exceeding of the functional requirement. It should be noted that any planned urban development should be included in the calculations.

3 Modelling of flooding from storm water system and rivers

3.1 From surface depression maps to sophisticated hydraulic models

3.1.1 Model tools

In connection with the choice of modelling tool for use in the analysis of climate adaptation, it is important to focus on the following questions:

- What is the purpose of calculations?
- What is the terrain in the area like?
- What data is available?

In many cases only knowledge about whether a flood event may arise or in which areas it may happen is required. In other cases there is a need for detailed calculations of return periods and extent of flooding.

The types of modelling tools that are useful for different problems depend largely on the urban drainage system dynamics and the shape of the terrain. In a simple urban drainage system where the dynamics are less important, it is often possible to implement a qualified calculation of flood extent based on the calculation of water balance. In urban drainage systems that are more complicated, it is necessary to use a dynamic drainage model.

Similarly, the terrain types are divided into simple cases, which are characterised by gully pots / basins without dynamics and more complicated cases where the dynamics on the surface are important.

There is often great variation in the level of detail and quality of data. For instance if there is any calibrated dynamic model of drainage area available and if it is possible to acquire a terrain model and GIS data of the houses and roads.

In GIS the digital terrain model, DTM is used to locate indentations in the surface and nominate these depressions as known risk areas. An increasing number of people are using DTM’s to assess the risk of storm water flooding in cities. In many cases, these depressions are not necessarily risky, as there may be drainage channels draining these gully pots, such as rivers, ditches, storm drains, etc. DTM’s are also used to assess flood risks from the sea in the same way as for storm water flooding, however, in this case the analysis is not necessarily complete: The depressions that appear as gully pots are only filled if there is a system directing water to the depression.

The analytical methods can be improved by modifying the DTM so that the assessments take into account any drainage systems directing water away from or towards the indentation. Finally, it takes into account that the water flow has a certain duration, which is then included in the application of numerical hydraulic models.

As shown, the DTM can be used at different levels of analysis of climate change impact on flood risk in the city: They can be used right from the very simple to the most complex methods. From surface depression maps to sophisticated computer models.

The technical analysis method, using the terrain model at one of the levels can be called *"technical path"* see Figure 3.1.

3.1.2 Decision making process

When using terrain models for analysis of climate change, it is very important to consider what the analysis will be used for: Is it for the initial flood risk assessments? Is it for determining the desired standards of services of storm water and river systems? Is it for assessing various climate adaptation options? Looking at the method from surface depression maps to sophisticated computer model as an odometer from left to right (see Figure 3.1) is like looking at a “decision-climate-meter” that ranges from "we must investigate climate adaptation’, to "we need climate adaptation", to "the city is climate adapted and we will monitor the city". The application can be called *"the political path”.* The political path follows the technical path since the policy-making processes require different degrees of technical knowledge.

3.1.3 The multidisciplinary angle

When implementing climate adaptation within municipalities terrain models and hydraulic assessments may be used for very different things: they can provide the city planner with an idea of the areas to be exempted from other applications and used as storage areas for storm water; they can be used by the officer to assess whether a planning permission can be given or not for a specific area or whether further analysis is required to authorise a permission; they can be used by environmental planner / river authority for advice on the establishment of wetlands for retention of nutrients and the landscape architect to assess how various natural elements may be placed. Again, the different disciplines require different applications of technical knowledge and follow "the climate-meter" for the technical path: City planners can use a simple "surface depression map" to determine land use, but in the local plan the hydraulic conditions in combination with terrain model must be known in more details before a definite land use may be established in a locality. The River Authority must know the specific water levels in rivers and thus hydraulic models of rivers and terrain levels are required in order to implement a stream-regulation which also has a positive impact on the climate adaptation.

The Landscape Architect may in some cases use the simple surface depression maps for example to place a lake, but in other cases known water levels are required to ensure that the lake will actually contain water! At the “climate-meter” a "multidisciplinary" path can be added, where applications of different disciplines in technical departments can be anchored.

3.1.4 Economy

The price for achieving the various levels of the “climate-meter” ranges from relatively cheap to relatively expensive, from left to right: One can relatively easily work out a "depression map" on un-quantified data, but very detailed and hard work is required to establish an advanced hydraulic model which includes the entire water cycle.

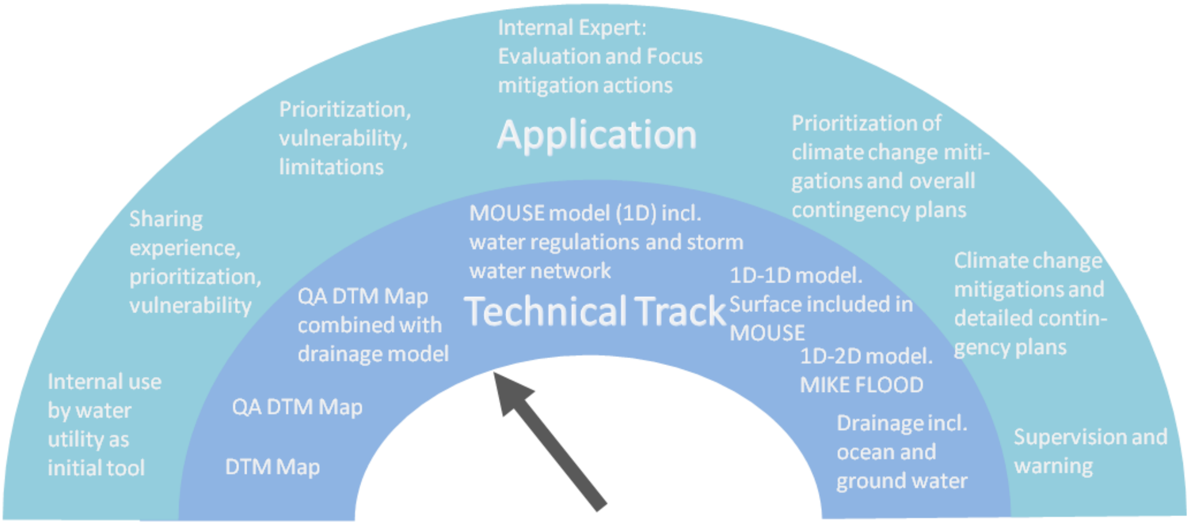


Figure 3.1 Illustration of the modelling tool (technical path) and what the different levels can be used to

Similarly, many other aspects of climate adaptation fit into the “climate-meter” to support the decision where to start and where to end, e.g. who may use the different methods: State, regions, municipalities or utilities, solution methods, environmental conditions and economy.

The illustration in Figure 3.1 can be used to communicate decisions. In subsequent chapters, the technical path will be reviewed in detail, examples of climate adaptation will be shown, and suggestions for carrying out risk assessments and prioritisation of adaptation to climate change will be given.

3.2 Calculation methods

This section describes the hydraulic models that can be used for assessing and prioritizing climate adaptation. The section is structured according to Figure 3.1, by starting with the terrain model (DTM) ending with the advanced hydraulic models.

1. DTM - Depression Map: GIS analysis, using the DTM is calculated depressions in the surface. The method takes only surface runoff into account and thus not the storage volume and hydraulics of the pipes.
2. Quality assured DTM Depression Maps: GIS analysis, using a quality assured elevation model (DTM) to calculate depressions in the surface. The method includes only surface runoff and does not include the hydraulics in the urban drainage network.
3. Depression Maps combined with simple runoff models. Simple volume account of precipitation and runoff capacities on terrain is incorporated in the "Depression Maps" calculation. This method provides a first estimate of risk zones.
4. Hydrodynamic model in 1D (MIKE 1D). The hydraulics in the pipes and channels are simulated. The method does not include overland terrain flow and does not simulate floods of terrain. The method does provide information on critical points in the urban drainage network.
5. Combined hydrodynamic drainage model and surface model (1D-1D). The surface is implemented in the 1D model (e.g. MIKE 1D) as basins connected to each other by overflow weirs. The method shows the risk zones, the amount to ponded water as

well as how far the water reaches spatially. The method does not describe the velocity and flow paths on the surface.

6. Combined hydrodynamic drainage model and 2D surface model (1D-2D) MIKE+ (MIKE 1D, MIKE HYDRO River and MIKE 21). The urban drainage model and the hydrodynamic 2D surface model are combined. The method includes the flow velocities and flow paths on the surface. It is relatively easy to set up, but is very computation intensive.
7. Simulation of the total water cycle. In the future it will be possible to combine models of runoff from the groundwater zone, streams, urban drainage system and the sea. This will provide a comprehensive overview of runoff in cities. Currently, the urban drainage system and streams can be combined with the groundwater hydrology in the zone, but it is very computation intensive and difficult to set up models in a detail that makes it worth executing the great work.

The following sections describe these methods in detail:

3.2.1 Terrain model - QA

A terrain model is a digital survey of the topography of an area, i.e. heights on the surface. A terrain model in itself provides some information as to where the extreme rainfall is likely to cause damaging floods. It is possible to identify depressions where water can gather.

In areas where there is not an existing drainage model and where the terrain mainly consists of gully pots, the terrain model (without a hydrodynamic model) is suitable for estimating smaller impact and for feasibility studies. The advantage of this method is that it can provide a quick overview of the problem. On the other hand, there may be considerable uncertainty in the method, and one should be very aware of the errors arising from ignoring the hydrodynamics of the system.

Processing of elevation data

Elevation data should be quality assured and then used to generate a terrain model for further calculations. Since most bridges will act as a barrier in the raw elevation data, there should be a review of these areas and where necessary culverts built. Similarly, all river sections should be examined because crossing pipe lines also act as obstacles. All areas around houses should be quality assured. An example of processing of terrain data is given in the following example.

Usually, there is a GIS registry of the largest bridges in a municipality. This can either be directly incorporated into the terrain model or used as a template for a manual revision of the areas. Figure 3.2 shows the changes in water levels that can be produced by proper validation of the digital terrain model.

Figure 3.2 Calculated depressions before culverts are opened (left) and after having been opened up (right). (Vejdirektoratet, 2009)

The analysis can be used to make an assessment of flow capacity under bridges, since the analysis before opening the bridges gives a picture of a potential flood event where the culverts and bridges are blocked.

3.2.2 Surface depression maps

Calculation of depressions

In calculating the potential flood areas, it is assumed that all surfaces are completely impermeable. There is no option for infiltration or runoff via drains and drainage system. The maps show potential areas of risk - namely depressions in the terrain where there is a possibility that water can gather and cause flooding. Maps can show the distribution of missing information about the spatial distribution and volume, and partly a list of the depths where the depressions fill up with water. When all depressions in a map are shown it may result in a noisy picture of the terrain model. Filtering the data can reduce the coverage of low risk flooding areas, e.g. by showing all depressions or depressions just above e.g. 100 or 500 m^3, as shown in Figure 3.3.

Figure 3.3 Reduction in the number of depressions based on volume. The first part shows all depressions, the second part shows depressions of 100 m3 and the third part shows depressions over 500 m^3

When depressions have been identified depths can be calculated, see Figure 3.4. Information about depressions can fairly easily be linked with data for the groundwater table.

This method provides no information on how much rain is required to fill the depressions in the terrain. Filling of the depressions may in the majority of cases be described as "worst case", i.e. an event which has a very high return period.

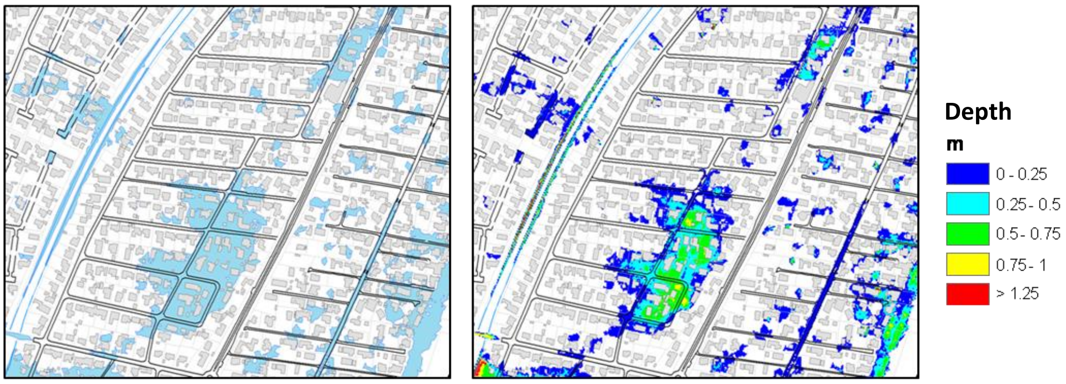


Figure 3.4 Identifying depressions and calculations of depths

The following section describes a very simple method of how rainfall and drainage capacity may be taken into account based on only volume considerations.

Waterways on the surface and contributing areas

Waterways on the surface can be calculated with and without houses in the terrain model. The difference between the two is shown in Figure 3.5.

Figure 3.5 Waterways on the surface calculated without houses (left) and including houses (right)

Choice of method depends on the level of detail since a terrain model including houses may cause some extra localised flooding, see Figure 3.6.

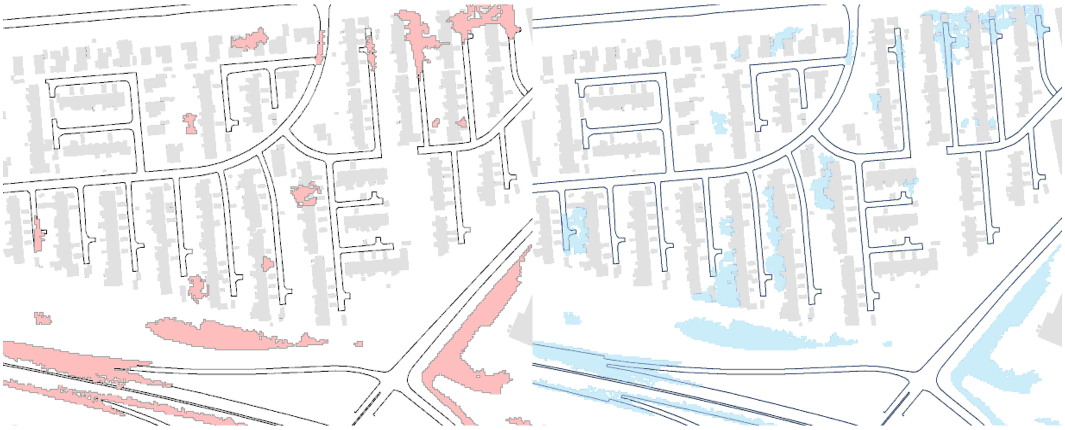


Figure 3.6 Depressions calculated without houses (left) and including houses (right)

Catchment boundaries are defined for all depressions over 100 m^3, see Figure 3.7. If larger basin boundaries are required, then larger volume or maximum depth of depressions can be selected.

Figure 3.7 Contributing areas

The area and imperviousness of the catchment can be used to calculate how many millimetres of rain are required to fill the depressions, see Figure 3.8. This may be misleading since flooding due to a half filled large depression may be critical.

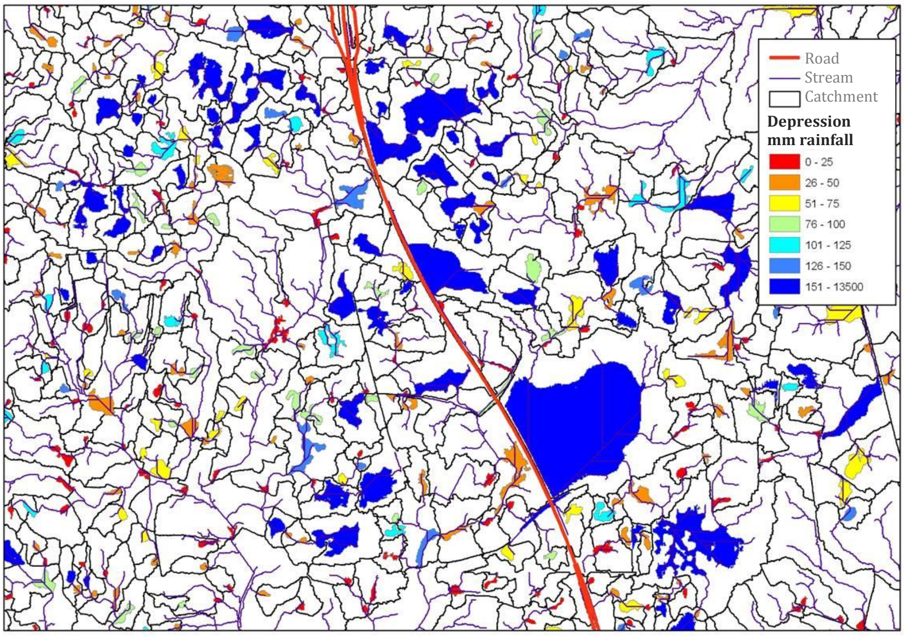


Figure 3.8 Millimetre rain per depression (Vejdirektoratet 2009)

A simple calculation of flood extent can be implemented by comparing the geometry of the depressions with the knowledge of the available capacity in the drainage system. Level of floods in small areas can be calculated based on knowledge of the capacity of the drainage system and out of the drainage system and catchment area, see Figure 3.9.

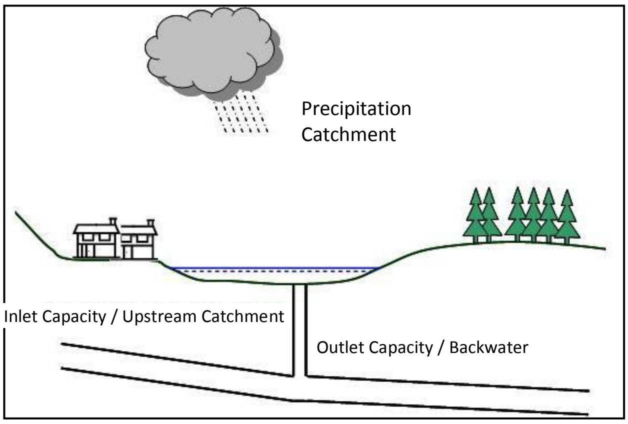


Figure 3.9 Sketch of smaller system

As a hypothetical example Figure 3.10 shows a basin of 4 ha, where the capacity of the outlet pipe is 80 l/s and the volume of drainage system is 43 m^3. Based on observations of water depth on the road in various heavy rain events, the imperviousness is calibrated to 45%. Figure 3.10 shows the effect of a 76 mm rain falling in 120 minutes (equivalent to a 100 year rainfall event). It is assumed that there is no backwater from the downstream system. The flooded area is 0.4 hectares and it will take two to three hours before capacity is regained in the drainage system.

Figure 3.10 Flooded area is shown in blue

Data from the terrain analysis can also be used for calculation of the return periods of maximum water level in depressions from the surface area, imperviousness, volume calculation and upstream contributions, see section 3.2.3 for more details. This means that the dynamics of the drainage system and any backwater effects are disregarded.

3.2.3 Hydraulic surface calculations

The depression map method calculates only depths in the depressions, the spatial distribution of depressions and flow on the surface. By using a photo analysis (Nielsen, 2010) and / or GIS analysis of terrain data, the surface can be supplemented with imperviousness. A proper hydraulic surface runoff calculation of flooding to current rainfall events can then be undertaken. The calculations can be implemented as 1D or 2D surface runoff calculations (see section 3.2.5 and 3.2.6).

The calculations provide a good estimate of the relationship between the contribution from the catchment and depression volume, but they do not account for contributions and capacity of the urban drainage system. In general, this leads to over-estimation of flooding upstream, while flooding downstream tends to be under estimated.

An example of a 1D surface calculation is shown in Figure 3.11. Flows at the surface are described using channels. Figure 3.11 shows the calculated maximum water depths for a 500 year event. There is a flooded area under the bridge deck which has a greater extent than the width of the road above. This is due to the bridge deck being removed in the original terrain model. Elevations under the bridge deck are uncertain, and the calculated volume and water depths will be affected by this. There is less volume available in reality which will lead to a wider flooding extent.

An example of comparison between calculated flood using Depression Method and a clean surface calculation is shown in Figure 3.12.

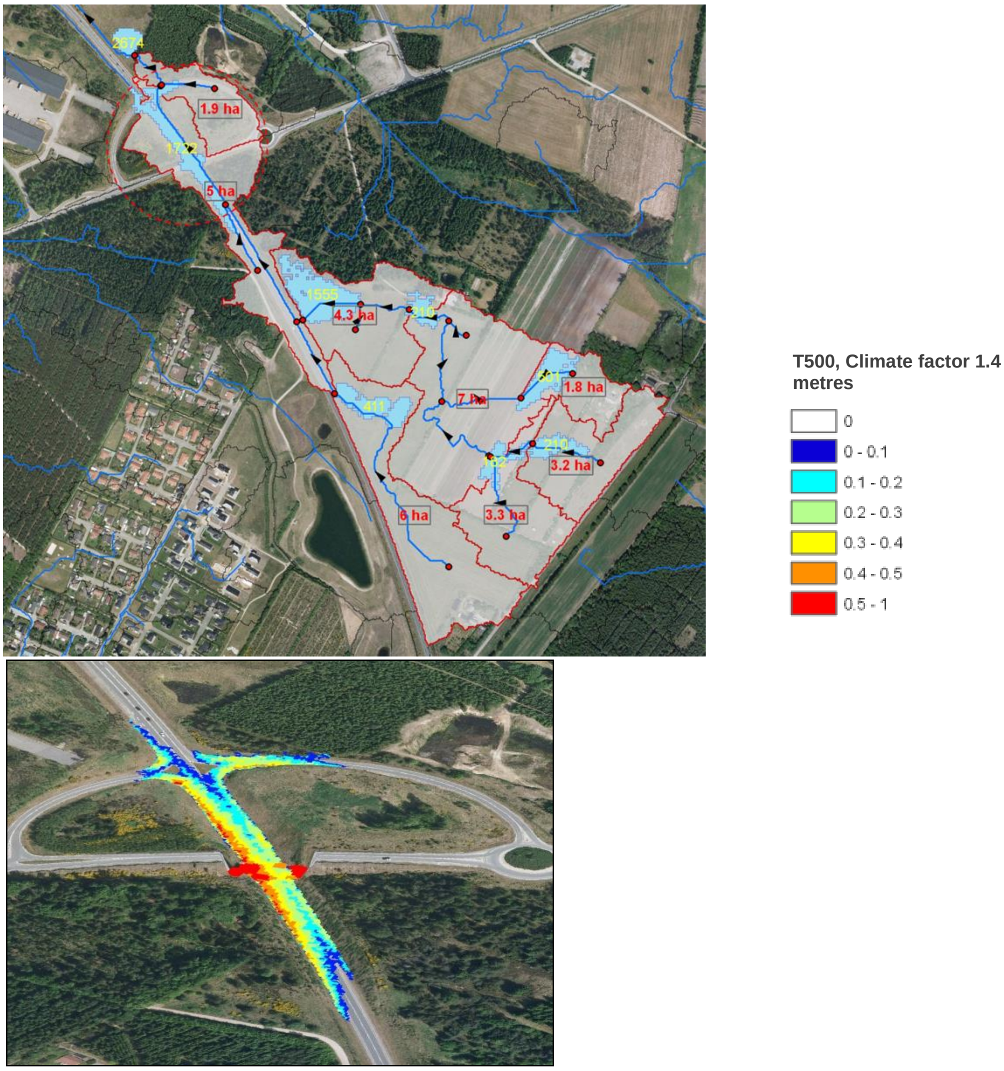


Figure 3.11 Example of a pure surface runoff model made for the Road Directorate in 2009

Figure 3.12 Example of flood results when hydraulic surface charge of 100 years of rain (red) compared with Depression Method (grey)

3.2.4 Hydrodynamic drainage model 1D

A hydrodynamic drainage model (1D) can be used to provide an initial overview of where the water first surcharges to the terrain. This can be combined with knowledge of how water flows on the surface, and where water can accumulate in depressions. If the water surcharges at several locations near a hazard zone classified by the Depression Map Method further calculations in this area should be undertaken.

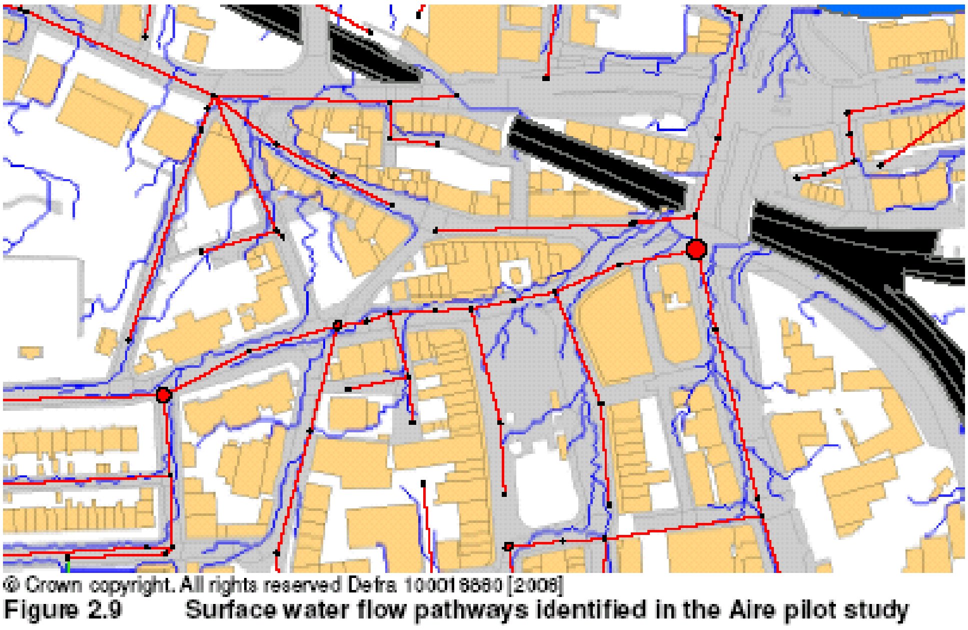


Figure 3.13 Example of use of Depression Map Method together with backwater effect calculations using hydraulic drainage model. [DEFRA 2006]

The hydrodynamic models should be validated and calibrated to measurements to ensure that the models represent real flows to a sufficiently high degree.

VandCenter Syd and Greve Forsyning have used data from meters to calibrate and validate models since 2004.

3.2.5 Combined hydrodynamic drainage model and surface model 1D-1D

A hydraulic drainage model (MIKE 1D, MIKE+, Info Works CS, SWMM5 or similar) provides an approximate determination of where water will surcharge to the terrain, but it does not describe the flow on the surface and hence no interaction between surface and drainage system. The consequence is that a traditional urban drainage model is flawed as soon as water surcharges to terrain requiring that the ground surface is implemented in the urban drainage model.

Digital analysis of a terrain model shows a complex system of flow patterns on the surface. Further analysis may reveal that the description of the surface can be simplified to be comprised of a series of depressions, channels and overflows similar to the calculation methods implemented in dynamic 1D drainage models. Many of the damaging urban floods in Denmark are caused by water collected in depressions, from which the water only flows when capacity is regained in the drainage system or by infiltration, or routed as surface flow when the depressions are filled up. Generally, the surface can be described as hydraulic reservoirs and overflow. In some cases the surface description can be supplemented with channels.

On the basis of the digital analysis a one-dimensional surface model can be generated consisting of ponds, weirs and channels after which the surface is implemented directly into the hydraulic drain model without coupling between different types of hydraulic models. Figure 3.14 shows the principle diagram of the 1D-1D system.

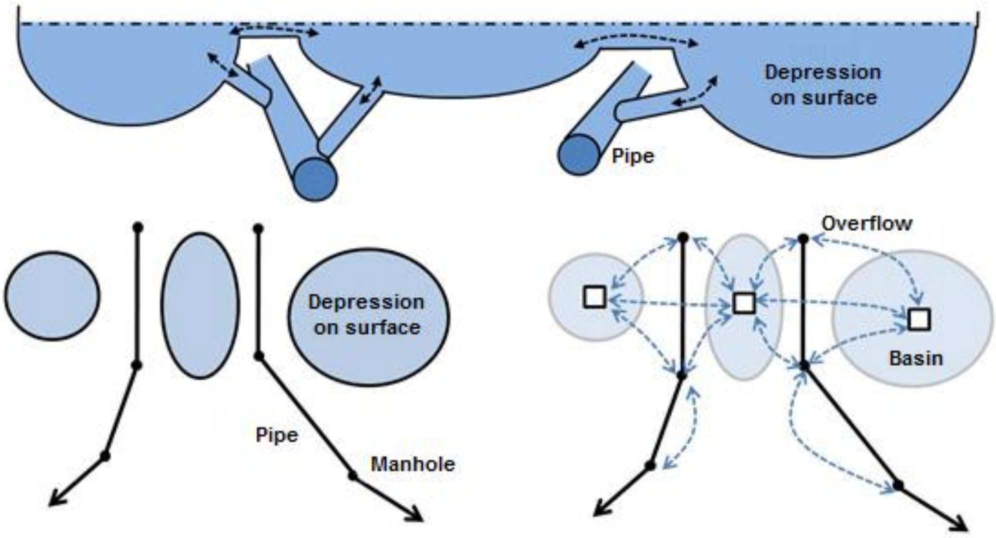


Figure 3.14 Principle sketch of 1D-1D coupling of drainage system and surface

Analyses of DTM data will reveal that the depressions and indentations on the surface are rarely neat and regular closed depressions. A depression calculated by the Depression Method as a single depression usually consists of many smaller depressions. Figure 3.15 illustrates a hypothetical example of two depressions. Often a depression found by the Depression Map Method consists of several hundred depressions depending on the grid size in the DTM.

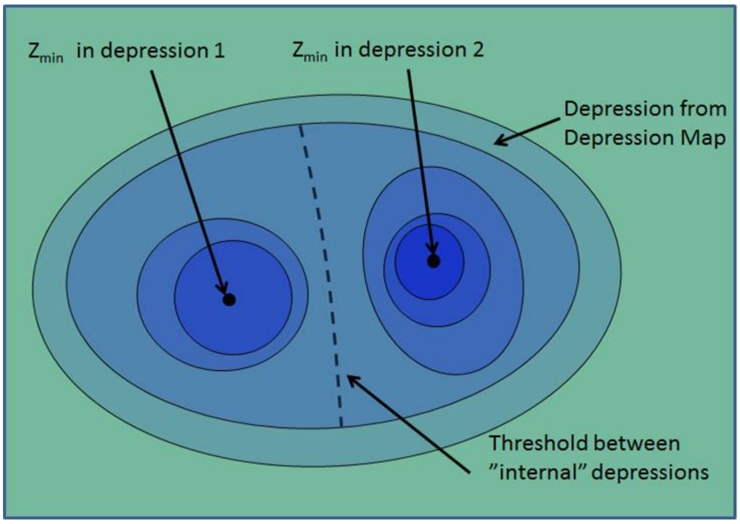


Figure 3.15 Depressions and inundations - depending on whether the differences between the threshold level and minimum elevations in depression 1 and depression 2 are combined in one depression or kept as two depressions

A method to generate a workable model of the surface is to make it as simple as possible without excessive loss of information. As an example, a model can be made up by ponds, canals and overflow when the number of depressions is substantially reduced. Reduction criteria such as minimum threshold depth in a depression, minimum area and / or minimum volume at threshold can be applied.

If the threshold for a given depression is less than the chosen threshold, then the depression can be merged with the adjacent depression. The consequence of merging of depressions versus separation is illustrated in Figure 3.16 and Figure 3.17. The selected values for threshold depths are mainly important in cases where water is primarily supplied to one depression and where both depressions have a relatively large volume under the common threshold.

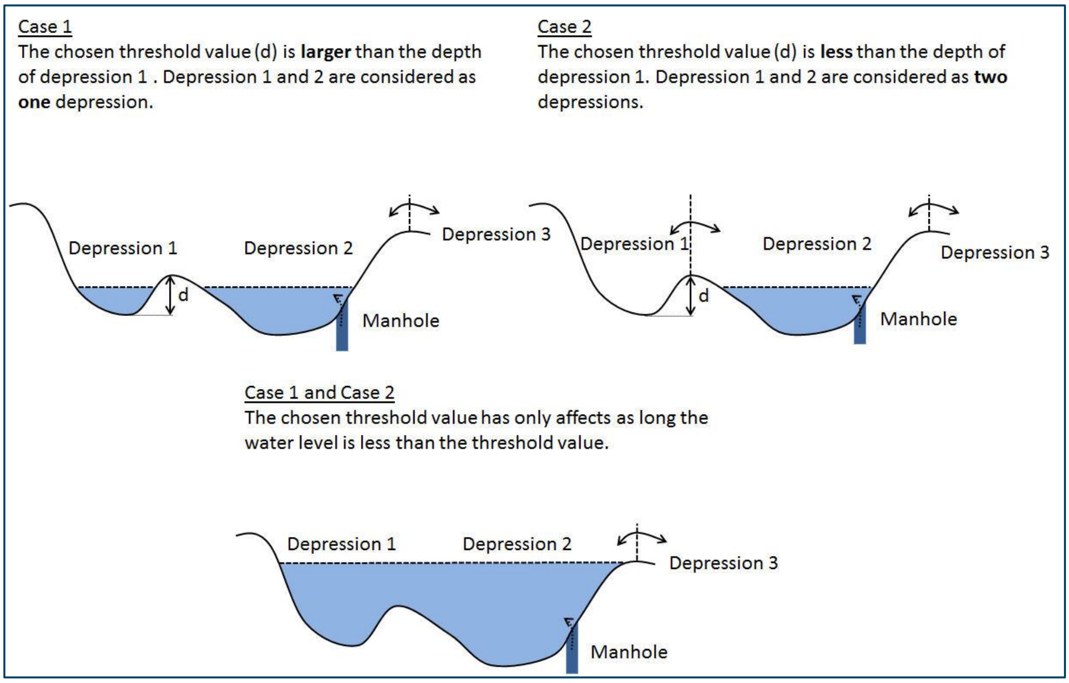
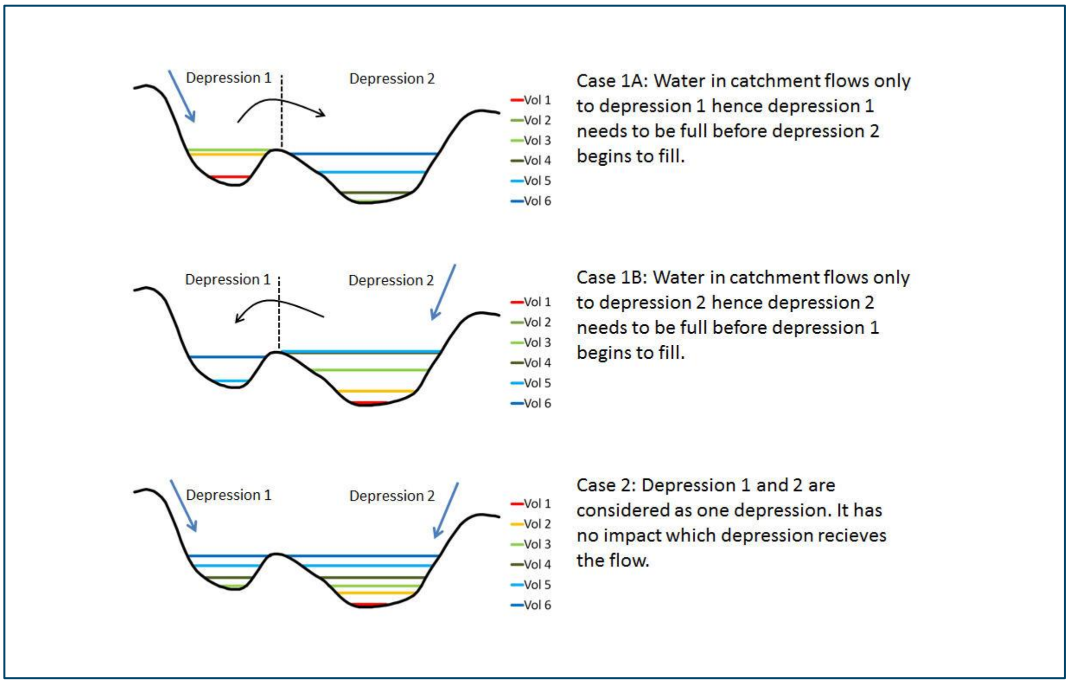


Figure 3.16 Illustration of the filling of depressions



Case 1A: Water in catchment flows only to depression 1 hence depression 1 needs to be full before depression 2 begins to fill.

Case 1B: Water in catchment flows only to depression 2 hence depression 2 needs to be full before depression 1 begins to fill.

Case 2: Depression 1 and 2 are considered as one depression. It has no impact which depression recieves the flow.

Figure 3.17 Quantitative illustration of the filling of depressions

When the detail method and level of detail is provided, surface depressions with associated level-area curve and overflow edges can be generated through GIS applications (Nielsen et al, 2009 and Jensen et al, 2010), after which they can be imported into a hydraulic 1D drainage model as basins and overflow.

The most accurate and detailed model is achieved by low threshold values of aggregation of depressions, but at a very high level of detail the complexity of 1D-1D model and the calculation time increase significantly. If a very high level of detail on the surface is required then it may be advantageous to use a 2D model for surface calculations (see Section 3.2.6).

A number of sensitivity analyses of detail level and edge effects have been undertaken. The main conclusions are that the level of detail of the result is higher or the same as the chosen degree of detail in the model. The error caused by the level of detail is greatest in sub-catchments situated on slopes with large storage capacity on the slope. In these cases, the capacity to retain water on the slope is ignored. In addition, the velocity with which water flows on the surface is overestimated (from nodes to reservoirs and between reservoirs) unless overland flow canals are incorporated. By contrast, the volume is conserved in the system corresponding to the selected drainage model and the selected time step.

Based on GIS-generated surface depressions and results from the 1D model the flood inundation and flood levels can be plotted in GIS, see Figure 3.18.

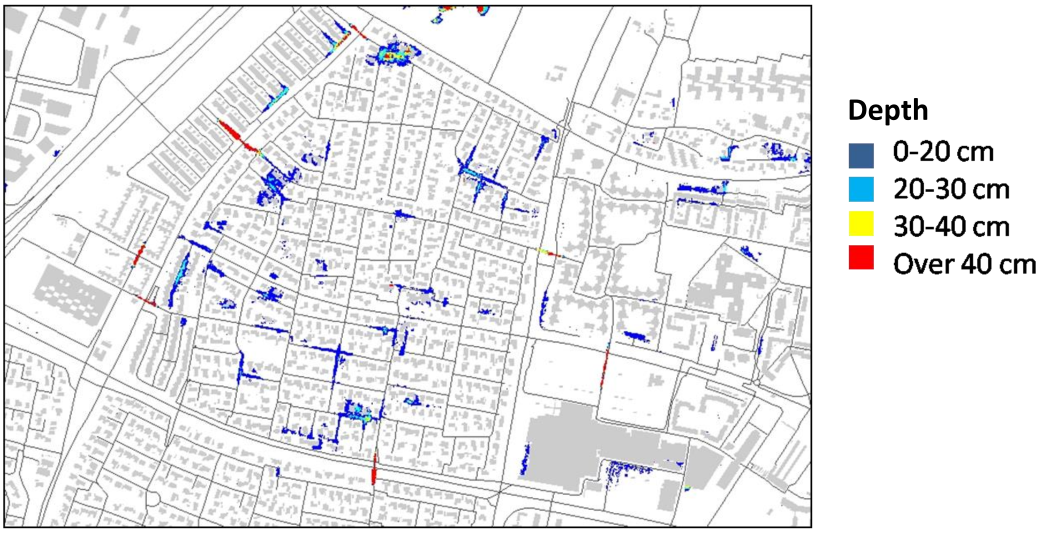


Figure 3.18 Example of representation of flood results

With 1D-1D model technique it is possible to implement flood calculations for model areas of considerable size and with a reasonable calculation time - without using sub-models. The model simulations of Odense and Greve have been undertaken by applying the 1D-1D model concept. (See Annex B and E).

In Greve, the method has been used for quality assurance of the priority of climate adaptation (as described in Chapter 6) and to generate risk maps for documentation to EPA authority.

3.2.6 Combined hydrodynamic drainage model and surface model 1D-2D

The hydrodynamic drainage model can be combined with a 2D hydrodynamic description of the runoff on the surface, i.e. MIKE+, (Mark et al., 2006). With the 2D surface model is it possible to give a detailed description of an extreme rainfall situation where both the dynamics of drainage system and the ground surface are included. Terrain data of good quality is required to take full advantage of the level of detail, and the calculation time increases significantly. At this stage it is not practicable with long time series of rain events due to calculation time.

The advantage of a combined urban drainage model and surface model is that there is potential for great precision of the flood extent during extreme rainfall events.

A calibrated MIKE 1D / MIKE+ model can be coupled with a 2D description of the surface water flows. A smaller sub-region can be selected where the two models are coupled. In the couplings water is exchanged dynamically between pipe flow model and the surface flow model. Because of the high calculation time, it is important to choose the area carefully. If there is a need for a high degree of detail in terrain, i.e. a grid size down to 1 x 1 m, it is recommended to select a smaller area. A typical grid size will be 2-4 m.

Input to MIKE+ consists of elevation models, which either originate from Laser Scans from airplanes or helicopters (also known as LIDAR - Light Detection and Ranging) or the xyz-coordinates for a terrain model and GIS-based polygons for houses and roads. A terrain model including roads, houses, etc. may be purchased from a local Danish distributor of such data, or it can be generated by putting themes together, e.g. by raising houses four meters above the terrain level and lower roads by 20 cm. This process is outlined in Figure 3.19.

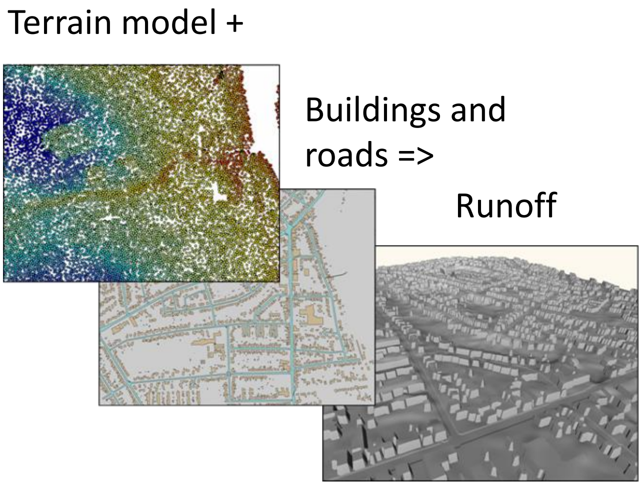


Figure 3.19 Surface model can be generated from terrain data, GIS theme of houses and roads

The 1D model and the 2D terrain model is coupled only in the area covered by the 2D terrain model and thereby not the complete area covered by the 1D model as illustrated in Figure 3.20.

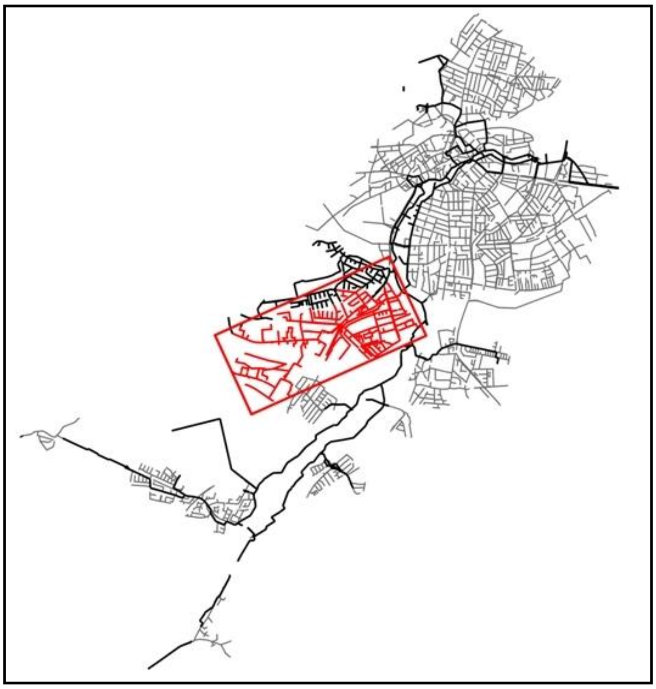


Figure 3.20 Collection system model coupled to 2D terrain model

Selected manholes from MIKE 1D / MIKE+ are coupled to the 2D terrain model. It is important to consider which manholes should be coupled to the surface, where and how by considering the density of pipelines and manholes and their terrain levels. In some cases it may be advantageous to move the coupling point in the surface model to a model grid point with a lower level or create an artificial weir to compensate for the volume located in all the pipelines and manholes not described in the urban drainage model.

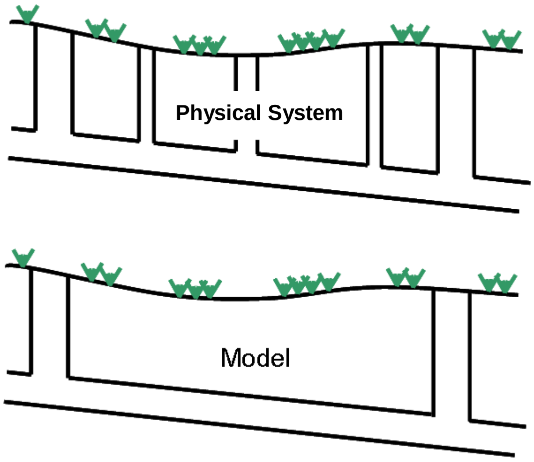


Figure 3.21 Sketch of the physical system versus model

There will be some uncertainty about how water is exchanged between the two models. How quickly the water can surcharge through grates and manholes in the selected area and how quickly it can return to the pipe network. Obviously, this can be a calibration parameter, but as a rule of thumb it must be assumed that there is a limit to how much pressure may be in the system before the water surcharges through all the grates and manholes. Similarly, it is believed that the water on the surface reenters the urban drainage system as soon as the hydraulic capacity is regained.

Calibration data for surface model may be based on observations of the extent of flood inundation in certain areas during one or more historical rain events, but often there is very little data available. The main tasks in a calibration are:

- Recalibration impervious parameters for different land uses in a drainage model
- Possible overland flow paths. Houses and other land uses may be aggregated during the conversion of the surface grid
- Are manholes appropriately coupled, and is the right amount of water exchanged between the two models?
- Roughness (Manning Number) on the surface is in most cases of minor importance, and it only affects the shape of the runoff hydrograph.

It is relatively simple to develop a coupled model, but calculation time is long and requires high quality inputs. Figure 3.22 shows results from a calculation with coupled models. An aerial photo is used as background.

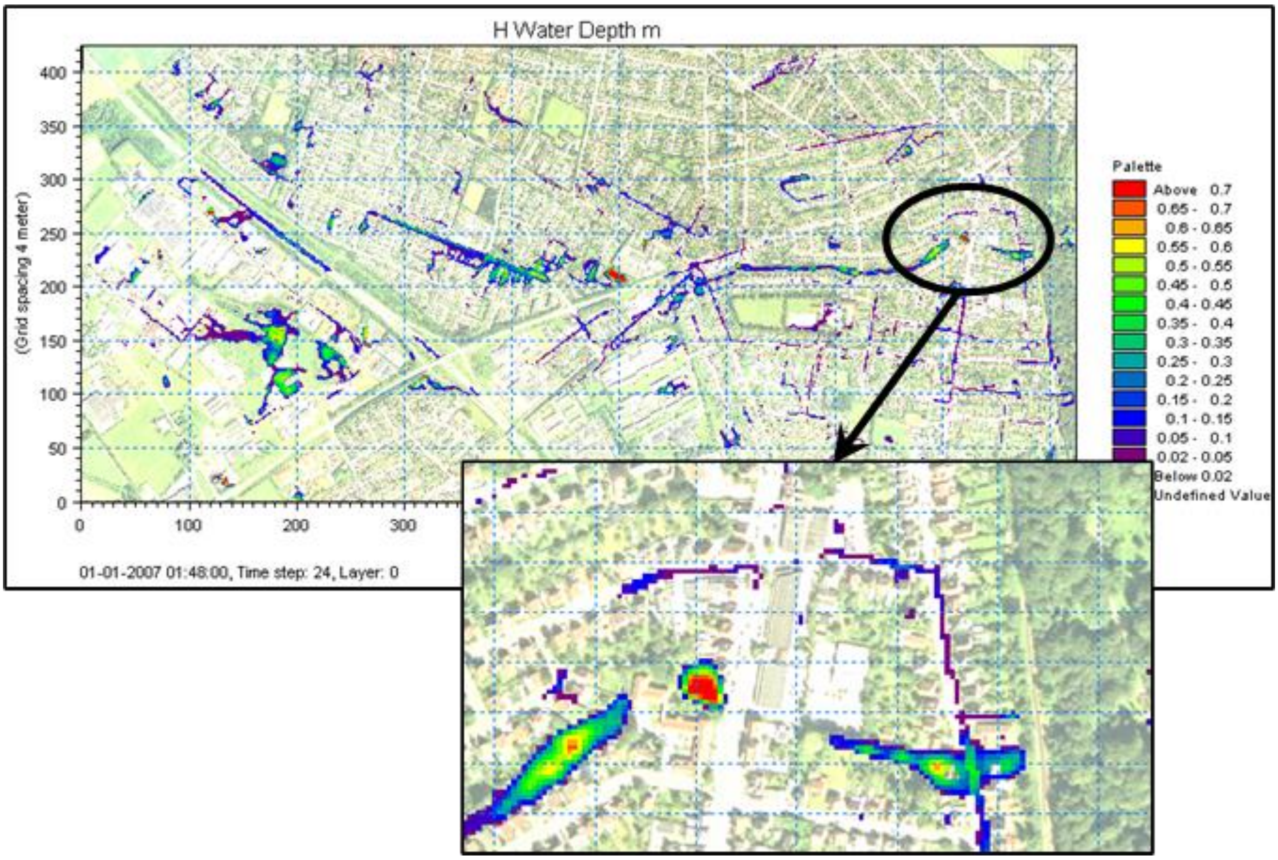


Figure 3.22 Example of calculation results from a coupled model

3.3 Comparison of methods

The terrain model and Depression Map Method provides a good description of areas where water can potentially be stored in depressions in the terrain. Analysis in GIS also enables the calculation of overland flow paths on the surface and the extent of contributing areas (catchment areas of depressions and gaps). The terrain model and Depression Map Method are both powerful tools in the initial surveys of catchment areas and initial ranking of priorities. The methods are especially suitable in areas where the database for pipe registration is poor or nonexistent.

Analysis of terrain data provides no information on the influence from drainage system, so it is important to emphasise that the results must be interpreted with caution. Based on overland flow paths and the extent of contributing areas, the analysis may characterise an area as low-risk zone without regard to contributions from the pipes in the urban drainage network. A GIS analysis would not have given rise to increased preparedness at Greve Hall or Ejersmindevej in Odense since the contributing areas have limited geographical extent.

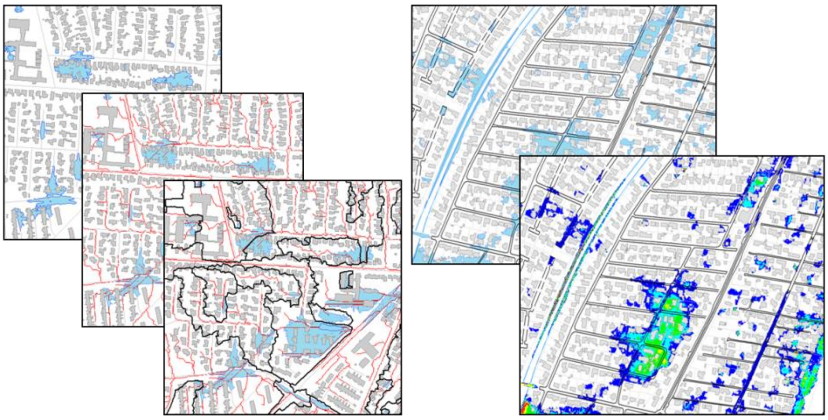


Figure 3.23 Terrain Models and Depression Method gives a good overview of potential flooding and flow on the surface roads

A hydraulic surface calculation of flooding due to current rainfall events may be undertaken on the surface, but when it does not take into account the contributions from and capacity in the urban drainage system the results are erroneous.

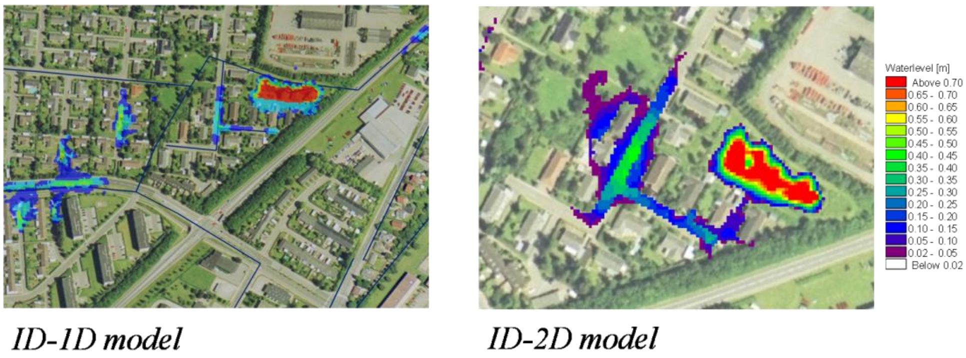
Figure 3.24 Correlation between results of Depression Method (grey), hydraulic surface calculation (red) and combined hydrodynamic drainage model and surface model 1D-1D (yellow) - Blue coincide hydraulic surface calculation and combined hydrodynamic drainage model

The traditional hydrodynamic drainage model provides a good indication of where the water will initially surcharge to terrain, but does not describe overland flow on the surface and the interaction between surface and drainage systems. It is therefore only possible to reliably estimate the intensity and the volume which the urban drainage system has the capacity to capture. When water is present on the terrain, results from the model are unreliable.

By combining data, methods and models of the different approaches, e.g. terrain model, Depression Method and drainage model, the required amount of information is gathered for undertaking high-level calculations to describe the interaction between the drainage system and surface. Depending on the purpose of calculations, 1D or 2D method can be chosen for calculating the flow on the surface.

The one-dimensional surface description provides an operational model with low calculation time and high stability. By contrast, there is a risk of overestimating the flood velocity, especially for areas with long flow paths and minor slopes. The two-dimensional surface description increases processing time significantly, but calculates the velocity on the surface which gives a more accurate description of the flood dynamics.

For both model types increased detail of the surface reduces the error in the surface flow description, but increases the calculation time. For 1D calculations, the number of depressions in surface controls the surface flow, while 2D surface is controlled by grid size. The results for the two surface models are comparable (Nielsen et al., 2009), but in areas where flow time on the surface is large (long flow paths with relatively low slope), a 2D surface description should be considered. Alternatively flow paths should be included in the 1D description for describing the flow on the surface.



ID-1D model

ID-2D model

Figure 3.25 Results from models with, 1D and 2D surface descriptions respectively

4 Flooding from the sea

Flooding from the sea is characterised by high water levels in the ocean resulting in inundation of lands which are usually not under water. This type of flood can occur either by water running off terrain or by sea water inundation through rivers or drainage systems.

As with the analysis of flooding from storm water system, there are several methods available to calculate flooding from the sea. These methods range from simple GIS analyses to the use of complex hydraulic computer models. The methods are described in this chapter and illustrated in Figure 4.1.

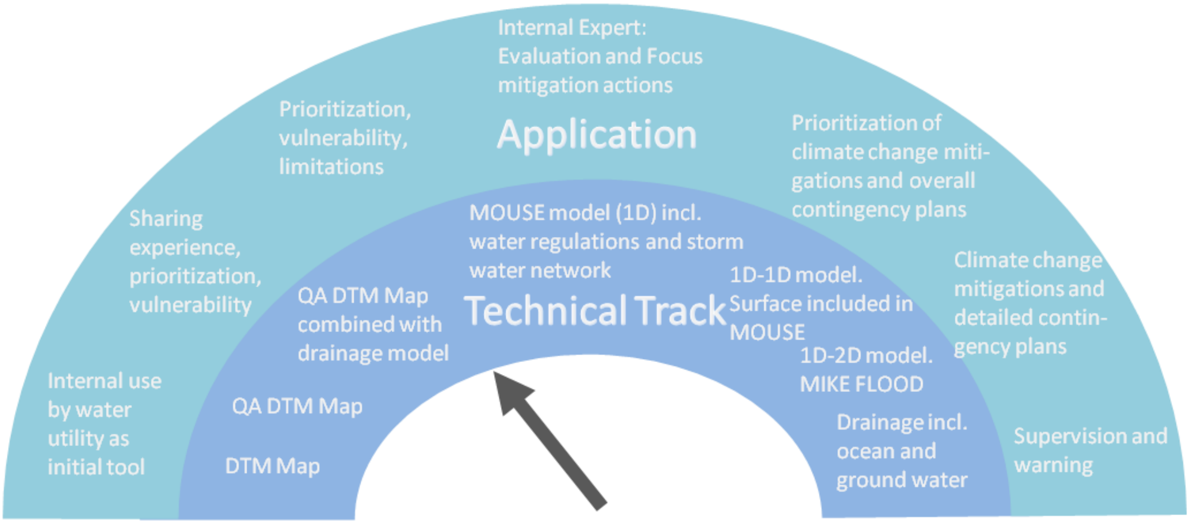


Figure 4.1 Illustration of the modelling tool and what the different modelling levels can be used for

4.1 Calculation methods

Methods for analysis of the risk of flooding from the sea include:

1. *"Water Elevation Maps"*: GIS analysis using only a digital terrain model to identify flooded areas. The method uses sea water levels and terrain elevations. This method shows only where there could potentially be water on terrain if there was a connection to the coast.

2. *“Water Elevation Maps of areas in connection to the sea” (in GIS terminology called “Cost Distance”:* GIS analysis where the influence from dykes and barriers on the flooding is taken into account. For this analysis a quality assured DTM is required.

3. *“MIKE 1D/MIKE+ calculation:* where only the pipes and possibly streams are simulated under various increasing sea-level scenarios. The calculation shows the potential extent of flooding from the sea through the storm water system and possibly rivers, but only at nodes.

4. 1D-1D depressions in the terrain model are implemented in the MIKE 1D/MIKE+ model including the complete drainage system (rivers and storm water/combined system). The water from the sea routes through drainage system

and terrain via the MIKE 1D/MIKE+ basins and pipe network. The model does not model flow velocities at terrain.

5. *Hydrodynamic modelling of flow on the terrain*: A 2D hydrodynamic model is used to simulate water flow from the ocean and onto the land. The routing of water follows the terrain elevation.
6. *Hydrodynamic modelling of flow in the terrain, combined with a hydrodynamic model of the drainage system:* The method uses a 2D hydrodynamic model to simulate water flow from the ocean and onto the land. The routing of water follows the terrain elevation. At the same time the water flow is calculated by the model of the drainage system and low-lying areas which are linked to openings in the drainage system that can become flooded.

Terrain Models

A terrain model is a digital topographic representation of the area. This model can either simply describe the topography in the form of contour lines (called a digital terrain model) or it can also include structures, in the form of dykes, houses, walls, etc. known as a height model.

When choosing which type of terrain model is the most appropriate, factors in the model area that may affect water currents need to be evaluated. Physical structures (dykes, houses, etc.) which significantly affect the water flow, must be included in the terrain model. Information on houses might be generated based on GIS layers containing information on the location of buildings. This information is often available in the municipality. A terrain model with descriptions of houses, roads and other vital structures can typically be purchased from a data supplier.

4.1.1 Water elevation map

A GIS analysis could easily provide information about where a given water level may flow over land and fill up to the given water elevation (see Figure 4.2).

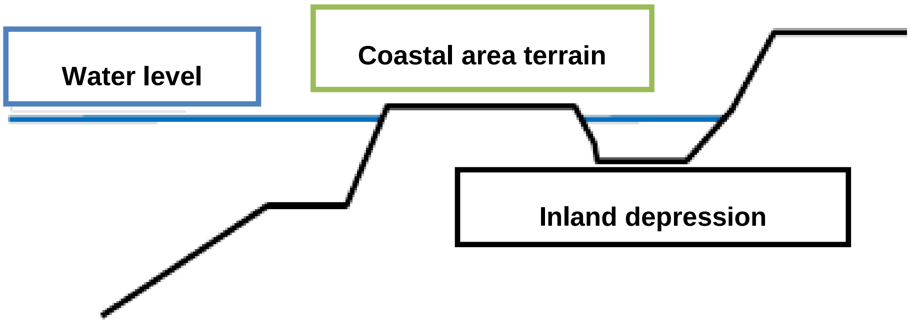


Figure 4.2 Illustration of elevation-map method using GIS analysis

The flood map can be developed by calculating the local water depth as the difference between sea level and the local terrain elevation. All areas in the terrain model, which lie below sea level will be flooded, even those not connected to the sea. This is done in practice by setting the signature for water level to blue until the required elevation is visualised (e.g. 2m level). This method is obviously subject to considerable uncertainty because the method assumes that areas which have no direct contact to the sea are inundated. If a method in which only areas with direct contact to the sea (through the terrain) are required, the tool "Cost-Distance" in ESRIs software can be applied.

The described method is most suitable for coastal areas with large slopes, meaning only areas near the coast are inundated. Limitation of the method is the fact that natural physical processes are ignored, e.g. the time it takes the water to flow on terrain. The method yields the maximum flood image and is especially good for rapid screening of the areas that are at risk of flooding.

In the following example a flood map for a maximum sea level of 2.24 m is provided. The digital terrain model of the area has a grid size of 1.6 x 1.6 m. The calculated flood is illustrated in Figure 4.3. The map shows flooding along the coast and in the areas behind the coast line.

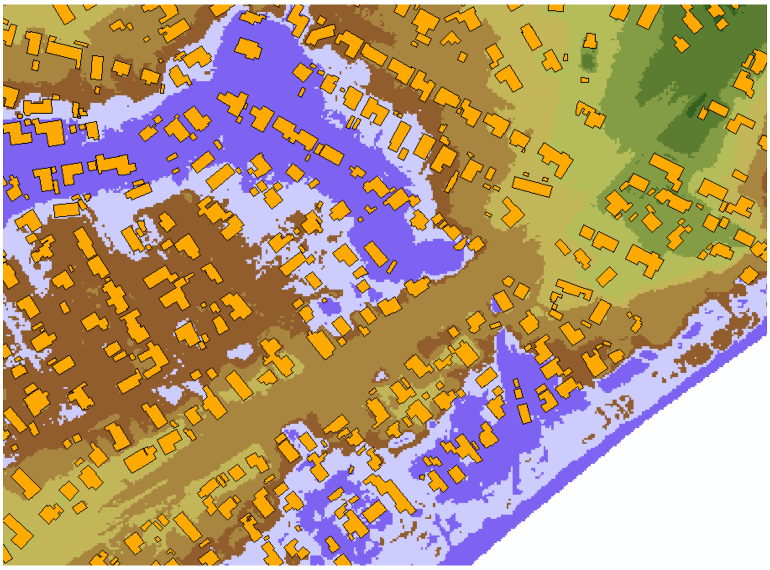


Figure 4.3 Flood maps based on elevation-map method - a pure GIS analysis

If it is assumed that only those areas which are in direct contact with the sea are flooded by the rising sea level, then the flooding is reduced significantly as shown in Figure 4.4.

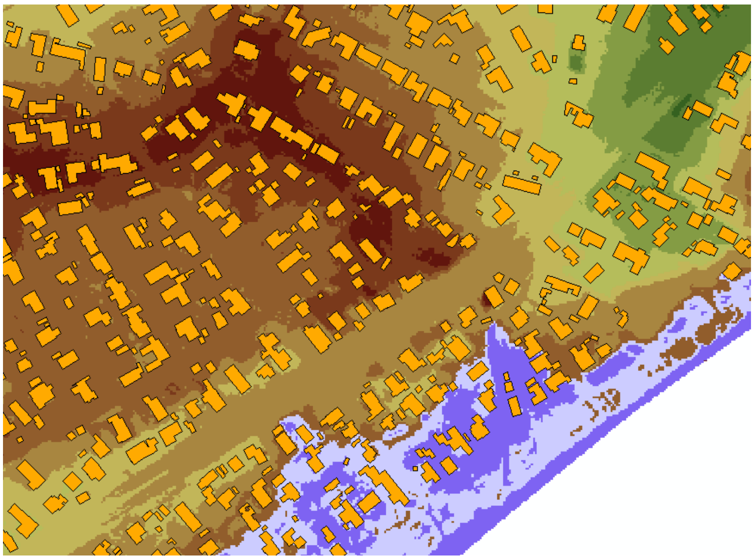


Figure 4.4 Flood maps based on Cost-Distance method (see below) - a GIS analysis. Only land which is directly linked to the sea is likely to be flooded

4.1.2 Water elevation map in connection to the sea

Obviously, it is more appropriate to analyse the areas that are directly in contact with the sea and therefore inundated. The Cost-Distance function considers which areas will be affected directly from a defined source (the ocean) using the information in the height model (DTM). At this stage special attention is required to areas where a gap is defined between sea and land in the DTM. Limitations in the existing definition of the DTM are listed below:

1. Rivers are not wide enough to be described in the DTM (if e.g. the stream is 1 m wide and the DTM resolution is 1.6x1.6m), which potentially may reduce the flooding modelled by the model compared to reality.
2. Rivers passing through culverts under bridges may not have been opened in the DTM (e.g. the roads and small bridges), which potentially reduces the flooding in the model compared to reality.
3. Dikes are not represented because the DTM is prepared before a dike is established (which leads to artificial flooding in the city by the model).
4. Bridges have been removed in the DTM, thus giving an artificial "gap" into the city (e.g. if there is a structure under a bridge that closes at high tide which is not represented in the DTM and results in artificial flooding of the city by the model).
5. Storm water systems and combined sewer systems with overflow to the sea are not described in the DTM. This is an overall situation because the DTM does not have any information about the pipe network under the surface. This restriction gives potentially less flooding in the model than in reality, unless non-return valves are installed on all outlet pipes and constructions.

Finally, it should be noted that the DTM only shows surface height and no information on whether the dikes which are described in the model can withstand the pressure provided by the water. Around Denmark there are many beach dunes, which from above look like dikes, but which may be washed away by storm surges.

The dynamics of the system (energy losses in streams) and duration of high water level are not included in this analysis and should be assessed by other criteria.

If the DTM is modified to address the limitations of the items 1-5 listed above, the Cost Distance method is a powerful tool to show the worst case flooding of cities combined with high water levels in the ocean.

The dynamics of the system (including energy losses in streams) and duration of high water level is still not part of the approach, but can be assessed by analysing the durations of storm surge and estimate the importance of this by using an average water velocity (e.g. 0.25 m/s). If the distance from the sea to a low-lying area is short, the duration has less significance compared to a long distance.

To ensure that "worst case" is assessed it is obvious that the DTM is quality assured. In Figure 4.5 an example of a cost-distance calculation is shown with and without correct description of the stream. As Figure 4.5 shows, it is necessary to ensure that all terrain features such as rivers, dikes, bridges and culverts are represented in the DTM.

This method does not account for storm water and the ability of sanitary pipes to transport water into the city. A rapid screening where this ability is included can be undertaken by opening the terrain model where pipes are located in the ground. If this analysis is carried out, then it is very important to be critical of the outcome, since the water will only enter the network at manholes.

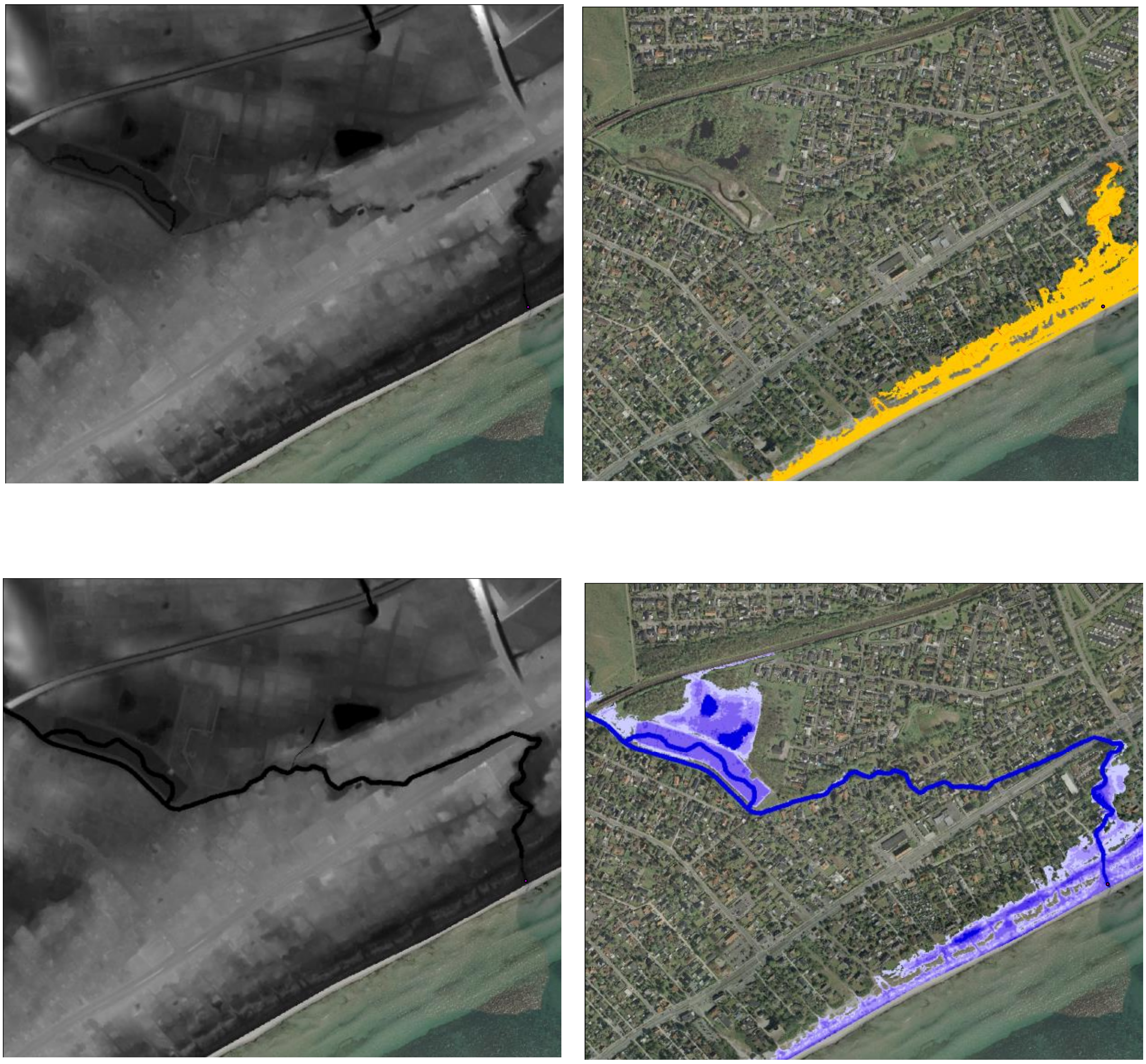


Figure 4.5 Illustration of a flood calculation of the cost-distance method using a raw data DTM (top) and a quality assured DTM (bottom), where rivers, dikes, bridges and culverts are represented (analysis and calculations are only carried out to illustrate the method)

4.1.3 1D-urban drainage systems

Calculations of flooding in the city resulting from inflow of water due to high sea levels can be undertaken with 1D hydrodynamic model. The sea water level is used as boundary condition at the outlets of the model. The result from the 1D simulations provides information at which manholes flooding may potentially occur in the city.

4.1.4 1D-1D two-layered hydrodynamic model

By using the method as described in 3.2.5 simulations of the risk of flooding can be undertaken by setting the boundary conditions at outlets to the sea level.

4.1.5 Hydrodynamic calculation of flood

This method uses a 2D hydrodynamic model to model the water flow on the terrain, and describes the flow between land and sea by applying the sea water level as boundary to te model. Compared to Cost Method, this method provides additional information in terms of flow velocities on the surface during flooding. This physically based method describes in detail the flow and time delay of water flowing through low-lying areas with complex geometry.

Input to the hydrodynamic calculation of flood

The description of the flow on terrain is based on input in the form of a digital terrain model describing the topography in model domain. The sea level represents the boundary conditions for the model domain, which define the variation of water level and the following potential flooding.

When the model domain is defined it must be ensured that the elevation of the inland area is greater than the maximum expected water levels in the ocean. In addition, the rivers, dikes, etc. must be described in the terrain model to ensure accurate descriptions of the flow around / over / through them.

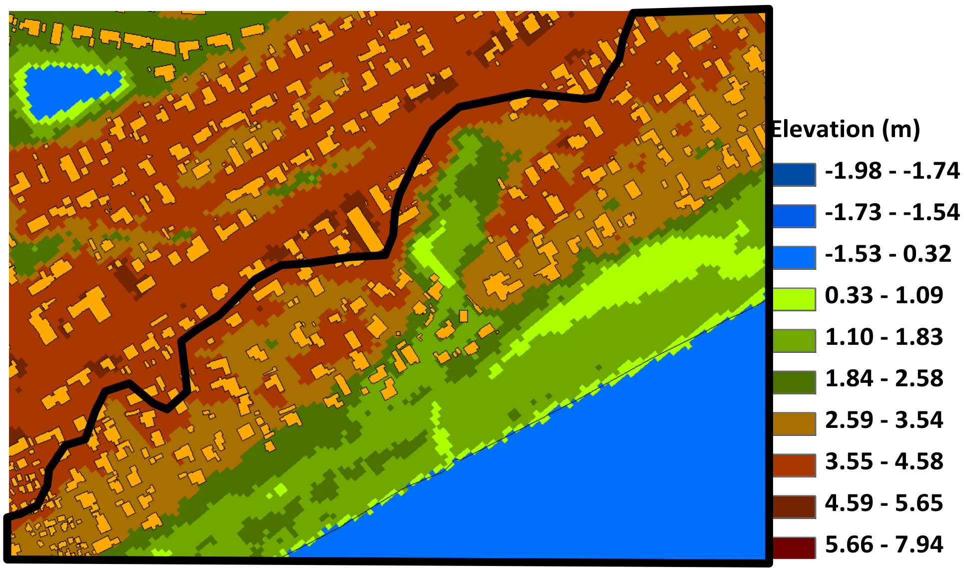


Figure 4.6 Model area when the expected maximum water level is 3.0 m

It is possible to calculate the effect in terms of floods from time-varying water levels in the ocean.

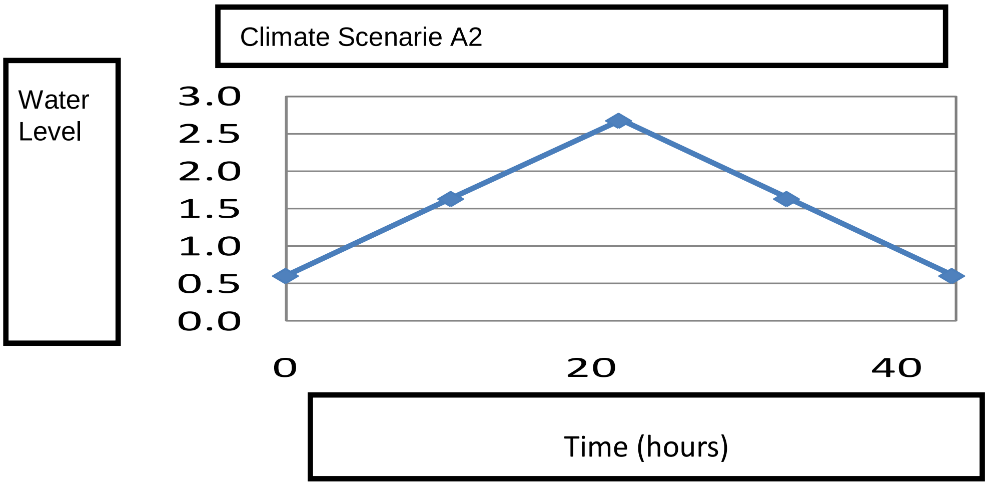


Figure 4.7 Illustration of a time-varying water levels in the ocean - as input to a flood calculation

Results

Model simulation results are temporal variations of water depths on the terrain. In addition, information on flow rates can be plotted, e.g. for an analysis of the influences from the forces of the water. The methods do not include the conveyance of water in streams and pipe networks to and from the city.

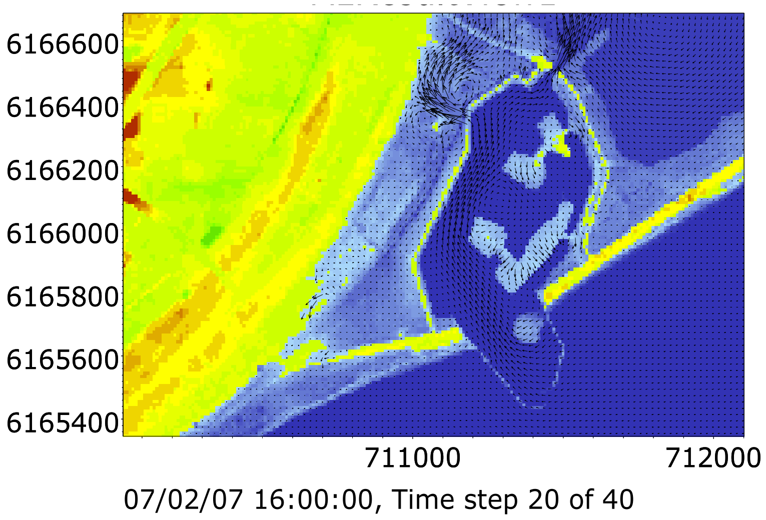


Figure 4.8 Example of model results showing water depths and velocities

4.1.6 1D-2D hydrodynamic modelling of the flow on terrain combined with a hydrodynamic model of the drainage system

A model describing the flooding from the sea can be combined with a model of the drainage system. This combination makes it possible to describe the water flow on land and through the drainage system. This is done by coupling a drainage model (e.g. MIKE 1D/MIKE+) and a 2D hydrodynamic model (e.g. MIKE 21). It is important to describe the pipe system, if it is located in an area where the inland terrain is lower than the coast. The advantage of this model application is the mapping of areas with flood risk which would otherwise erroneously be assumed flood safe.

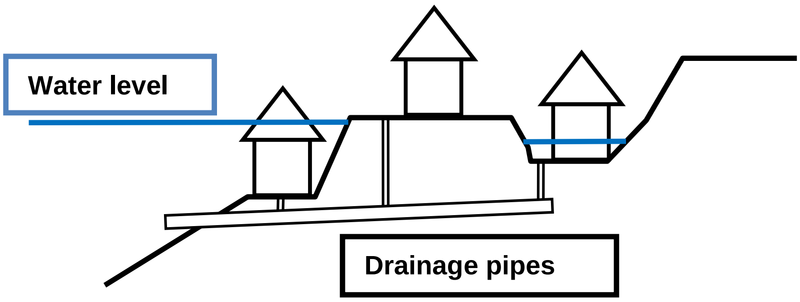


Figure 4.9 Illustration of the components in a calculation with a drainage model in combination with a model describing the flooding from sea

A 2D model describing water flow on the terrain is built as described above and can be linked dynamically to a calibrated model. The coupling of the two models can be reduced to the locations where the drainage system can potentially contribute to flooding on the surface. In areas which are significantly higher than the expected maximum water levels in the ocean, there is no need for linkage between the two models. In addition, the level of detail in the drainage model can be reduced at those locations far away from potential flooding areas. Simplified drainage models with fewer couplings to the 2D flow model will reduce the simulation time.

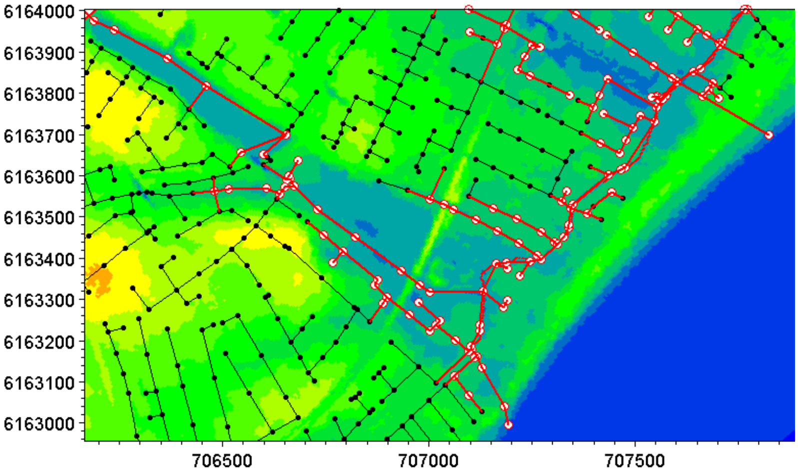


Figure 4.10 Only selected areas of the drainage model (shown in red) are coupled to 2D flow model. This optimises the calculation time

A time series with the variation of sea level is used as boundary condition for calculation. In addition, the urban drainage model can be loaded with rainfall. Then the combined effect of high tide in the ocean coinciding with a rain event can be analysed.

Results

Model results are temporal variations of water depths on terrain along with flooded areas. In addition to this information on flow velocities can be plotted, e.g. for analysing the impact of forces from the water as well as information on water flow and water levels in drainage system.

5 Urban climate adaptation

Climate change adaptation in urban areas is described in this chapter by applying risk assessments in practical solutions in order to achieve desired standards of services in preparation and layout of contingency plans.

5.1 Risk analysis

5.1.1 Damage assessment using a risk analysis

Assessing the risk of damages in an urban drainage catchment can be undertaken at different levels, from broad qualitative analysis to quantitative analysis. Other impacts may be taken into account in the analysis. Besides the influence of extreme rainfall there are also risks in the general operation of drainage systems.

A complete risk analysis of the system can be undertaken by systematically examining how the drainage system operates under different conditions during both extreme rain events and periods with disruptions in the service by weighting the various disruptions by their importance. A simpler risk analysis focused on extreme flooding is also possible. Analyses at both levels are very useful tools that can be used in prioritizing the maintenance, and operational actions should be continuously made to upgrade the drainage system.

Traditionally, damage caused by surcharged water on terrain is divided into three categories:

- Direct damage - typically damage caused by standing or flowing water.
- Indirect damages – e.g. traffic accidents because of aquaplaning, traffic disruptions, administrative costs, labor costs, loss of production, etc.
- Social costs - negative long term effects of a more economical nature, such as reducing the value of property in areas subject to flooding and slower economic growth.

A big advantage of a risk analysis is that all causes of flooding are assessed and weighted. Hence optimizing the time and avoiding disproportionate spending of time on some measures, while others, perhaps more important, are overlooked. As an example a pump failure of a pumping station due to obstruction or power failure during a moderate rain event could result in flooding comparable to the flood caused by an extreme rainfall event. One method to find the cost related to flooding in urban areas is to collect information on documented flood incidents by the insurance companies, as e.g. made in Norway (König et al., 2002), Denmark (DANVA, 2005) or Brazil (Nascimento et al., 2005). An internationally recognised technique to quantify the damage is the use of "Flood Damage Curves", describing the extent of the damage as a function of land use and water level, refer (Speight, 2006) and (Nascimento et al., 2005). Currently, such "Flood Damage Curves" do not exist for any areas in Denmark.

The following issues should be included in an assessment of damage related to flooding:

- To prevent that the population is brought into contact with a mixture of sewage and rainwater due to overloading of the drainage systems
- That vital community functions, such as electricity supply, water supply, heat supply, communication points and access to hospitals are not out of operation due to flooding

- That the number of affected basements and buildings are minimised
- That the number of flooded electrical power cabinets and other equipment is minimised
- The impact from flooding on traffic is minimised.

5.1.2 Risk analysis

Definition of risk concept

Risk is the combination of the probability of an adverse event (e.g. failure of wastewater treatment plant / pump station, basement flooding, releases of hazardous substances, errors in management / SCADA) and the magnitude of the consequences (e.g. damage to facilities, personal injury, odor, traffic delays, fish kills) and severity (is the release of 1 litre or 100 litres, is it the hospital that gets flooded, how many are injured).
Mathematically expressed as: risk = probability times consequence.

A plan for managing risk includes the following seven steps:

1. Identify the risks (e.g. what can go wrong?)
2. Assess the likelihood and consequences of these risks.
3. Determine the risk mitigation options
4. Assess the economic, environmental, public relations and operational costs and benefits of the options
5. Prioritise the mitigation option
6. Identify the decision makers
7. Develop the implementation plan.

The steps in a risk analysis are illustrated in Figure 5.1.

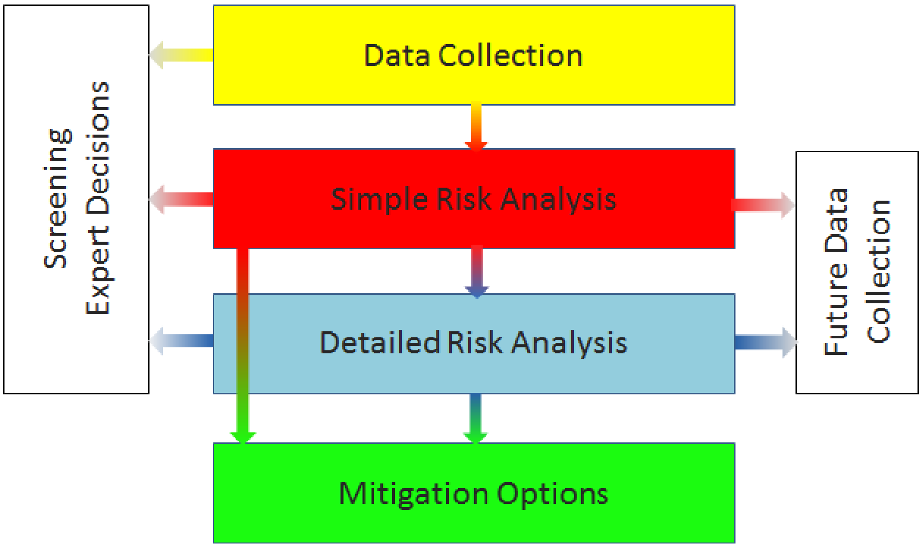


Figure 5.1 The process of risk analysis

The first step is data collection, where knowledge of the drainage system is obtained. This is followed by a coarse risk analysis during which a screening of infrastructure is undertaken by experts and special risk tools. After the coarse risk analysis, there are two options; either to prepare a detailed risk analysis with focus on selected areas from the coarse risk analysis or to go directly on to identify mitigation measures. If it is decided to proceed with the detailed risk analysis then it is possible to quantify different priority risk mitigation measures.

In order to prioritise the selected sites, it is necessary to establish three matrices:

- A frequency matrix
- A consequence matrix
- A risk matrix

The frequency matrix consists of seven intervals named F1 to F7. F1 is an event that statistically occurs less frequently than once every 10,000 years. F7 is an event that statistically occurs 10-100 times a year. The frequency ranges are constructed according to a logarithmic scale. Because of the logarithmic scale it is not important to know the frequencies of adverse events accurately. It is important to know the magnitude of a given event to be used. The frequency matrix is shown in Figure 5.2.

Frequency Interval	Classification	Frequency per year
daily to monthly	**F7**	10 – 100
Monthly to year	**F6**	1 -10
1 – 10 year	**F5**	0.1 – 1
10 – 100 year	**F4**	0.01 – 0.1
100 – 1000 year	**F3**	0.001 – 0.01
1000 – 10000 year	**F2**	0.0001 – 0.001
< 10000 year	**F1**	0.00001 – 0.0001

Figure 5.2 The frequency matrix

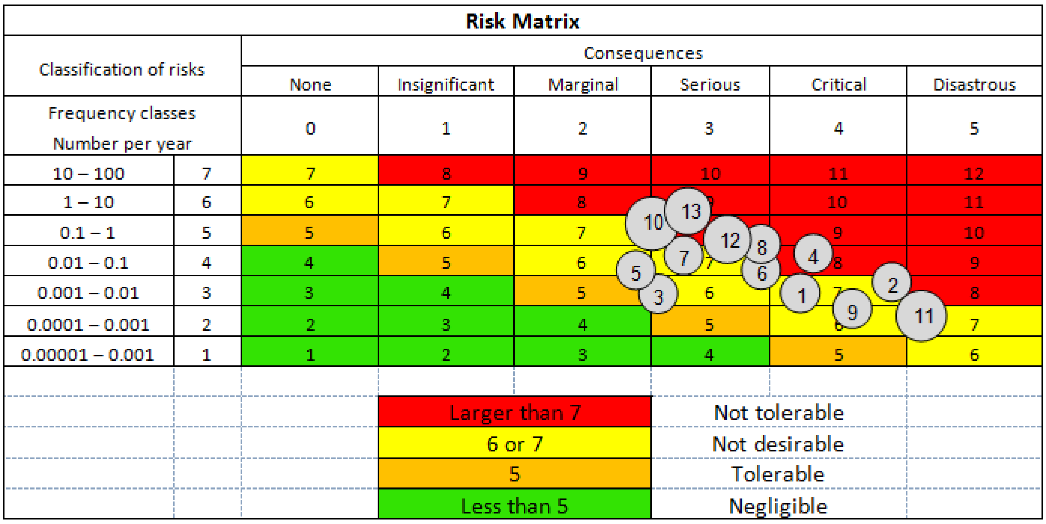
A logarithmic scale is used between the individual impact categories in the matrix to make it possible to compare the impact groups. "Negligible" for instance indicates an economic value of 10,000 to 100,000 DKK, while "Marginal" indicates a value between 100,000 and 1 million DKK.

The economic scale used in the consequence matrix is not arbitrary. Each figure is estimated from available sources and practical guidance numbers.

The consequence matrix can describe the different impact categories ranging from no/negligible impact to the disastrous impact described in both qualitative and quantitative terms.

The accumulated risk matrix is shown in Figure 5.3.

Four colours are used in the risk matrix to indicate whether the calculated risk level for a given event is tolerable or not. A risk level above six or seven shall lead to implementation of defined actions to reduce risk levels. According to Figure 5.3, identified mitigation measures must be implemented for the two events classified in the non-tolerable region (indicated by circle No. 4 and No. 13 in Figure 5.3).



Risk Matrix

Classification of risks		Consequences					
		None	Insignificant	Marginal	Serious	Critical	Disastrous
Frequency classes Number per year		0	1	2	3	4	5
10 – 100	7	7	8	9	10	11	12
1 – 10	6	6	7	8	9	10	11
0.1 – 1	5	5	6	7	[illegible]	9	10
0.01 – 0.1	4	4	5	6	7	8	9
0.001 – 0.01	3	3	4	5	6	7	8
0.0001 – 0.001	2	2	3	4	5	6	7
0.00001 – 0.001	1	1	2	3	4	5	6

🟥 Larger than 7	Not tolerable
🟨 6 or 7	Not desirable
🟧 5	Tolerable
🟩 Less than 5	Negligible

Figure 5.3 Risk matrix. In the matrix are examples of selected sites in sewers placed in relation to the assessed frequencies and consequences

All items located in the yellow area should be evaluated based on a cost-benefit-analysis that can determine what and how much is required to reduce the level of risk and whether an investment should be made here and now, or only when the impact occurs.

An analysis provides the basis for assessing the risk level for the entire drainage system and to assess this level relative to the acceptance threshold defined in the risk matrix. For incidents above the acceptance threshold risk mitigation measures must be identified and implemented. For incidents which lie in the acceptance area, an identification of optional mitigation measures must be undertaken and assessed through a cost-benefit-analysis.

5.1.3 Risk of flooding from extreme rainfall

A risk analysis of flooding from extreme rainfall alone can be based on flood maps, see Chapter 4. The simulation results of rain with high return periods may be plotted using GIS themes or aerial photos in order to identify problematic areas. Each area must be assessed as to whether flooding is a problem and whether there may be damages.

The assessment shall be based on the following considerations:

- If a park or football field is flooded for a given return period, is it acceptable? Is the inundation from a separate or combined system? How long does it take before the area can be used again and is clean up required?
- What flood levels will affect basements, first floor, electrical cabinets or parked cars, etc.?
- How much does the number of different damages increase caused by climate change? Is there a risk of more damages related to urban development and what is the flood impact from planned upgrades of drainage system? Can damages caused by flooding be exported to other locations?
- What is the level of uncertainty in the model results? How well is the model calibrated, and has a safety factor been included? Is it reasonable to interpret the results directly, or should a safety factor be applied to the results?
- Compilation of damages.

The cost of flood damage varies depending on what is damaged, if the damaged items have been completely or partly written off, replacement cost, etc. Moreover, the cost depends on whether the flooding was caused by rain water and sewage, and where the flooding occurred. It is therefore very difficult to generalise the damage costs. A general list that accurately describes the cost of flooding of electrical cabinets, basements, houses etc. cannot be developed. It is therefore recommended to first determine the number of damages by type and then to cost the damage.

To quantify the loss by flooding it is desirable to have a geographical overview of what values might be flooded. Typically, municipalities have records of where the buildings are located, and housing registration (BBR in Denmark) contains information about location of basements. The basis for the comparison is established by combining the building theme and BBR data. Public buildings will often have a higher value than a single dwelling, so it may be appropriate to categorise the public institutions in terms of use, i.e. as kindergarten or a nursing home.

Streets convey rainfall water into the drains. However, when the capacity of the drainage system is exceeded the water may surcharge to the roads. The roads are then used to convey the excess water during the rainfall event. In these situations it is important to know estimates of water depths, water velocities and where the water flows. Roads are usually designed to drain storm water quickly and efficiently. However, when there are significant amounts of water on roads, it might conflict with the original design of the road. If an analysis shows that a road under future climate conditions will be flooded more frequently, it should be discussed and resolved with the road authorities. The road construction may be adapted. In connection with damage assessments of roads it is pertinent to examine the criteria for the operation: How much water on the road is allowed by the Authority before the road must be closed? And to investigate the road quality, so it can be determined how much water it takes to destroy the foundation of the road and how long the road can be flooded before damage occurs.

Valuation

The following parameters can be used for valuation of flooding:

- Housing
- Crèches
- Kindergartens
- Nursing homes and sheltered housing
- Water distribution. Flooding of the building of the water treatment plant causing possible contamination of clean water
- Water wells, flooding may lead to contamination of the bore field
- Petrol stations where there may be a risk of water flowing into the tanks, so the petrol runs out (Service Stations with newsstand sales, Auto Service etc.)
- Areas of storage of oil and hazardous waste near recipients
- Companies with oil and petrol separators connected to the sewage system and storm water system. Oil/gasoline may either surcharge inside a building or outside. (It will run approx. 50-100 l from each separator.)
- Especially for wastewater systems:
    - Avoid overflows from sewage pumping stations.
    - Avoid swimming pools becoming contaminated with sewage

It is important that people with the greatest knowledge of the area being examined are consulted to determine appropriate values for the various categories above. In some cases, the GIS staff has a good overview of the information available. The boundaries of what can be illustrated and calculated from GIS primarily depends on what information is available. Below are a few examples for inspiration.

Figure 5.4 shows a theme with houses inundated by various return periods. The GIS layer of simulated floods is linked to the GIS layer of houses taking into account the foundation level.

In Figure 5.5, the electricity cabinets are illustrated with floods exceeding 40 cm, by which flooded electricity cabinets can be identified and counted.

Figure 5.4 Example of GIS theme of the houses flooded at different return periods

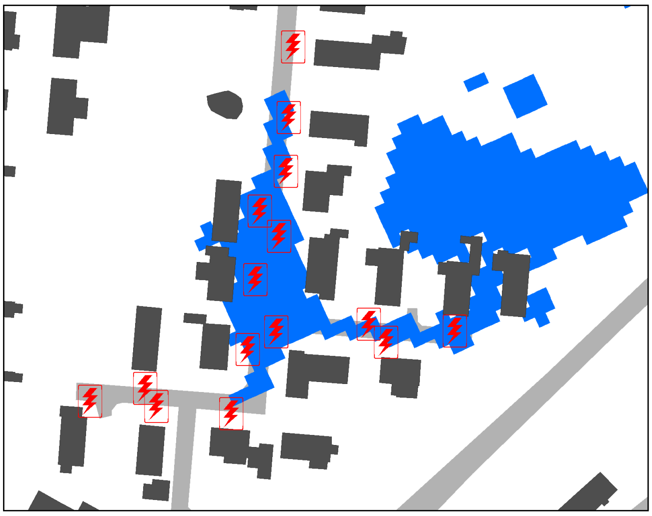


Figure 5.5 Example of GIS theme of electrical cabinets damaged. Placement of electrical cabinets is pictured together with water levels above 40 cm

Figure 5.6 and Figure 5.7 show the specific buildings plotted together with extent of the flooding and flood depth. In this example schools, kindergartens and service stations are shown. This type of GIS illustration shows how and where health or environmental issues may arise.

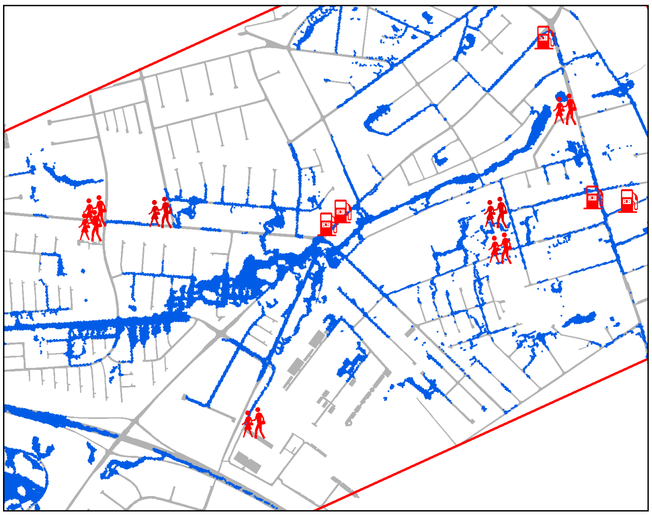


Figure 5.6 Example of GIS theme showing specific buildings. Flood propagation is pictured together with the location of schools and kindergartens and gas stations

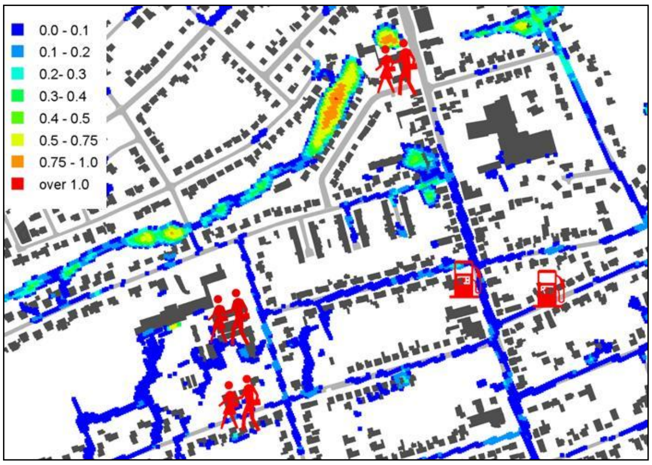


Figure 5.7 Example of GIS theme showing specific buildings. Flood levels are pictured together with the location of schools, kindergartens and gas stations

For valuation of a new road foundation the following should be noted:

- it varies according to thickness, etc..
- most expensive is asphalt layered roads. In this situation it will be necessary to remove and deposit the asphalt before construction of new foundation, followed by a new asphalt pavement.
- in parts of the foundation there will be cables, and costs associated with coping and any repairs due to damage caused by replacement of the foundation are impossible to estimate. Worst Case = much more expensive than road foundation and asphalt replacement.

5.2 Priority adapting to floods under a changing climate

As it appears the risk analysis can be used as a basis for prioritizing actions to prevent floods and to adapt to climate change, but in many cases it will not be necessary to implement the full risk analysis to get started.

Analyses of climate adaptation can be achieved at many different levels (as described in the introduction to Section 4). These methods can be used for different degrees of priority: Establishing a basis for getting started, where models shall be established, prioritizing measurement programs, prioritisation of specific climate adaptation in the form of installations, priority for emergency action, etc.

In relation to the specific climate adaptation it will be necessary to implement priorities of both the economy as technical measures, which are highly political decisions, but the political decisions must obviously be made on a sound technical basis.

Priorities can be carried out based on assessments of risks of flooding, but can also be implemented based on economic assessments: where do you get the greatest reduction in flood risk or most climate change adaptation for the money?

Prioritisation of climate change adaptation can be based on the climate-meter. Among others it will be possible to prioritise where to undertake registration of the pipe network if it is not available in a digital form. The digitisation can be undertaken based on the relatively simple Depression Map Method combined with a simple hydraulic model, refer to section 3.2.2.

In Greve Municipality it was decided that the entire urban drainage network must be upgraded so that the water level in these systems only surcharge to terrain once every 10 year. Based on the experiences from the flooding in July 2007 and a flood risk map prepared using the so-called quality-assured Depression Method, the entire municipality is divided into 42 urban catchments, and priorities of the climate change adaptation is planned for the next 12-15 years.

The hierarchy is based on the idea that those who have been hit hardest must be climate change adjusted first. This plan is politically decided.

5.2.1 Urban prioritisation in Greve municipality

Model domains in general follow the storm watersheds in order to ensure that hydraulic analysis of climate change adaptation can be adequately undertaken for the urban drainage network.

The following information was used to help guide the prioritisation of upgrade works:

- Experiences from the floods in July 2007, as reported directly from citizens or landowner associations.
- The digitisation of the storm water system.
- The digital terrain model for Greve Municipality which is used to calculate the depth of the depressions in the surface, the "Depression Map Method".
- GIS theme of buildings in the municipality and the theme of business and public buildings.

5.2.2 Description of the method for prioritisation in Greve

Urban areas ranked by the experience of flooding in 2007.

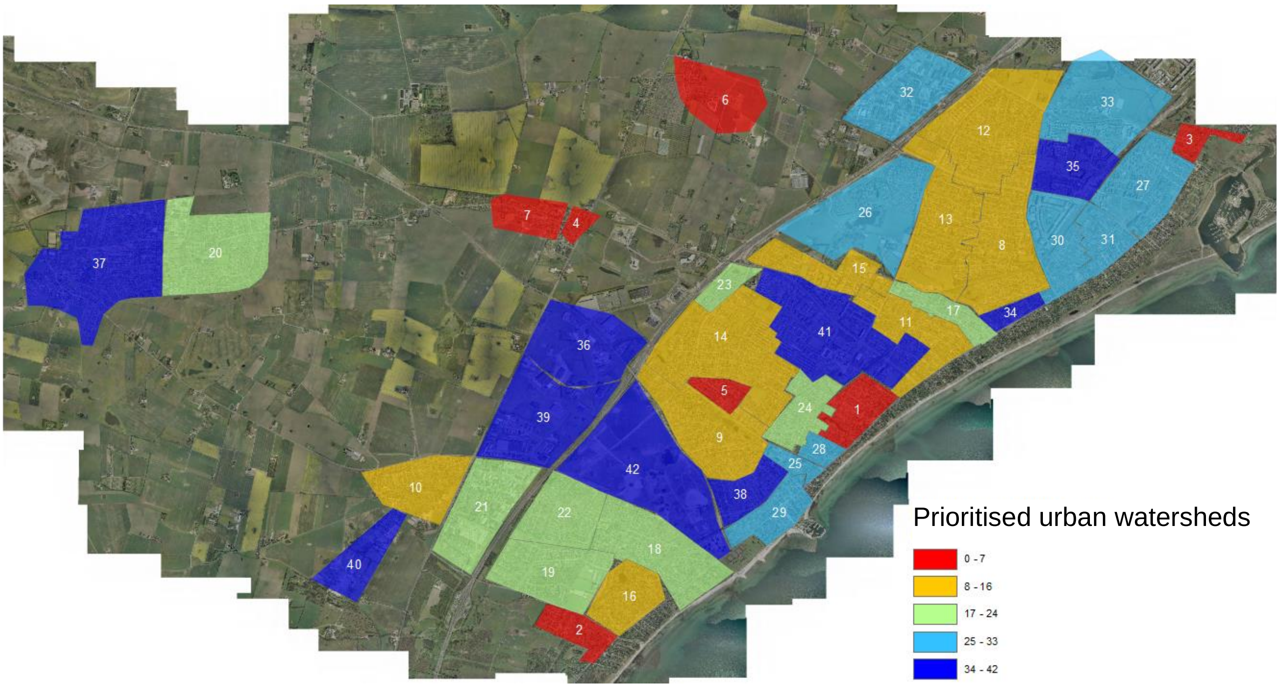


Figure 5.8 Prioritisation of urban water sheds. The numbering reflects the order of implementation

Figure 5.8 shows the prioritisation of urban areas. Urban area no. 1 is the first area to become adapted to the climate change, followed by urban area no. 2, etc.

In order to give an idea of the flood risk to commercial and public buildings, the number of these located in the depressions is shown for each urban area. However, these commercial and public buildings were not included in political decision on the prioritisation of climate change adaptation.

5.2.3 Quality assurance of priority

The hydraulic models will be improved and updated through monitoring programs and calibration. Improvements in the models due to additional data may lead to future changes in prioritisation. Similarly, economic aspects may lead to reprioritisation. It may for instance appear that a relatively simple and inexpensive augmentation will have a major positive impact on climate change adaptation (such as is done with the establishment of an outlet pump at a main outlet or the provision of terrain planning).

A similar ranking, where the number of affected properties is investigated, is implemented by using 1D-1D surface calculations as described in section 3.2.5. After the hydraulic calculation the number of houses within the flooded areas is counted, and priorities are implemented and compared with the first priorities.

5.3 Options for adapting the urban drainage system

The expected higher rainfall in the cities should either be discharged or stored in order to avoid flooding. Possibly, part of the water can infiltrate locally before it enters the urban drainage system. A wide range of technical options exist to solve this. The drainage system can be built out with additional or larger pipes, and ponds for storing can be constructed. In the following examples various augmentation options are given.

Main groups of options are:

- Active reduction of inflow of rainwater to the drainage system, i.e. through increased infiltration of rainwater
- Temporary controlled storage of rainwater, i.e. using wetlands
- Augmentations in the drainage system that increases capacity, i.e larger pipes, basins, etc.

5.3.1 Physical measures on drainage system

Addressing the increased rainfall from our urban areas in order to meet the standard of services and reduce the flooding can be done in a variety of ways.

There are three types of solutions: To avoid the increased volume of water discharged to the drainage system, increasing the discharge or the storage capacity of the drainage system or possibly a combination of these. Reduction of inflow to the drainage system can usually only be achieved by establishing local infiltration of water. Drainage of storm water can be done through open channels or closed pipes to the recipient, to larger infiltration units, or with any wastewater to treatment plants.

Storage systems can be either traditional basins like concrete boxes or pipe-basins, or it can be lakes and ponds. Beyond the physical conditions in the catchment, treatment plant capacity and conditions in the receiving waters, it is crucial whether the drainage system is a combined system or a separate system. In a separate storm water system, it is usually much easier to find diversion options for a local recipient, than it is for overflow originating from a combined system. Figure 5.9 shows an overview of possible ways of regulating storm water into a drainage system.

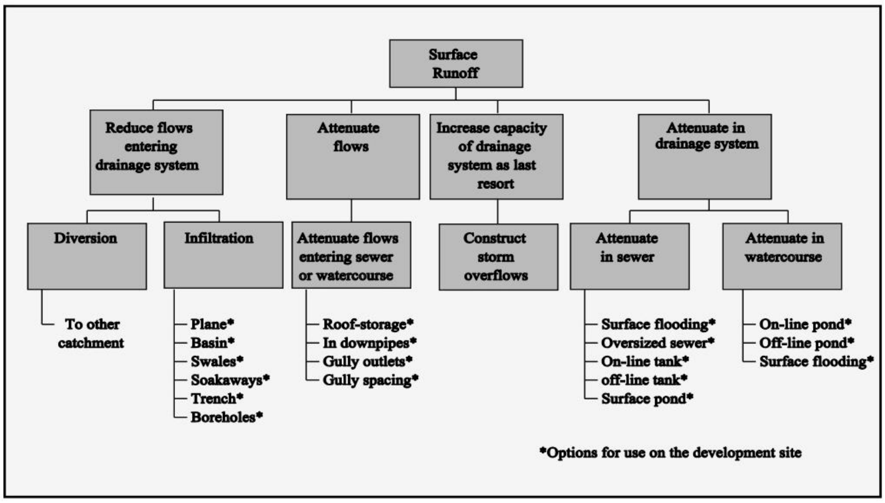


Figure 5.9 Schematic overview of possible ways of regulating runoff. Source: Parkinson & Mark 2005

The following describes some of the most common approaches expected to be used for augmenting existing drainage systems, so that they can meet performance requirements during the future increased load. The municipality should be aware that actions often lead to a need for revision of both wastewater and discharge or infiltration permits, e.g. if overflow volumes or local infiltration is increased/established.

5.3.2 Infiltration of storm water

Where it is geologically and hydrologically possible, infiltration of storm water can be established at each property, or complete infiltration solutions can be made for small urban areas. Storm water from roads, sites, car parks etc. may in some cases be infiltrated, but in those cases in must be determined whether the infiltration may pose a threat to groundwater quality.

Infiltration is basically the best environmental approach for discharging unpolluted rainwater, as it largely corresponds to the natural way and results in only limited interventions in the natural water cycle. Drainage structures should be designed so that there is emergency overflow from infiltration facilities to the public storm water system. This reduces the risk of flooding and the size of the infiltration facilities required is limited. However, this has the unfortunate consequence that during heavy rain the fascines can be filled up, resulting in a quite instantaneous and uneven flow back to the drainage system, which must therefore be designed to cope with these peaks in the flow.

The capacity of fascines may typically be of a size equivalent to 20-30 mm of rain, but there is no assurance that fascines are empty at the beginning of rainfall events. For this reason it is not certain during an extreme rainfall event that flooding is reduced significantly. However, fascines can reduce the yearly runoff volume considerably and increase groundwater recharge.

Combination of infiltration and storing

As mentioned infiltration systems for storm water usually have a limited capacity, requiring water to be stored during periods of major inflows. The optimal combination of storage size and infiltration capacity can be calculated or estimated based on knowledge of soil infiltration capacity, flow conditions, etc., refer Guide 25.

5.3.3 Separation of combined systems

Many of the most appropriate measures to address the increased rainfall are ill-suited for combined systems. The mixture of sewage and storm water is so polluted that the water must be treated with caution. Human contact with the water poses a risk of disease, and there are aesthetic problems at outlets. Functional requirements are therefore much more stringent to the combined systems than to storm water systems. It is natural to consider changing the old combined systems to separate systems, especially if the spare capacity of the combined system is limited requiring major built-outs. In practice, this involves so many problems that only a few places exist where it is implemented. It is very expensive and very difficult to build a completely new drainage system, which also requires that the pipes located at each parcel are converted to a separate system.

Separating the combined system is carried out in smaller communities and new built-outs, but rarely in the old city centers where the need is often the greatest. Therefore, there is a need for other solutions to address at these sites. There is currently a “standard” solution for these city problems.

5.3.4 Increasing pipe sizes

If the conceptual layout of a drainage system cannot be changed, it can be chosen to simply increase the dimension of all the pipes in the system, so the capacity will meet the requirements in the standard of services.

Alternatively, an additional pipeline can be added along the existing pipeline. Prior to this augmentation the drainage system should be carefully analysed in order to only make the necessary substitutions, and it should be considered to increase existing dimension on some stretches, and whether there are alternative pipeline options, which can reduce costs for expansion.

Trunk mains

The increased runoff flow from a catchment can be conveyed through larger pipes or stored in basins. Due to lack of space it may be difficult to expand the sewage system, and an option could be to build tunnels conveying the water from strategically well-placed nodes in a catchment area to the recipient or main trunk line. The tunnels can also act as extra storage capacity. The technical and economic feasibility of using such solutions have been considerably improved in recent years. It should be noted that the increased water flow can be critical to the rehabilitation method that can be used, and thus the expense.

5.3.5 Overflow

In combined systems overflow or spillways are often installed to prevent the water level in the drainage system from exceeding a certain level which protects areas from flooding as well as ensures that only the designed volumes of water are conveyed through the system. Overflow discharges across a weir to basin, outlet pipe or recipient. To ensure the same hydraulic functionality at the overflow structure during higher inflow and constant outflow, it will be required to increase the width of the weir crest or lower the weir crest level. The latter will, however, have the unfortunate consequence that the number of overflow increases.

To ensure the best hydraulic function of an overflow structure, i.e. ensuring that most water flows through the structure without an increase in the backwater, the weir structure can be equipped with movable weir, dynamically controlled crest level or a moveable flap. This can also maximise the basin effect in the upstream drainage system.

In addition to the hydraulically justified augmentations, treatment measures are also installed at overflow structures. Normally, automatically cleaned strainers or grids but in some cases more extensive treatment measures, i.e. removal of nutrients and sanitation. The development will certainly lead to such cleaning being more and more prevalent, providing increased and better cleaning methods for use by local treatment. If the discharged water is sufficiently cleaned, the cleaning can compensate for the increased overflow volumes, so that the impact on the recipient is reduced despite the increased overflow.

5.3.6 Basins

At many locations where it is chosen to reduce the hydraulic capacity in an outgoing pipe, basins are built which can act as buffer in the drainage system. Basins are often constructed with an overflow ensuring only overflows to the recipient at a chosen frequency. The basins can both be designed to store the extreme peaks of the runoff, so flooding is avoided or reduced, and they may also reduce the overflow to the recipient. In combined systems the stored water is conveyed to the water treatment plants in the normal way after a rainfall event. In separate systems, basins are usually used to smooth runoff flow, but also add some treatment of the water before it is discharged into the recipient.

Sizing of basins in combined systems can be made from the discharge capacity of the basin and selected return period of overflow. There are formulas in Guide 26 to determine the required volume of the basins, but it is recommended that updated rain series are used and in addition the effect of climate change incorporated. A subsequent calculation is undertaken with historical rain to verify the function of the basin.

Basins in separate storm water systems can often be engaged in recreational areas and therefore have other functions than just smoothing the runoff. In this case the size of the basins may be determined by the permissible water level variation, i.e. of requirements to retention time limits. The retention time may not be too short because it gives too little withdrawal of substance, and it must not be too long as it can cause excessive algae growth in the basin/pond. This type of basins may also be recommended because they are often very flexible to increased inflows partly because overflows due to the location do not cause major damage.

5.3.7 Local storage

Wherever there is a possibility it will be a good idea to store rain water in extreme situations. It should therefore be considered to place basins in as many small watersheds as possible, i.e. in drainage of minor roads, parking lots, etc. Perhaps at some locations the storm water inlets can be made so large that they can act as smaller basins during extreme rainfall by reducing the outgoing pipe capacity. Developments such as these can be performed when there is still rehabilitation undertaken, and can thus assist in compensating for extreme rainfall beyond the level of service.

It could be considered at the planning stage that newly paved areas can serve multiple purposes, so that planned activities in this area are not harmed by water depths of approx. 5-10 cm in the area during extreme rainfall in a short period.

5.3.8 Control and regulation of drainage system

Drainage systems are dimensioned to handle a design rainfall and thereby meet performance requirements. Since rainfall often falls unevenly across a catchment basin and the capacity of the pipeline system is often varied, there may be a good opportunity to improve the use of a drainage system by introducing dynamic control of certain elements in the system, e.g. the outflow from the basins. This can contribute to both reduced flooding and in combined systems reduced overflow to recipients. For drainage systems with multiple basins, pumping stations, etc. it is strongly recommended to investigate the potential for dynamic control. As part of augmentations in the system it may be appropriate to examine whether control can allow for more appropriate solutions to problems such as the storage basins or large pipe basins can be better placed in the system.

5.3.9 Use of the road system

Normally, runoff from the roads is conveyed to the drainage system to avoid water or aqua planning on the road. In some cases it may be considered to exploit the road profile to convey water away during extreme rainfall. If the terrain is suitable and a model can be assessed in terms of how the system will operate, then it may be an excellent way to get the water transported from critical areas to suitable recipients or storage options. The method can be recommended only to be used to separate storm water systems and in situations where the design rainfall has been exceeded (i.e in emergency situations).

5.3.10 Augmentation on private property

Physical measures

It may be useful to encourage owners to collect and divert rain water on their own land in order to avoid that the water is collected and hence requiring large drainage capacity. Additionally, less effect on the water circulation in the area is achieved by infiltrating the water locally. However, it requires that groundwater, soil and terrain conditions fulfill certain conditions so that it is possible to divert the water locally, without introducing local problems and damages.

If a parcel with a relatively small impervious area of 150 m^2 is considered, this corresponds to the fact that landowner must be able to store and dispose 7.5 m^3 of rainwater in a 5-year rainfall event (rainfall equivalent 50 mm), if there is no connection of storm water to sewer. This amount equates to 30 standard rain barrels or a pond in the grounds of 5 by 5 m and is 30 cm deep. If more water falls the owner needs to have a management plan in place for handling this extra amount of water volume locally to prevent flooding on his own or other people's parcels.

Managing storm water on their own land without drainage to the combined drainage system may therefore be recommended primarily for environmental reasons and in order to recharge groundwater. When looking at the hydraulic balance, these constructions are not the solution, but a complement to climate adaptation.

It is recommended not to base an adaptation solely on efforts by private landowners for many reasons. The fact alone that it is not possible to control when landowners are ready to disconnect their storm water system is reason enough not to rely on this method from a hydraulic standpoint.

There are several methods that can be used by landowners if they want to reduce storm water discharge to the public system:

Infiltration of rainwater

This refers to the diversion of rainwater into fascines on the site. Infiltration requires adequate soil conditions. Fascines are often designed in a size equal to 20-30 mm of rainfall, but no certainty exists that the complete capacity is available when the rainfall starts.

If e.g. grass armor stone or similar surfaces are used in parking spaces, etc., a large part of rainfall is infiltrated on site depending on the soil type. But in case of intense rainfall water will run on the surface and be discharged to the drainage system.

Rainwater barrels

By collecting rainwater in rain barrels a reduction in the discharge to the drainage system is obtained and water consumption is reduced in cases where the water replaces the standard drinking water supply used e.g. for garden watering. The volume that can be collected is often very limited, 200-500 l is often seen, and this is only a modest proportion of the volume of extreme rain on a roof. Rainwater barrels can be full at the start of the rainfall and therefore not reduce runoff at all.

Reuse of rainwater

Use of rainwater in homes as a substitute for water supply has only been implemented in a few places, but has the same advantages as rain barrels and the further advantage that consumption - as opposed to irrigation - is more evenly distributed over time. A major drawback is also here that the storage capacity is limited and therefore there is no guarantee that systems can store water during critical situations.

In Rørcentrets guidance "Use of rainwater" the use of a tank of 3 m^3 for such plants is recommended, and it is estimated that a tank like this will be able to store a large part of the annual precipitation to be used in the dwelling for toilet flushing and washing machines. In connection with extreme rainfall an overflow is required to divert water, since a 5 year storm event alone requires at least 7.5 m3 for a single-family house. Re-use of rainwater should be in regulatory guidelines (see EPA guidelines and Rørcenteret guidelines).

Green roofs

Techniques have been developed for using the so-called green roofs, where a grid of growth layers in which plants can grow, are laid out on the roofs of buildings. The aim is to store the water fallen on the roof in the growing layer where it is absorbed by plants. However, the storage ability of the growth layer is limited, only 6-10 mm, so the storage effect during extreme rainfall is limited. However, on an annual basis a quite good effect can be achieved in terms of reduced inflow to drainage systems.

Green roofs can therefore only be recommended for reasons of aesthetics and have very limited effect on the hydraulic system in the event of rain.

As shown in the mentioned examples of actions on private land, it is hard to find solutions for the public which are as safe and easy as discharging to the public drainage system, and it is hard to find solutions that can handle the very critical periods of extreme rainfall.

Private prevention of basement flooding

If a landowner needs to guard the basement against flooding from sewers non-return or check valves can be installed so that water cannot flow backwards into the basement. If the basement drainage system is connected to a pump wet well pumping to drainage system, then even higher security is gained towards basement flooding. This also ensures that the private installations can be used regardless of the water level in the public drainage system.

Administrative actions against private property

There is an opportunity in the law that the municipality allows a private property which diverts rainwater to the municipal drainage, to be disconnected to the drainage system for all or part of runoff. It requires a voluntary agreement between the municipality and the property owner. The municipality may reimburse connection charge for this storm water drainage.

5.3.11 Drainage of road space

Drainage of road space works in most places very effectively. This is also the target from the road authority's side, since water on the roadway constitutes a danger to traffic and water in the road paving and road base layer may damage the road. Drainage of especially smaller roads and streets, however, could perhaps be made so that the water in a lesser degree were led directly to the drainage system, but first had to pass through some retention devices such as infiltration devices. There is also scope for increased use of semi-permeable pavements, where part of water on the road infiltrates through.

5.3.12 Examples of local handling of rainwater

The following are examples and illustrations of local handling of rainwater.

It is estimated that water in the urban environment will help to increase the recreational value. Water storage in the urban environment will often require a landscape design that involves green areas and thereby achieve positive side effects such as cooler urban areas in summer and greater recreational value.

Projects in Odense and Copenhagen have shown that a solution based solely on local infiltration is probably not sufficient, both because of increases in the groundwater table and required space for creation. It will need additional measures such as storage of rainwater in the terrain for which modelling is required. In Odense a contingency plan has been established for handling rainwater at Sports Park.

Figure 5.10 Relief channel to reduce flooding at Sports Park in Odense, established in 2008

The dimensioning of the channel was based on simulations with the surface model so that both the size and location led to the desired effect. The channel has subsequently been in operation for a number of rain events and has functioned as intended. Since it was established there have been no damages to buildings and other infrastructure. The intention is to extend the urban drainage system and establish alternative storm water management in the area, so that the channel will increasingly become a part of the solution which only comes into operation during rain event with a return period of approx. 10 years and higher.

5.4 Flood emergency preparedness

Municipalities shall determine the desired standards of services which they will offer citizens. This has to be done under conditions that are more extreme than the defined desired standards of service which cannot prevent floods. However, it is possible to minimise damage and inconvenience by increasing emergency preparedness. The level of flood emergency preparedness needs to be balanced by the financial effort (see Section 5.1Risk analysis).

Preparedness involves a wide range of activities and assessments that can protect assets and people from damage caused by water. The contingency plans should of course contain important phone numbers and other important administrative information, but in this report only the hydraulic aspects of preparedness will be discussed.

Preparedness can be divided into before, during and after because the state of emergency must be investigated and planned ***before*** it occurs, actions may be required ***during*** the emergency situation and there will be an evaluation ***after*** the event where the experience will be evaluated and possibly incorporated into new updated contingency plans.

In Figure 5.11, the possible components of flood preparedness is shown.

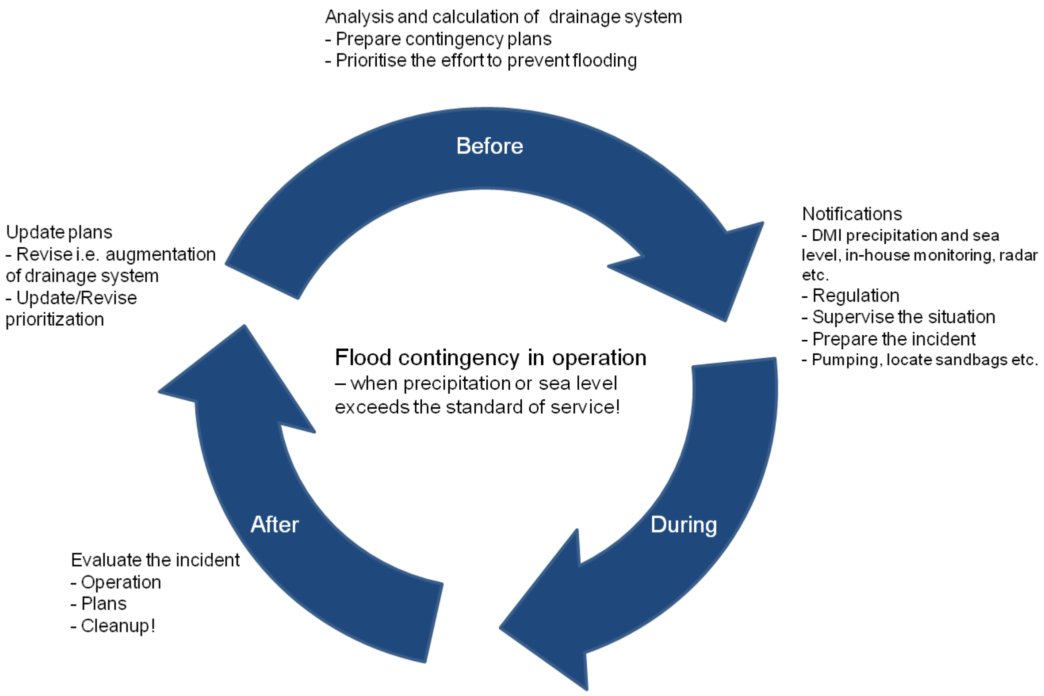


Figure 5.11 Illustration of a flood preparedness

In the following sections, the flood preparedness components are elaborated.

5.4.1 Before the rainfall event

Establishment of contingency plans if necessary for climate change adaptation

All municipalities must, as a part of the overall civilian preparedness, have a contingency plan in place. There is currently no requirement for the municipalities to develop a specific plan for operation of urban drainage systems and wastewater treatment plants. Some municipalities have, however, made such plans which accommodate a number of issues that are critical to the operation of the urban drainage system, e.g. power failures, flood damages in exposed locations, staff/contractor preparedness for emergencies that could maintain a minimum service level.

Contingency plans are plans which are used by municipalities to respond to overloads to urban drainage system and water surcharges to terrain, and they include:

- Actual physical measures to reduce the effects of an extreme rainfall situation and resulting floods such as earth embankments and walls designed to hold water back in pre-defined depressions.
- Preparedness for emergency ad hoc efforts, i.e. placement of sandbags and use of mobile pumps
- Information/alerts both internally within the municipality's operations and externally
- Preparatory work must be undertaken where all details related to physical measures, acute ad hoc efforts, information and alerts are reviewed.

Priority for contingency plans

Contingency plans should be available to all urban and possibly rural areas where it is estimated that flooding may cause significant either human health related or costly damages.

Once contingency plans have been established for a large area, e.g. a municipality or a region, priorities for all catchment areas in the region should be set. This must be done before a critical situation occurs, because there might not be sufficient personnel and equipment available to implement the effort in all catchments at once. A prioritised contingency plan would be a good decision support tool for incident management team.

The hierarchy of plans can be implemented using the same principles as the prioritisation of climate change adaptation.

Structural responses to flooding

In relation to obtaining a climate change service level for a catchment area, analysis and detailed projects will uncover the critical issues within the area. The solutions that exist could to some degree be expanded without significant additional costs. It may also be required to be able to protect vulnerable housing areas using banks of earth or terrain regulated through embankments or excavation so that water can be conveyed to less critical areas.

Examples of permanent measures include embankment at Godsparken in Greve to prevent a river from flowing into an urban area, and a gutter near the Sports Park in Odense, which convey the water onto the running path to avoid damage to floors in buildings, see Appendix A.

The embankment at Godsparken is not expensive in construction and ensures not only against extreme long term rainfall, but also against extreme water levels in the ocean.

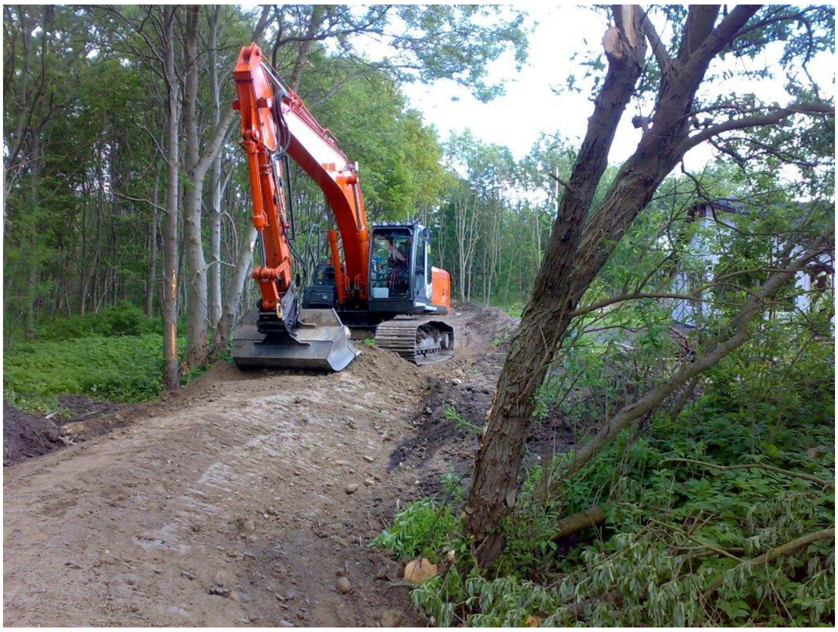


Figure 5.12 Establishment of embankment at Godsparken in Greve

Mobile preparedness actions

Besides the stationary emergency response there is a wide range of possibilities for mobile emergency measures, e.g. mobile pumps, sandbags and shutters. Partly through terrain analysis, calculations and experiences a strategy can be created in advance for how surface water is conveyed in an emergency situation and the necessary dimensions for pumps and mobile walls can be assessed. It is essential that the number and precise location of such sandbags is known and that everything is available in stock and ready before the situation arises.

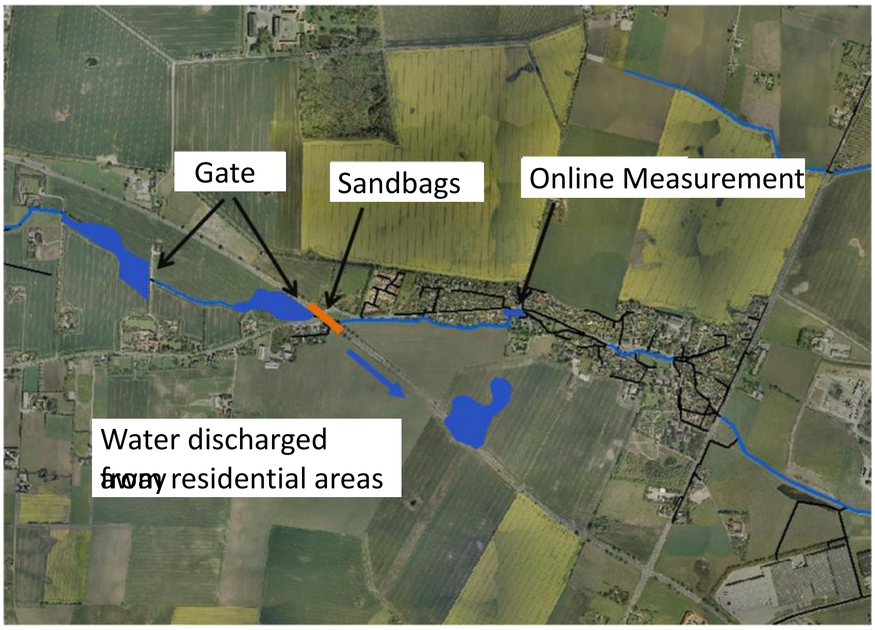


Figure 5.13 Sample proposals for mobile emergency response in combination with online measurement

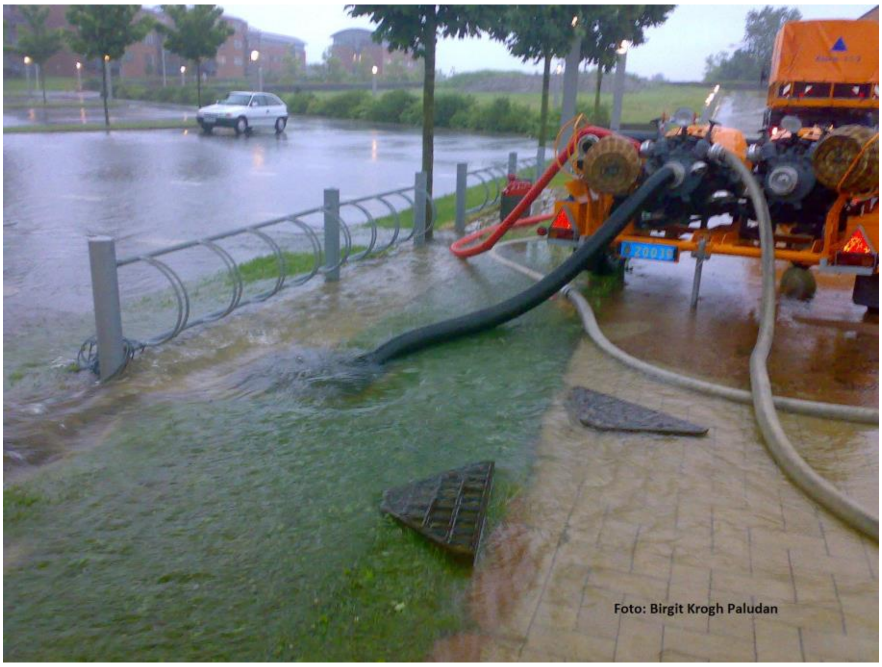


Foto: Birgit Krogh Paludan

Figure 5.14 Mobile Pump used at Greve Gymnasium during extreme rainfall in Greve on 5th July 2010

Warning

It is essential that the municipality and wastewater utility is warned about possible adverse events that should be acted upon. Meanwhile, it is also appropriate that citizens are warned that flooding is expected and adviced to secure personal belongings. .

DMI forecasts heavy rainfall events in Denmark today, but the risk of subsequent floods in cities are often based on experience. This is inadequate because local conditions in the urban drainage systems determine if flooding occurs or not. Alerts are currently used in selected locations abroad to reduce costs associated with flooding. Can the urban drainage system for instance be partially emptied until rain arrives, or traffic radio can be used to warn people to stay away from urban areas at risk of flooding, cf. Chumchean et al. 2005, Rene 2011.

Some floods are acceptable if people are informed in a timely and appropriate manner about how to behave. However, this requires that the municipality is in possession of an appropriate action and contingency plan that can be executed when an extreme rainfall is warned. If an analysis shows that there will be flooding in an area under future climate change conditions which are not acceptable, then it will take some time from the analysis is performed until new infrastructure is built. In this period a warning is useful.

When the warning comes into force, it is important that the wastewater utility has a communication channel set up through which information to the citizens about the measures affecting them can be communicated. Before the emergency situation occurs, citizens must be aware of how to seek information: Website, radio or similar.

In Denmark it may be appropriate to have a contingency plan based on a warning of heavy rainfall for viaducts or similar flood prone sites. Using the warning, such sites can be isolated before the flood is so high that people are at risk if attempting to walk or drive through the water. Whether the warning will be appropriate and economically viable must be assessed on a case-by-case basis.

Responses to the flooding may depend on:

- Existing storage basins, canals, streams, rivers and lakes that can be drained before the emergency situation arises, ensuring an optimum volume available in the systems.
- How soon operational staff can be warned so they are ready to implement contingency plans
- Existing grates, outlets, non-return valves, etc. are reviewed to ensure that they are fully operational before the rainfall occurs.

Control and supervision

Control can be implemented in urban drainage systems if there is additional storage available or long transport times present.

A control strategy could be developed when a sufficient understanding of how the urban drainage system functions are available. The coupled models described in Chapter 4 may be useful to provide an overview of where it is appropriate to control the water, e.g. by implementing gates or pumps. The analysis may have identified a critical area where it may be useful to store water upstream by flooding less critical areas. By applying on-line meters at strategic locations in the urban drainage system, gates or pumps can be controlled by set points and be in operation at the right time. Additional storage can be created by emptying existing ponds, canals, rivers and lakes before the situation arises.

Establishment of supervision of critical locations in the systems is highly relevant for decision making during a flood situation. Thus it will be possible to implement management of pumps and valves in a critical situation and to prioritise efforts.

A combination of warning and control can be used to ensure the required volume in the system where it is expected to be most needed.

5.4.2 During the rainfall event

During the extreme rainfall and the time just after (depending on rainfall character) the urban drainage systems are monitored and the contingency plans are initiated when required.

Capture of evidence and experience

To ensure that the entire organisation will be wiser from the experience gained during the incident, it is very important to conduct a detailed documentation of the incident. The documentation should include at least the log of adjustments and operation actions in urban drainage system (who has done what and when), and preferably include notes of why and on what basis the action was implemented. Observations in the field are very valuable (preferably with pictures) when experience should be used in further analysis and possible in updating the contingency plans.

After a flood event very detailed knowledge of what exactly happened during the incident is required.

Control

The control is implemented before the incident as outlined in the plans.

5.4.3 After the rainfall event

After the floods a clean-up of both the urban drainage systems and the terrain is required. It must be ensured that facilities have not have damaged and that the function and capacity have not been reduced by trapped items.

Updating contingency plans

Thorough documentation and experience of the flooding incident may be used to evaluate whether the contingency plans need to be updated. This includes evaluation of the prioritisation of the plans, whether the hydraulic model requires recalibration after the incident as well as finding solutions to the challenges or ensuring that service levels are met.

Operating experience

It is valuable to compare experiences with expectations and conclude if flooding is caused by operational problems or lack of capacity in the urban drainage systems.

6 Summary and conclusion

The Climate Cookbook is an update of the previous edition from 2007 and contains the status of knowledge on climate change that has been reported from the Danish state and recommended for use when calculating the risk of flooding from the sea in the cities. In regard to calculations of the effects of changes in precipitation, it is recommended to use the recommendations in the Guidelines published by the Wastewater Committee of the Danish Engineering Association.

Methods for analysis of flooding and flood risks in cities from both the rainfall as well as the sea is described in the report. The methods are differentiated from the very simple GIS method to the most advanced hydraulic model that includes several elements in the hydraulics of the drainage system.

The calculation methods are used in many contexts to assess interventions against flooding due to climate change. It includes examples from Greve and Odense.

The methods described in this report are generic and can thus be used when the existing climate scenarios is updated with new estimates of precipitation and variation in sea level.

Providing the level of desired standard of service on runoff from cities is very important when deciding whether to analyse climate change and especially when making very costly decisions about specific adaptation of drainage systems. The Climate Cookbook contains a description of service on rainwater and water conditions and a proposal for how this can be disseminated.

A challenge in management and prioritisation of climate change is estimating damages to society due to flooding. The principles behind the calculation of damages due to floods is described along with methods to reduce damages. There are still some unresolved issues, including pricing of damage, before it can be more than just an enumeration of the various types of damage.

The methods described in The Climate Cookbook can be used as the basis for the preparation of risk assessments and maps, providing decision support on many different levels and to prioritise climate adaptation efforts. It includes a description of how to implement a detailed risk analysis of floods, how to prioritise, and finally it provides examples of what type of solutions can be deployed at the specific climate adaptation.

In recent years, floods in Danish cities show that there is a very real need of having a good contingency plan of rainwater when rainfalls exceed what the systems can handle. The Climate Cookbook is a comprehensive approach to precipitation emergency described and given examples of contingency operations "before, during and after" extreme precipitation events.

Thus, The Climate Cookbook is a guide for both technicians to conduct the tests and the basic hydraulic work that planners must establish to inform decision makers on climate adaptation and work with the effort against flooding in cities.

The descriptions of the methods are supported by examples in Odense and Greve. The Climate Cookbook shows that there is no justification for postponing the analysis of the risk of flooding due to rainfall and sea level rise - on the contrary methods are available for analysis of the challenges, so it is just getting started, so that conscious choices on solutions to known challenges can be taken.

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APPENDICES

APPENDIX A

Odense – Sports Stadium

(Project implementation: 2007-2009)

A Odense – Sports Stadium

A.1 Terrain regulation at Odense Stadium

The new sports centre of approx. 1,400m^2 at Odense Stadium has been flooded three times since its completion in 2005, most recently on 30-06-2007. Photos from one of the flooding events are shown in Figure A. 1.

Figure A. 1 Map of the Odense Stadium area

In the following a 2-D model is applied for simulation of surface run-off resulting from water held back in the sewage system. Calculations are made on the flooding events on 13th and 18th August 2006 together with a 100 years' CDS rainfall, and calculations with suggested solutions based on terrain adjustment are made.

If the rainfall event on 13th August is compared to the historical rainfall series (standard national rain series) it is found that the rainfall event is T = 5-7 years for high intensities, up to a variation of approx. 15 minutes. In this connection it should be mentioned that precipitation in August 2006 was record-breaking. From 1st August to 13th August precipitation was 78.2 mm, of which 42 mm fell on 11th August. On 13th August the drainage system in the Sports Stadium has obviously still been draining off water from the event on 11th August. The water level in the Bolbro trench has probably also been higher than normal, also due to a high groundwater level.

On 17th August 17.8 mm rain fell in 28 minutes. Highest intensity was 30 µm/s. The rain was a 4-year rainfall event for 5-minute intensities, but a 2-year rainfall event for 10-minute intensities, i.e. a less intense rainfall than the one on 13th August, however, it did result in damages in the form of flooding.

Drawing material of the drainage of the Sports Stadium has been received from Odense Vandcenter and it shows the following, see Figure A. 2:

Drainage to the rain water system:

- The whole area around the sports hall drains surface water to the rain water pipe. The new athletic facility probably also drains to the ø1000 rain water pipe.
- Ice stadium and skating hall discharge surface water to the ø1000 rain water pipe.
- The cabin house in the biking stadium also discharges to the ø1000 rain water pipe via a ø300 pipe under Møllemarksvej
- According to municipal information four drainage pipes are connected to the rain water pipe in the Sports Stadium. There are probably also a number of connections upstream. Presumed drainage volume to the rain water pipe is 20-30 ha.

Drainage to combined sewers:

- A ø400 concrete combined sewer passes through the eastern part of the soccer stadium. However, it is placed too high for drainage from the athletic and soccer fields
- The bowling hall drains off surface water to the combined sewer in Møllemarksvej.
- The tunnel under the biking stadium can be emptied by means of a pump discharging to the combined sewer in Møllemarksvej.

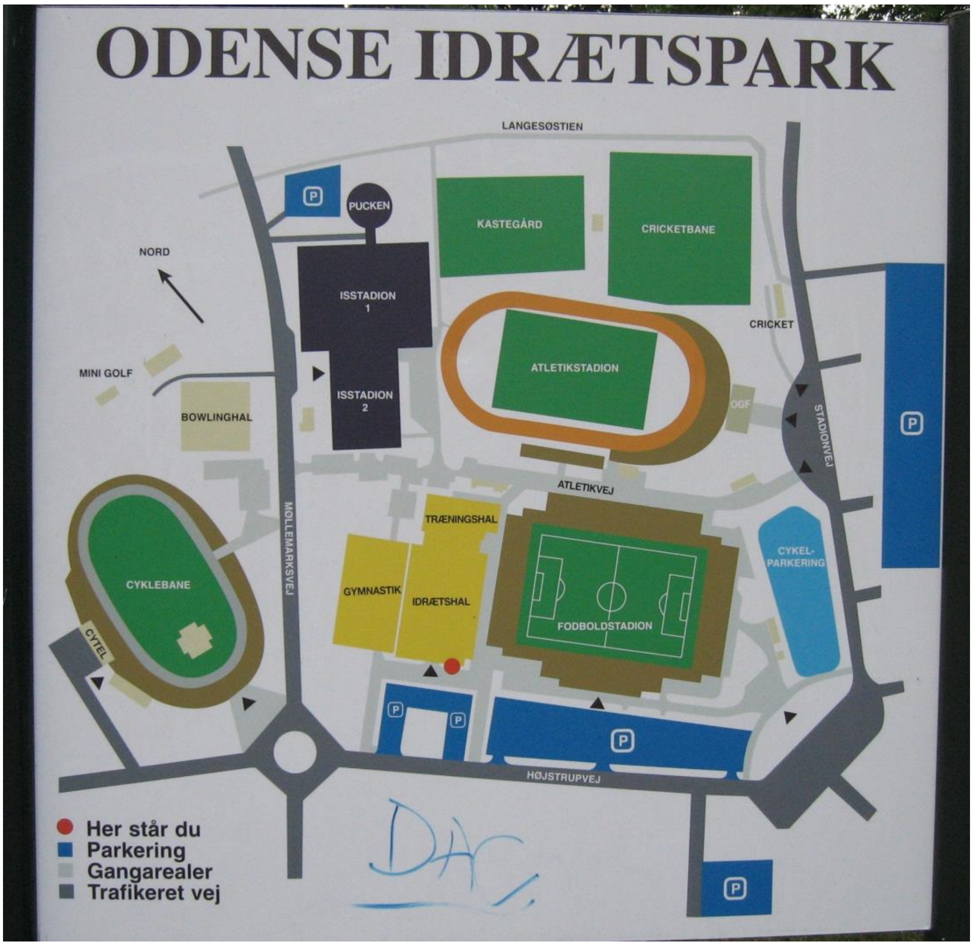

Figure A. 2 *Map of the Sports Stadium*

Figure A. 3 shows the sewer system around the Sports Stadium. The blue line is a ø1000 rainwater pipeline discharging to the Bolbro trench. The pipe starts in Ole Worms Gade and receives overflow water from the combined system in the wells marked with a red circle (wells J50O025 and J51F16X).

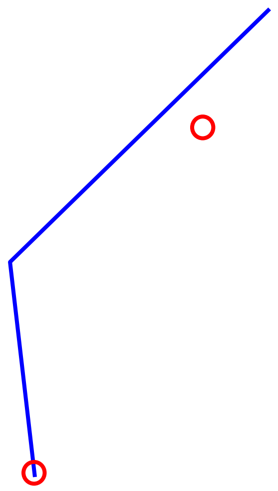

Figure A. 3 Sewer system in the Sports Stadium

Figure A. 4 shows a MIKE 1D model and surface (elevation conditions) for the area around the Sports Stadium.

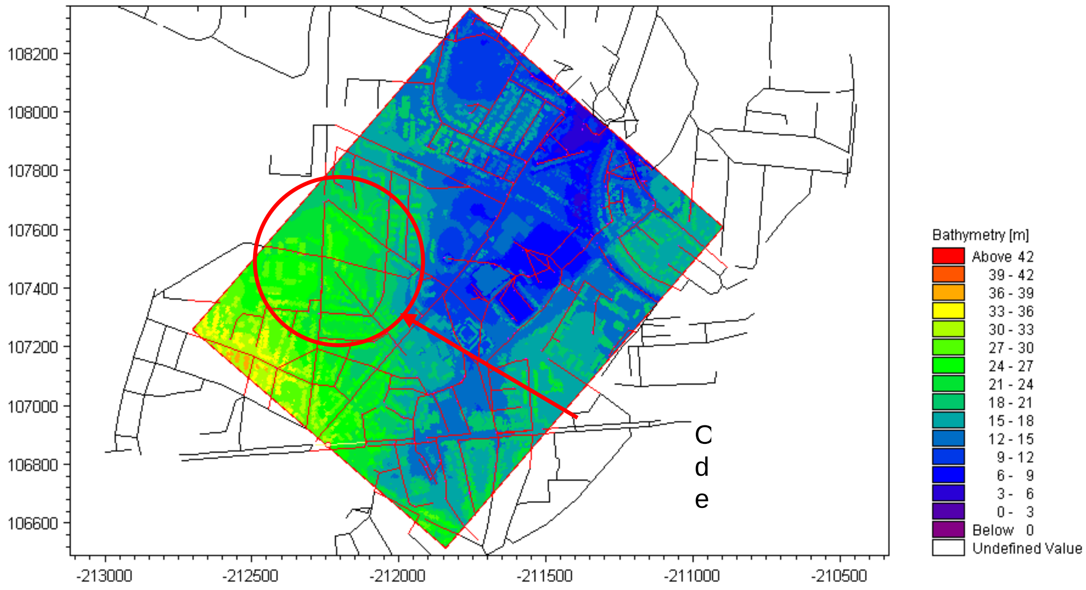

Figure A. 4 MIKE 1D model and surface at Odense Sports Stadium

A.2 Design assumptions

The calculation tool MIKE+ is used as a link module between the programs MIKE 1D (sewer system), MIKE 21 (surface 2D) and MIKE HYDRO River (streams etc.). The last-mentioned can be left out and is not applied in the following. Configuration of these programs is made individually. A time interval of 2 seconds is applied, resulting in a running velocity of the models, cf. surface extract Figure A. 4, of approx. 5-6 hours per real hour (2.6 GHz Pentium).

Inlet hydrographs and the sewer system is calculated in MIKE 1D. The model applied has been supplemented with drain pipes and other pipes in the area around the Sports Stadium, among others drainage systems have been established under the football stadium (Fionia Park) and the athletic field. This information stem from sewage plans received.

For calculation of existing conditions precipitation data from SVK rain gauge 28181, Bolbro Waterworks, have been applied due to its geographical location relative to the Sports Stadium.

The terrain model is supplied in DVR90, and therefore all levels in the MIKE 1D model has been converted from DNN to DVR90, cf. Section A.4.

Data basis for calculating surface flows is a so-called digital terrain model (DTM). Contrary to DTH (digital height model) DTM does not include roads, houses, etc. The DTM applied is based on a 5 m grid where the height uncertainty is 35 cm. The reference system is System34/DVR90. Appendix A is an extract from the DTM model in the Sports Stadium area. The figure shows the density of ground levels which form the basis for the MIKE 21 calculations.

The interpolation between height levels results in the terrain being levelled out, e.g. on the soccer and athletic fields. Therefore, the terrain levels have been manually adjusted to match the actual conditions.

The MIKE 21 model is set up in a j,k-system with a chosen grid size of 4 metres rotated 50.65^0 relative to the MIKE 1D model, in order that among others relevant roads (Møllemarksvej and Højstrupvej) are placed approximately parallel between the axis of the j,k-system. This is the most appropriate method since the flux between the grid points can only take place parallel to the j or the k axis. The surface covers an area of 1.448 m x 1.140 metres corresponding to 362 j-points and 285 k-points. The grid size of 4 metres is chosen partly due to the solution of the digital terrain model, partly in consideration of the calculation velocity.

Roads, houses and other sealed areas appear as shape files (ArcGIS). The shape files are converted and exported to the terrain model in MIKE 21. Roads and sealed areas are digitised separately in ArcMap prior to export, since the items do not appear as closed polygons (areas). Roads and other sealed areas are imported into the terrain model deducting 20 cm, and houses are raised by 3 metres compared to the terrain model.

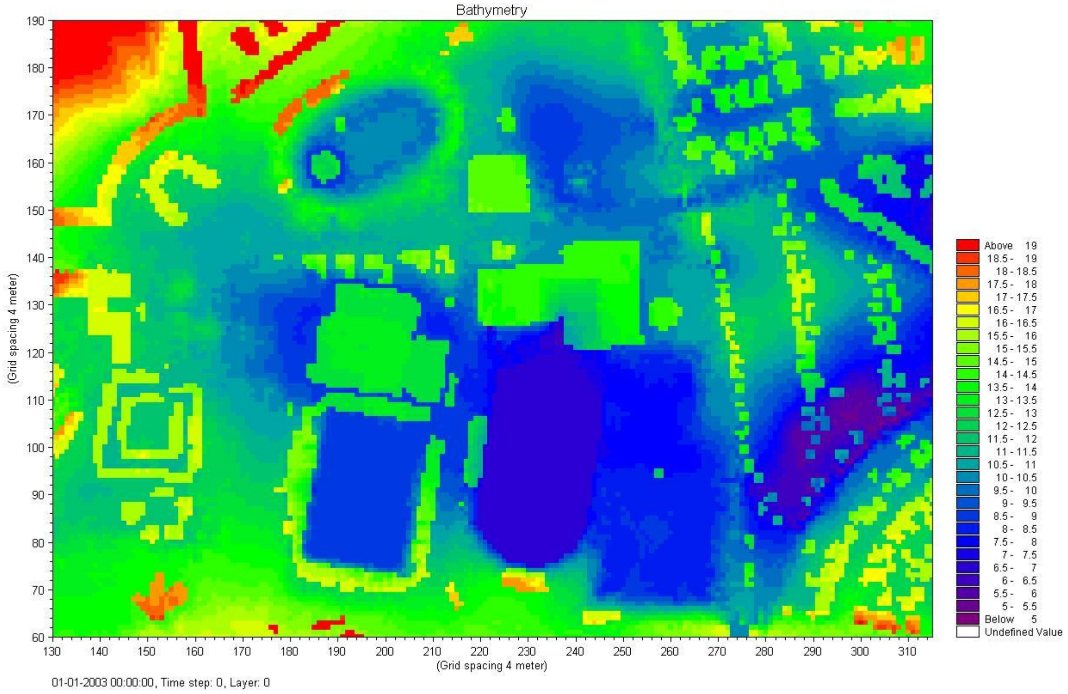

Figure A. 5 Surface of the area surrounding Odense Sports Stadium. The map is turned as the extract in Figure A. 4

A.3 Status calculations

Initial calculations are made for the events on 13th and 17th August 2006 respectively in order to verify the model compared to the observations and to show how the two events resulted in damages in the Sports Stadium due to surface run-off. Furthermore, a calculation of a scenario with 100 years' rain (CDS) has been made.

On 13th August 40.6 mm precipitation within 4 hours and 50 minutes was registered by rain gauge 28181 at Bolbro waterworks. 30-40 cm water was observed in the new gymnasium, 10 cm water in the club rooms of the ice skating stadium, and 30-40 cm water in the locker and storage room of the athletic field.

Figure A. 6 shows a snapshot at 16:16 (GMT), where the water depth in front of the entrance to the gymnasium is calculated to 35-40 cm (yellow colour). This is the max. water depth in front of the gymnasium, and it corresponds more or less to the observation mentioned above. The rainfall started at 11.11 (GMT), i.e. the max. water level is found approx. 5 hours later.

It should be noted that the new sports hall (gymnasium) established in 2005 is not included in the aerial photo, however, it has been added to the surface.

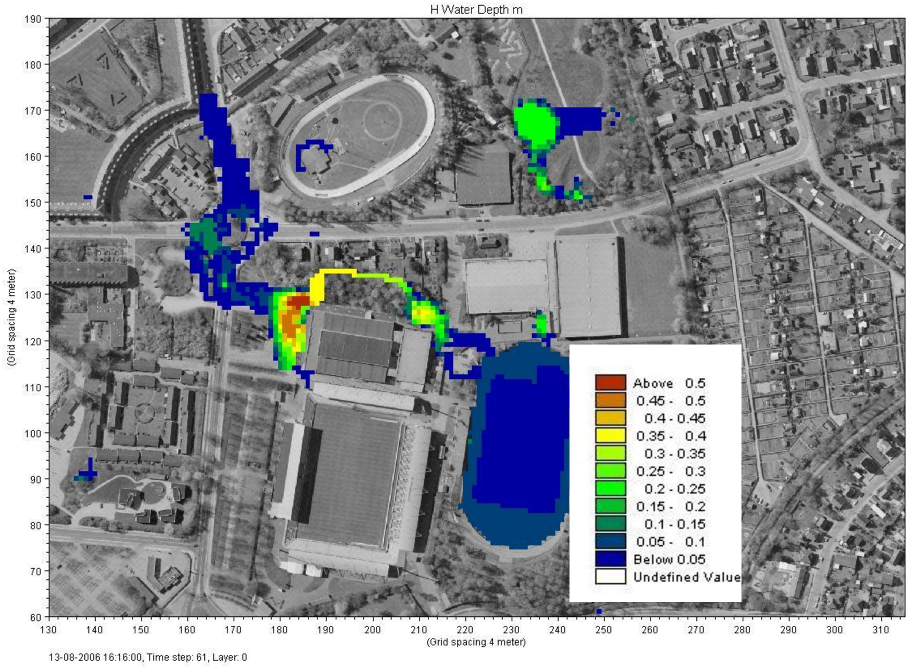

Figure A. 6 13/8 2006. Status calculation with data from rain gauge 28181 Bolbro waterworks. Water depths at 16:16 GMT are shown

On 17th August 17.8 mm precipitation within 28 minutes was registered by rain gauge 28181 at Bolbro waterworks. The rainfall started at 12:23 (GMT). The result was basically the same as on 13th August, however, the max. water depths were a little bit smaller. Figure A. 7 shows the situation at 13:03.

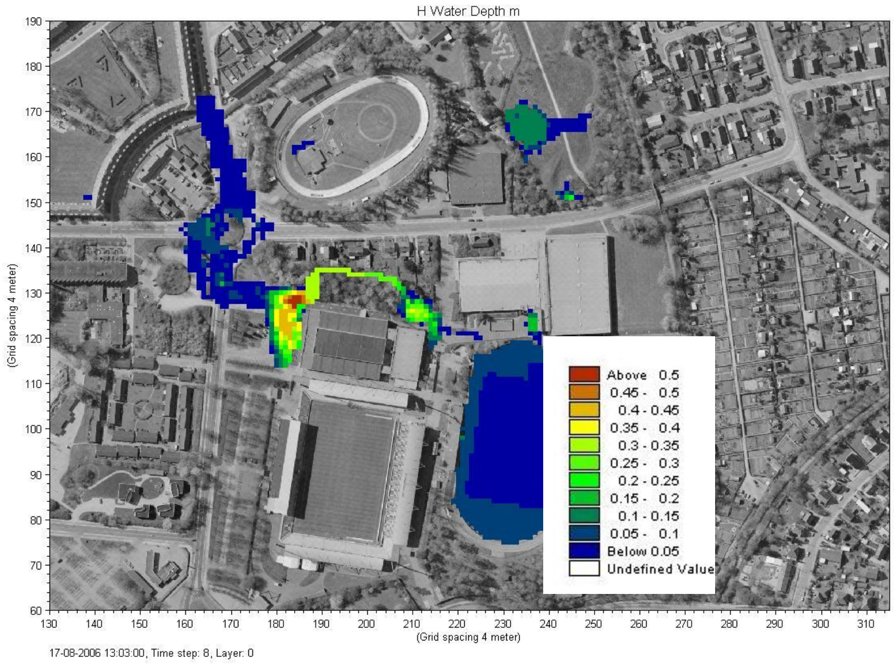

Figure A. 7 17/8 2006. Status calculation with data from rain gauge 28181 Bolbro waterworks. Water depths on 17th August at 13:03 GMT are shown

A calculation with a 100 years' CDS (**C**hicago **D**esign **S**torm) rainfall with a duration of 2 hours has been made. This results in a max. intensity of 61.4 μm/sec (3.7 mm/min) and a rainfall depth of 48.9 mm, cf. Figure A. 8.

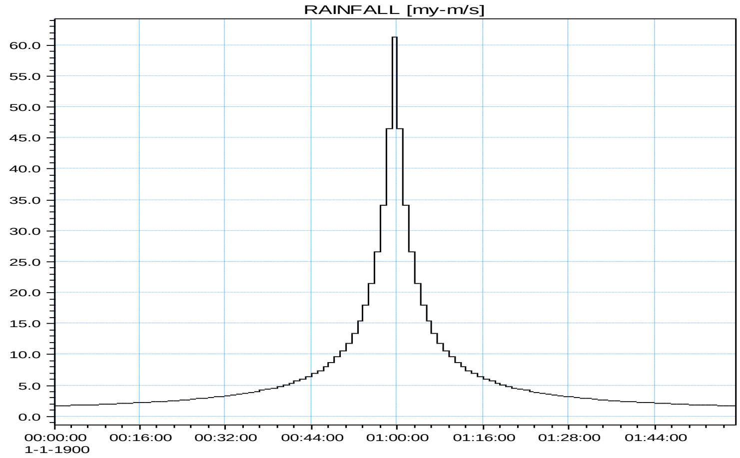

Figure A. 8 100-years' CDS rain with a storm duration of 2 hours

The rainfall results in water depths in the area in front of the sports stadium of up to 70 cm and water depths at the athletic field of approx. 50 cm.

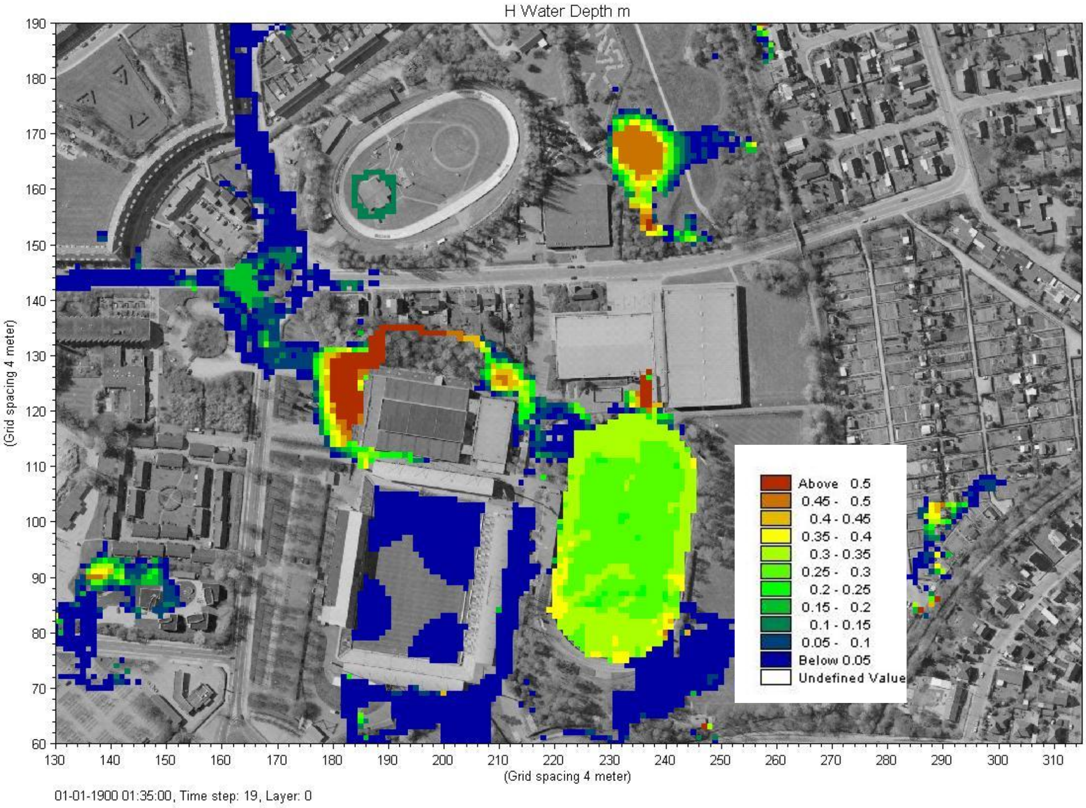

Figure A. 9 100 years' CDS rainfall. Water depths 1 hour and 35 minutes after the rainfall started are shown

A.4 Suggested solution

The height difference between the floor level and the athletic field grass is approx. 2 metres. This could be used to establish a trench or a canal with an average gradient of 6.4 per mille and with outlet in a yet to be determined place in the area surrounding the athletic field which is the lowest point in the area (level 6.85 DVR90). The distance from the front side of the sports stadium to the athletic field grass is approx. 300 metres. In this way the athletic field is used as storage capacity. After this the area is trained to the Bolbro trench. Dikes must be established in some places to keep water away from the buildings, among others the ramps at the ice skating stadium, the facilities at the athletic field and other facilities where water may enter.

The property office of Odense municipality has prepared a sketch of above-mentioned proposal for terrain regulation at Odense Sports Stadium, cf. Figure A. 10. The plan with terrain regulation is to direct water to the lowest point in the area, i.e. the athletic stadium. Flooding of the athletic stadium is not critical compared to the wooden floor in the sports hall being destroyed by water.

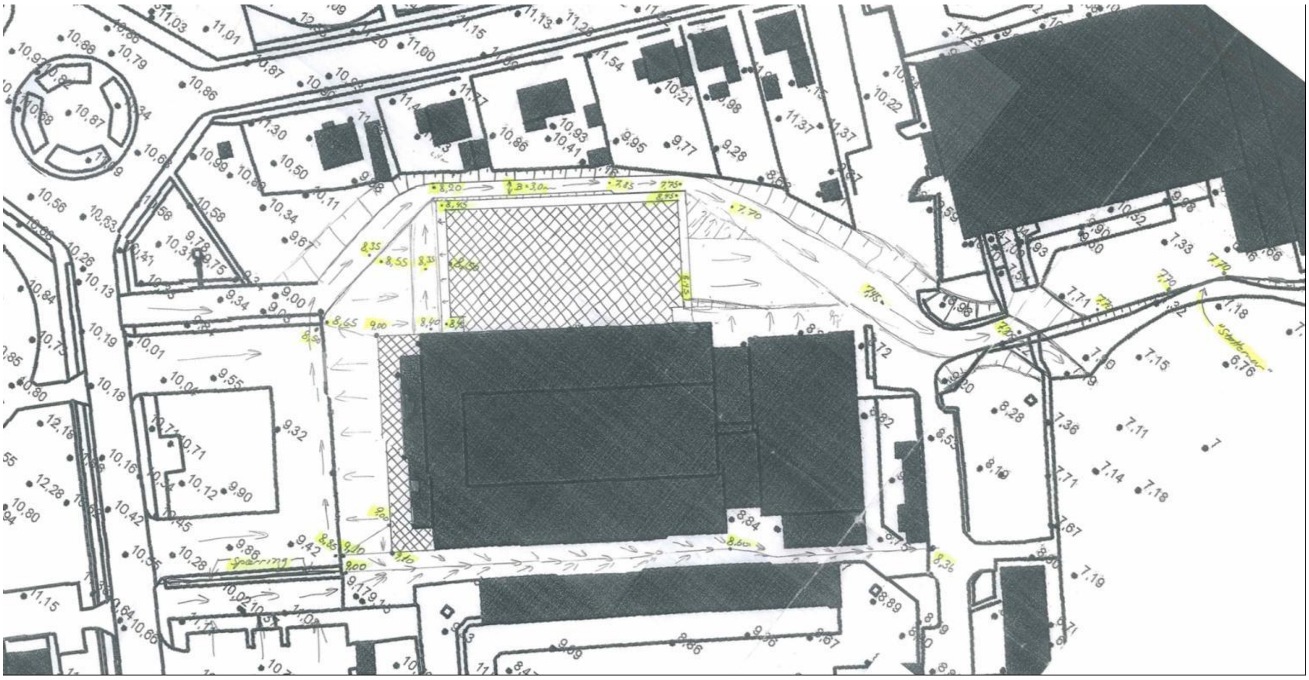

Figure A. 10 Odense municipality’s proposal for terrain regulation

The proposal of the municipality increases the recurrence interval for flooding of the sports hall floor from approx. 1-2 years to less frequent than every 5 years. The proposal can be optimised by choosing a surface with less resistance (concrete slapping), a more steep gradient at the start before the profile narrows at the corner around the sports hall, and a wider profile along the wall of the sports hall towards north-west. The final canal is shown in Figure A. 11. The canal has been in use twice and has prevented flooding of the sports hall.

Figure A. 11 Photos from the area after terrain regulation

APPENDIX B

Climate Analysis for Greve Midt and Karlslunde

B Climate Analysis for Greve Midt and Karlslunde

B.1 Introduction

On 1st August 2002 Greve centre received a rainfall event of 100 mm in three hours. The incident caused damaging flooding at the city hall and high school. The rainfall event is estimated to be an event that statistically occurs less than every 500 years.

On 3rd August 2002 the same area received another rainfall of 30 mm, which became detrimental because all storage capacities and volumes within the municipality were filled from the previous rainfall.

Since this incident Greve Municipality has focused on optimizing the operation of the storm water systems and ensuring that the desired standard of services is met and staying on top of problems before they occur despite the fact that it is beyond what is required through the desired standard of services.

Greve Municipality has chosen to use many resources to improve the operation of the storm water system when it became clear that it is not a question of whether there will be extreme rainfall events, but rather when they will occur. It is indifferent to Greve Municipality whether the more frequent extreme rainfall events are due to climate change or not.

In August 2002, the centre of Greve was hit hard as the centre of the rainfall event was just above Greve centre where the city hall and gymnasium are located.

At that time it was not clearly stated who was responsible for doing what, i.e. who would be responsible for pumping when and where. In the hindsight it would have been helpful to have identified who should do what in such an extreme rainfall event. The centre of Greve is therefore used in this case, as it illustrates how the overloading of drainage systems can be analysed.

The drainage system in the centre of Greve has a separate sewer system. All storm water drains to a main storm water channel called Streget, which drains into the Bay of Køge via a gravity outlet with invert level in Streget in elevation 0m DNN. Additionally to this there is a combined sewer outlet and a pump which in 2005 was upgraded to provide 1 m3/s and is controlled by the water level in the Streget. In this case the focus is solely on the separate storm water system.

The Greve Utility works currently on upgrading the storm water system in the centre of Greve, so it fully meets the new desired standards of services for newly built drainage systems. This case describes the solutions being applied to achieve functional requirement and focuses on describing the damage that can be expected if no action is taken on the system and what actions can alleviate some of the problems occurring during extreme rainfall events.

During the period 2003 to 2007 Greve Municipality worked on getting a good understanding of the physical conditions in the drainage systems through the use of continuous measuring systems, where water level, velocity and rainfall data were measured simultaneously in different catchments. The measurements were used for calibration of hydraulic models, analysis of the operational situation and to some extent to alert risks of flooding. In this case, possible warning systems for Greve will be described.

The model used in this case is covering the storm water system upstream the high school and has been calibrated using the water level, velocity and rainfall gauges. In the case study urban climate cook book concept is applied.

B.2 Catchment description

The city area around the centre of Greve has a separate sewer system with a total area of 520 ha divided into 11 catchments. The total impervious area of 260 ha drains to the main storm water channel, Streget. Streget drains by gravity through an outfall pipe and by pumping at the outlet to Køge Bay. The area is very densely populated. In the area there are eight basins, 50 km storm water pipes and approx. 1,250 rainwater manholes.

B.3 Future rainfall - Greve

According to DMI's climate forecasts we can expect during this century both a modified annual distribution of precipitation and changes in rainfall intensities of the individual rainfall events. A significant increase in extreme rainfall and rainfall intensities especially during summer is expected. The DMI (pt. "worst") climate scenario A2 (period: 2071 to 2100) predicts the annual precipitation to be slightly increased, and the extreme rainfall events during summer to be more frequent and more powerful. Summer rainfall is expected in total to be slightly smaller.

At DTU's Department of Environment & Resources they have in some projects calculated the increase which climate models predict for extreme rain events (repetition periods of 5 and 10 years). For climate scenario A2 it is found that for these repetition periods increases in rainfall depth of approx. 20-50% can be expected. However, the modelling does not show that a different intensity distribution of precipitation is foreseen. It is therefore believed that the increase in precipitation is best recognized by a factor (climate factor) of rain as the ones used today. Due to the uncertainty about climate change it has been decided in Greve to use a climate factor of 1.2. In addition, the MIKE 1D model for Greve is partially calibrated, and this is why a model uncertainty of 20% is chose, i.e. the total factor on future CDS rain is 1.44. A current and a climate projected 10-year CDS rain (including model uncertainty) for Greve seen in Figure B. 1.

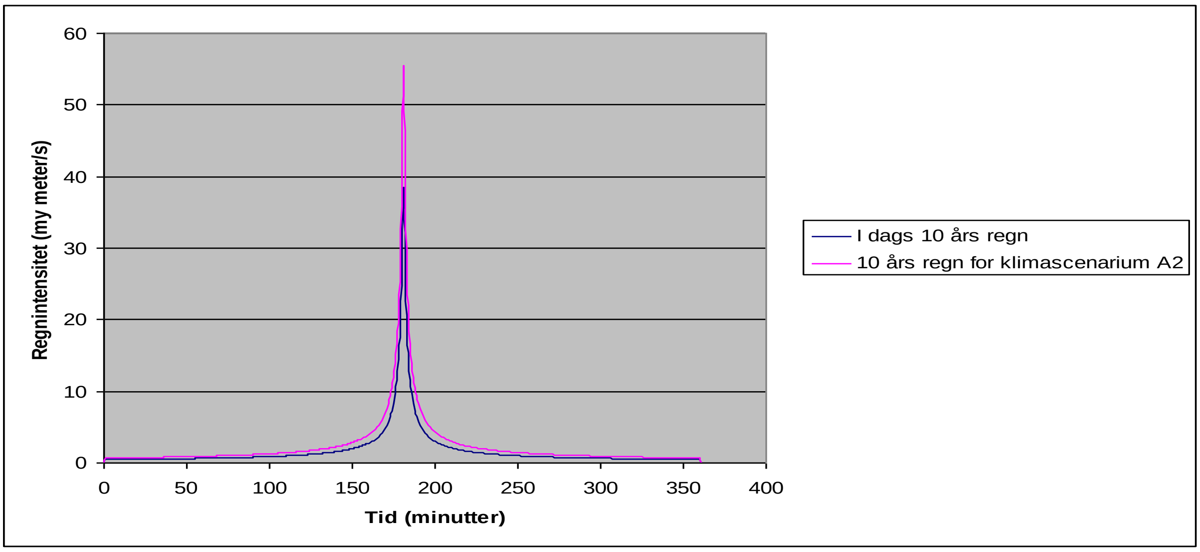

Figure B. 1 Present design and climate projected 10-year CDS rainfall for Greve. Time step = 1 minute. Climate factor = 1.2. The climate projected rainfall is based on scenario A2

B.4 Development in meeting functional requirements in Greve

Greve municipality is interested in analysing the development of how the sewage system meets the present functional requirements under the influence of climate changes. In order to prioritise initiatives made on the sewage system, the time-related development in climate changes is simulated by linear extrapolation of a 10-year CDS rain and the water level in Køge Bay for climate scenario A2. This results in the following simulations:

Time horizon	**Expected sea level rise**	**Rainfall**
Today	0 cm	10-year CDS rainfall
In 10 years	3 cm	10-year CDS rainfall x 1.22
In 25 years	7.5 cm	10-year CDS rainfall x 1.26
In 100 years	50 cm	10-year CDS rainfall x 1.44

This means that problem identification is made first by running ordinary MIKE 1D pipe calculations and identifying flooded places. Since the terrain is not described in the most common MIKE 1D models, the indicated flooding depth is only indicative. The result of the four simulations is shown in Figure B. 2 to Figure B. 5.

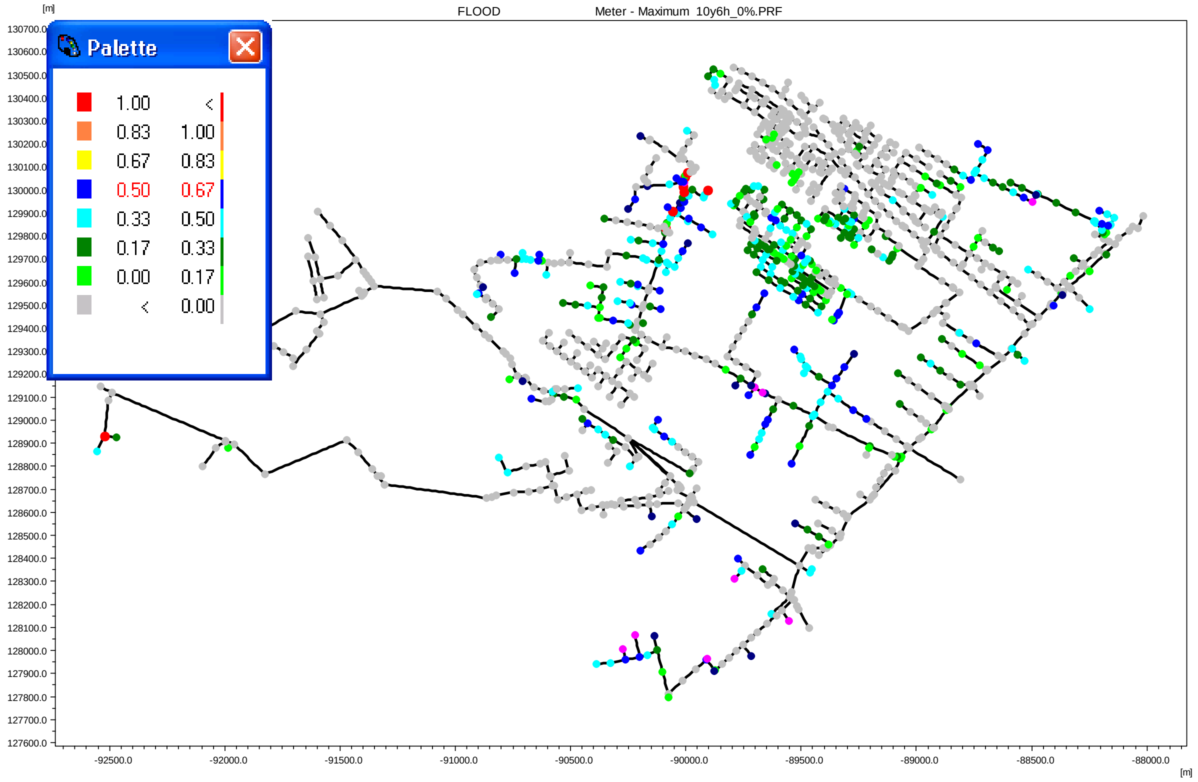

Figure B. 2 Indication of flooding depths i.e. places where the drainage system will run into problems today for a 10-year rain. Input 10-year CDS rainfall

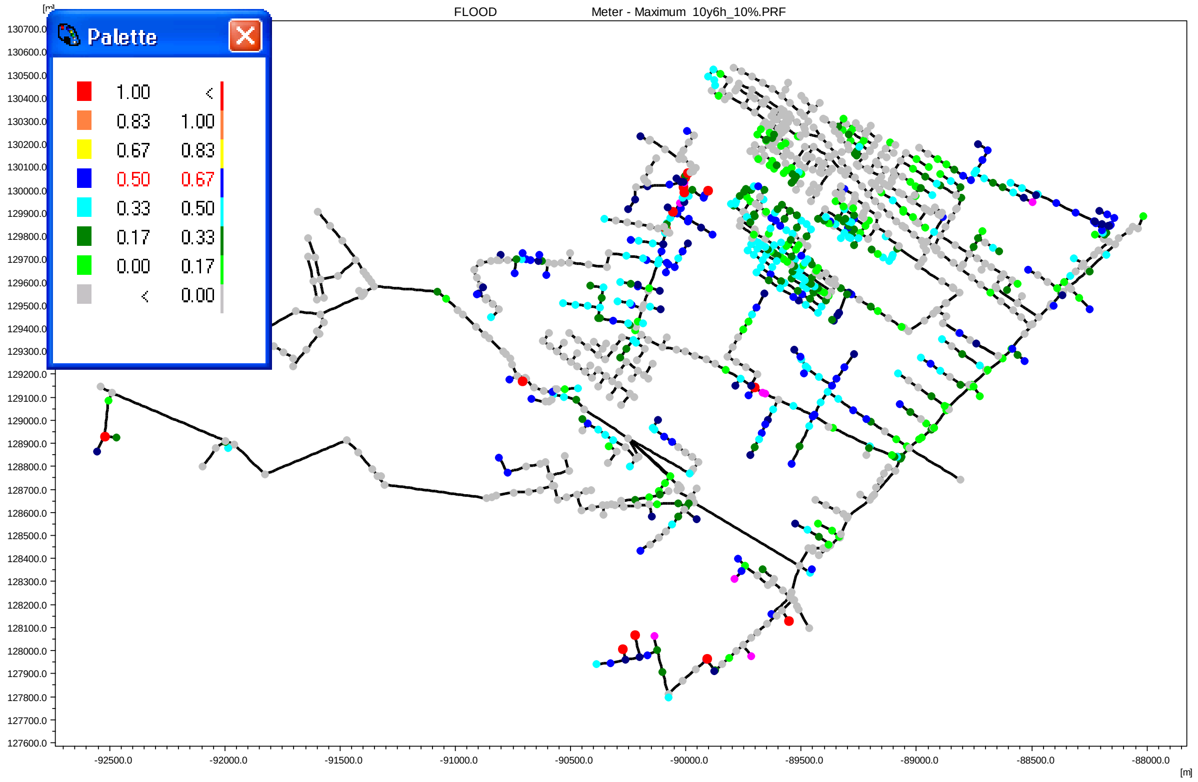

Figure B. 3 Indication of flooding depths, i.e. places where the sewage system in 10 years will have problems for an extrapolated 10-year rainfall. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

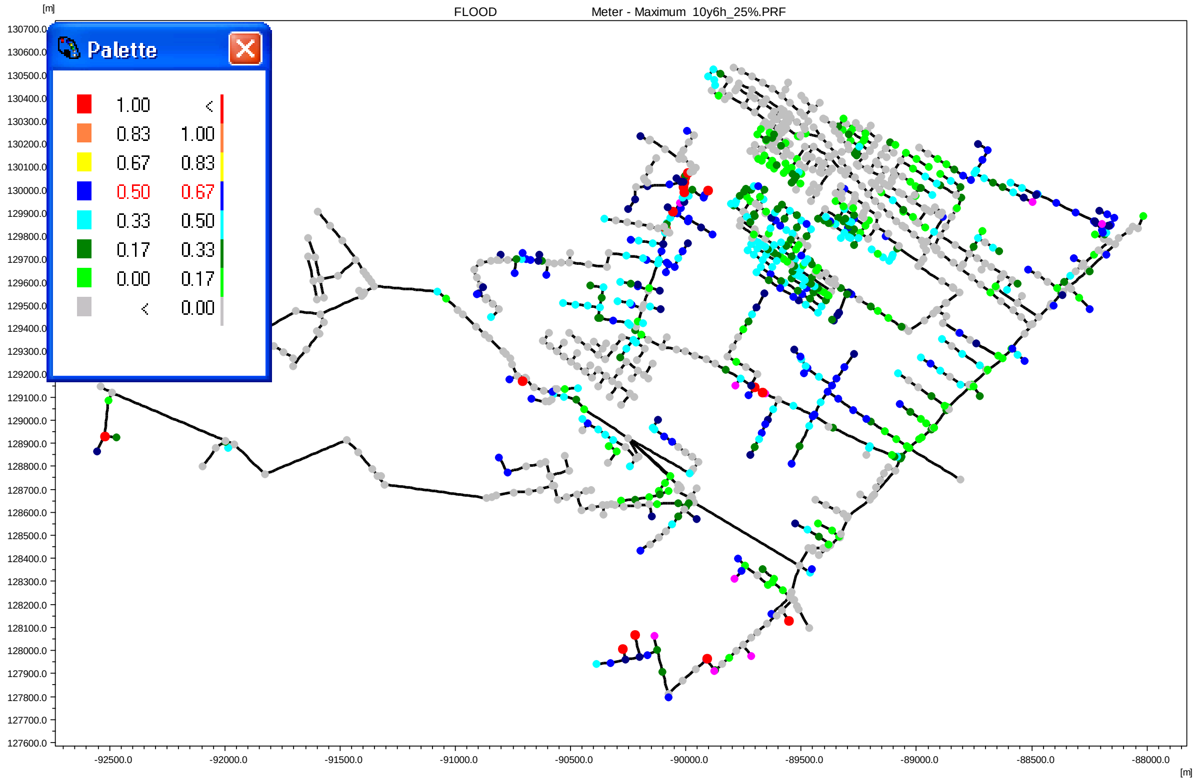

Figure B. 4 Indication of flooding depths, i.e. places where the sewage system in 25 years will have problems for an extrapolated 10-year rainfall. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

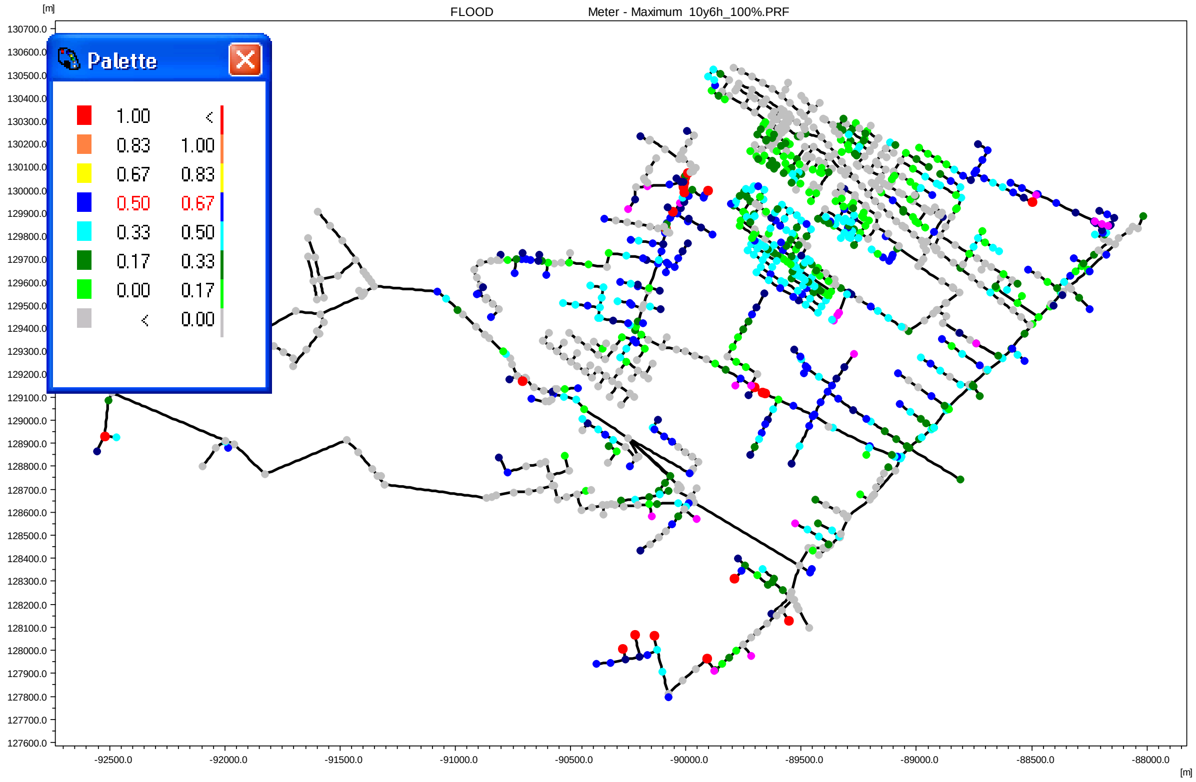

Figure B. 5 Indication of flooding depths, i.e. places where the sewage system in 10 years will have problems for an extrapolated 10-year rainfall. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

After having made a problem identification, the extent of the flooding must be quantified and damages assessed. For quantification of flooding a digital terrain model is set up to be used as surface model for MIKE 1D/MIKE+. To illustrate the method it has been chosen to focus on the area at Greve High School and Greve Town Hall, i.e. the two areas which were struck by flooding in 2002. As it appears from Figure B. 2 a great deal of flooding is expected in this area for a 10-year CDS rainfall today. The combined MIKE 1D and hydrodynamic surface model (MIKE+) are used to calculate the flooding in detail. Figure B. 6 shows that flooding (of up to 33 cm at the high school) can be expected in 10 years, if climate changes follow climate scenario A2. Please note the uncertainty factor of 20%. Figure B. 7 shows the calculated flooding depths for climate scenario A2 in 100 years. It is seen that climate changes are now expected to cause flooding of up to 83 cm at the high school. A comparison of the calculated distribution of flooding for a 10-year rainfall at Greve High School in 10 years and 100 years respectively is shown in Figure B. 8 and Figure B. 9. It is seen that the development in a 10-year rainfall and in sea water levels gives rise to more extensive flooding, which is expected to further increase over time.

In the present situation (today's 10-year rainfall) no safety factor is applied in the area, since the model is calibrated for the present situation. For the future situation with climate changes and e.g. extension, a safety factor of 1.2 is applied.

Thus, the above calculation reflects the function of the sewage system in two fields:

1. Development in fulfilment of the functional requirement, and

2. Conditions under extreme events where the design precipitation and water level in Køge Bay has been exceeded. It will be 2) which will form the basis of a decision-making as to how to react in case of very extreme events where the sewage system

cannot and is not expected to be able to handle the rain water. A solution could be warning systems utilizing the existing systems more efficiently in order to minimize damages and lead the water to places where it is less damaging, e.g. green areas.

Figure B. 6 Max. flooding depths calculated for a 10-year CDS rainfall extrapolated by 10 years. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

Today, Greve municipality has quite a lot of digitalised information on the infrastructure. This information is among others found in the GIS system of the municipality, making it possible to easily estimate the extent of damages under the designed conditions. Important information on infrastructure in relation to flooding could be: Supply boxes (boxes placed at all cadastres); fiber point (junction box with optical fibres); stations connecting supply boxes; buildings with basements; public buildings and environmentally heavy industrial companies. Examples of comparisons of the municipal GIS data with designed flooding are shown in Figure B. 8. Among other things it is seen that the flooding in the area around the town hall is expected to develop from a scenario with quite a lot of water in the streets to a scenario with flooding of a child care centre. At the same time it is seen that the service station will be flooded already in 10 years, and therefore the consequences of a flooding like this should be taken into account.

Figure B. 7 Max. Flooding depths calculated for a 10-year CDS rainfall, extrapolated by 100 years. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

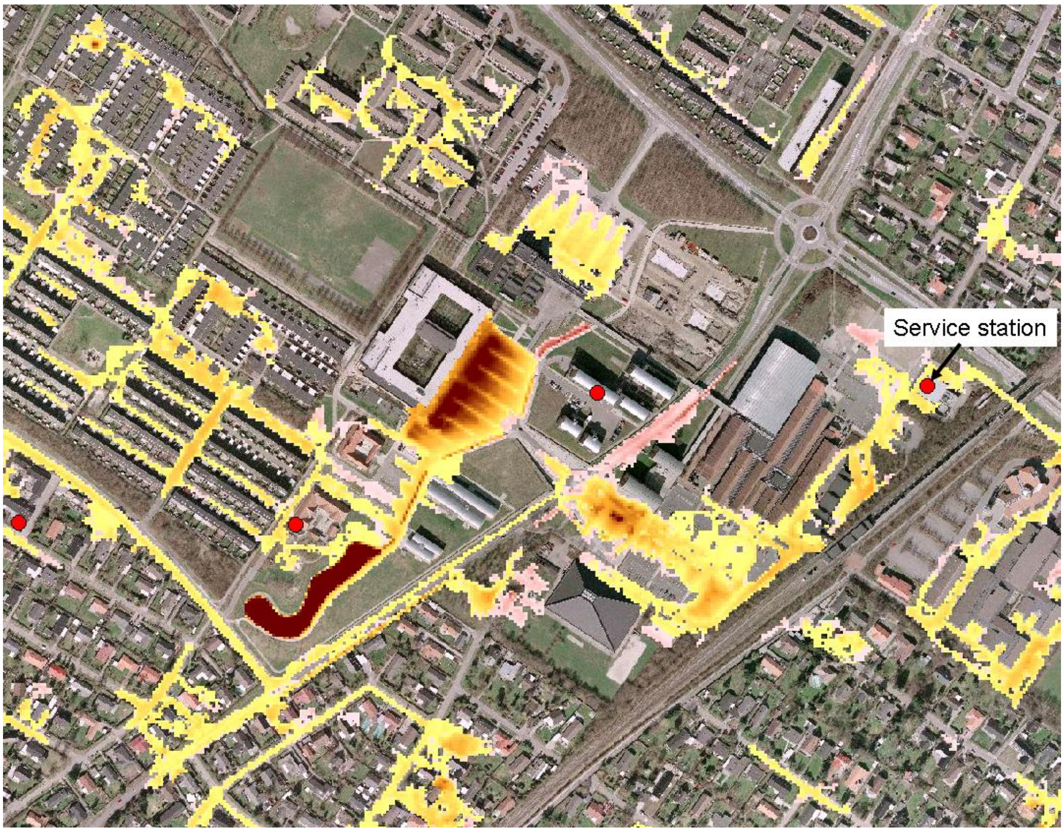

Figure B. 8 Yellow/brown colour indicates flooding calculated for a 10-year CDS rainfall, extrapolated by 10 years. Rosy/pink colours show flooding calculated for a 10-year CDS rainfall, extrapolated by 100 years. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

B.5 Alternative solutions to reduce damages from flooding in Greve

Immediately behind the town hall and the high school there is a football field belonging to the high school. During the flooding in 2002 this area was not flooded, because it is at a higher level than the high school and town hall. Figure B. 9 shows the football field.

Figure B. 9 Football field behind Greve High School which could be used for storage of rain water during extreme rainfall

Since a mound has already been established around the football field, it was investigated whether it is possible to close the mound completely and then use the football field as rain water basin during extreme rainfall. If so, water from the sewage system will be pumped to the football field. Two pumps were added to the sewage system model, each with a capacity of 0.5 m^3/s. Furthermore, in the terrain model 1.2 metres have been digged from the whole surface of the football field in order to obtain extra basin volume during extreme rainfall.

The result of the calculation shows that the extent and depths of the flooding is heavily reduced. Figure B. 10 shows that the max. water depth in the terrain outside the high school has been reduced from approx. 83 cm to 17 cm. Furthermore, the extension of flooding in the area has been heavily reduced, cf. Figure B. 9. In this figure it is also seen that the utilisation of the football field for storage of water has the additional effect that the tank station and child care centre are no longer flooded in the climate scenario. It should be noted, however, that the quality of the football field after a possible excavation of 1.2 metres of soil has not been tested in the project. In order to secure the high school in a situation as mentioned above, the curb in front of the school entrance must be increased by approx. 20 cm.

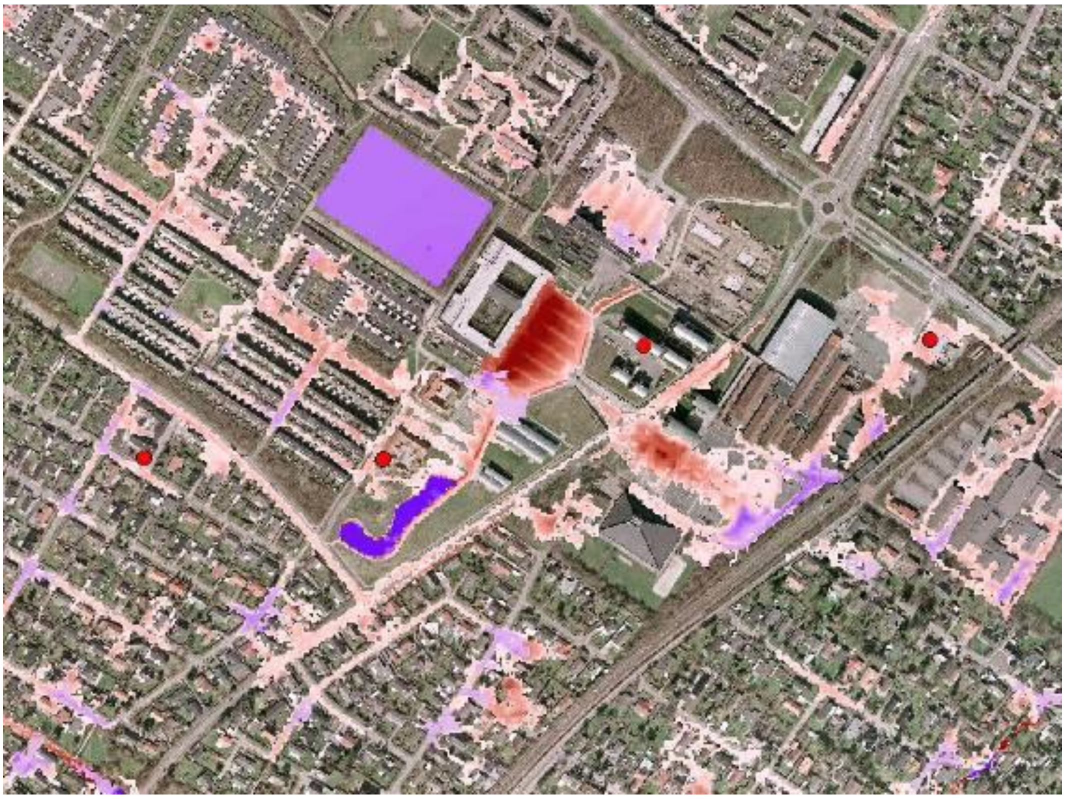

Figure B. 10 Blue/purple colour indicates flooding after installation of two 0.5 m^3/s pumps and utilisation of the football field as rain water basin. The red colour shows the extent of flooding before installation of the two pumps. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

Figure B. 11 Max. water levels after installation of two 0.5 m^3/s pumps and utilisation of the football field as rain water basin. Reference calculation is shown in Figure B. 6. Input: 10-year CDS rainfall and water level in Køge Bay extrapolated for climate scenario A2

B.6 Effects of climate changes on the water level in Køge Bay

The expected climate changes will result in increased water level in Køge Bay. As described in section 7.2 the expected time-related development in the mean water level will be as follows:

Time horizon	**Expected sea level rise**
Today	0 cm
In 50 years	15 cm
In 100 years	50 cm

A relatively quick analysis of the ”direct effect” of increased sea water level on a coastal municipality like e.g. Greve can be made with advantage. “Direct effect” means the possibility of backwater from the sea to urban areas in the event of extreme high waters.

In Greve municipality a GIS analysis has been performed, where the terrain level at all cadastres in the city have been compared to the existing extreme water level and the future level (estimated to be 0.5 metres higher, which is probably a little lower than what can be expected, since changed wind patterns will lead to increased storm surges). Figure B. 12 shows the recurrence intervals for the water level at Drogden Lighthouse, which has turned out to be representative for Mosede Habour in Greve. It is seen that a 10-year event corresponds to a water level of approx. 1.3 metres.

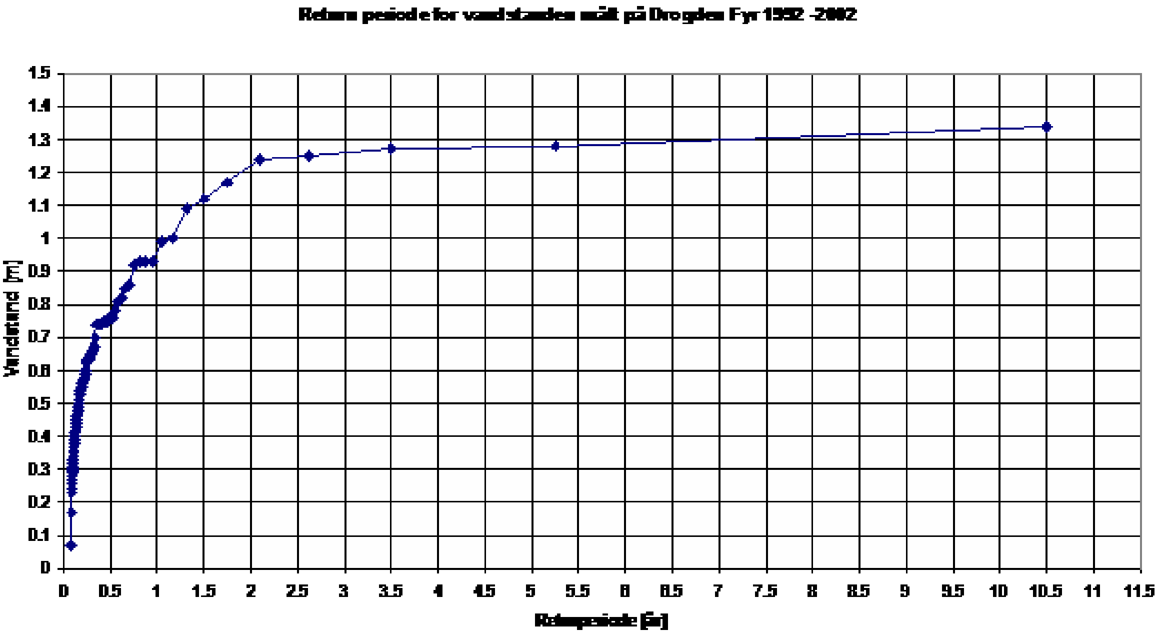

Figure B. 12 Recurrence interval for max. water level at Drogden lighthouse, data from 1992-2002

In the existing situation the GIS analysis shows that 165 cadastres are situated below this water level and thus potentially threatened in the event of extreme high waters. If the level is increased to 1.8 metres (1.3 + 0.5 metres) the number of potentially threatened cadastres is increased to 1,179, cf. Figure B. 9. This analysis can be extended to include also cadastres including houses with basements, levels to ground floor, etc.

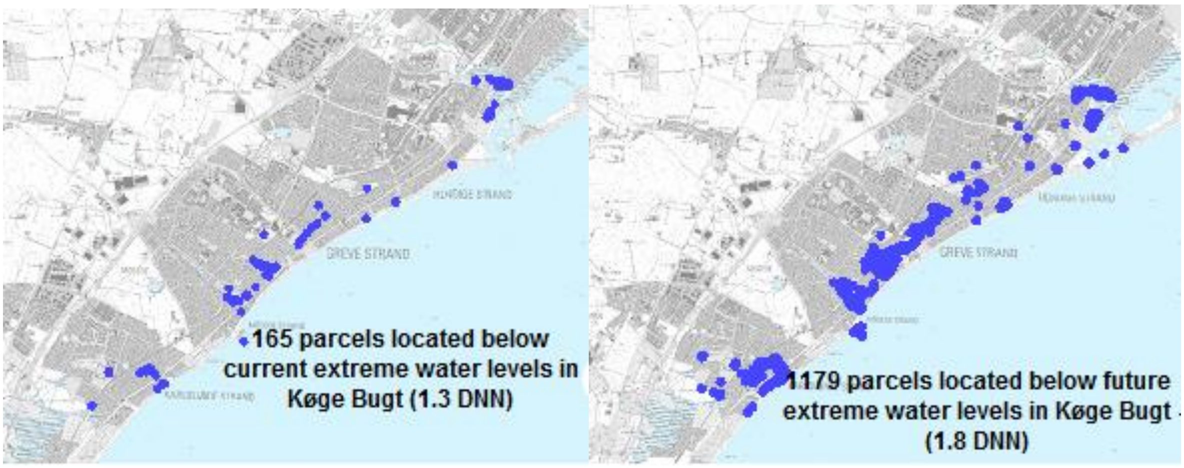

Figure B. 13 Number of cadastres lying below sea level today and under future climate changes due to increase in extreme water level in Køge Bay

Whether in the future there will be a convergence between extreme water level and extreme rainfall cannot be predicted at present. However, in order to clarify conditions in the sewage system it is a very relevant analysis which should be performed. Under the existing conditions there is no convergence between extreme rainfall and extreme water level in Køge Bay.

B.7 Summary

This example shows how you can extrapolate climate rainfall and analyse the sewage system as to where problems may arise, and how you can quantify the extent of the flooding and potential damages.