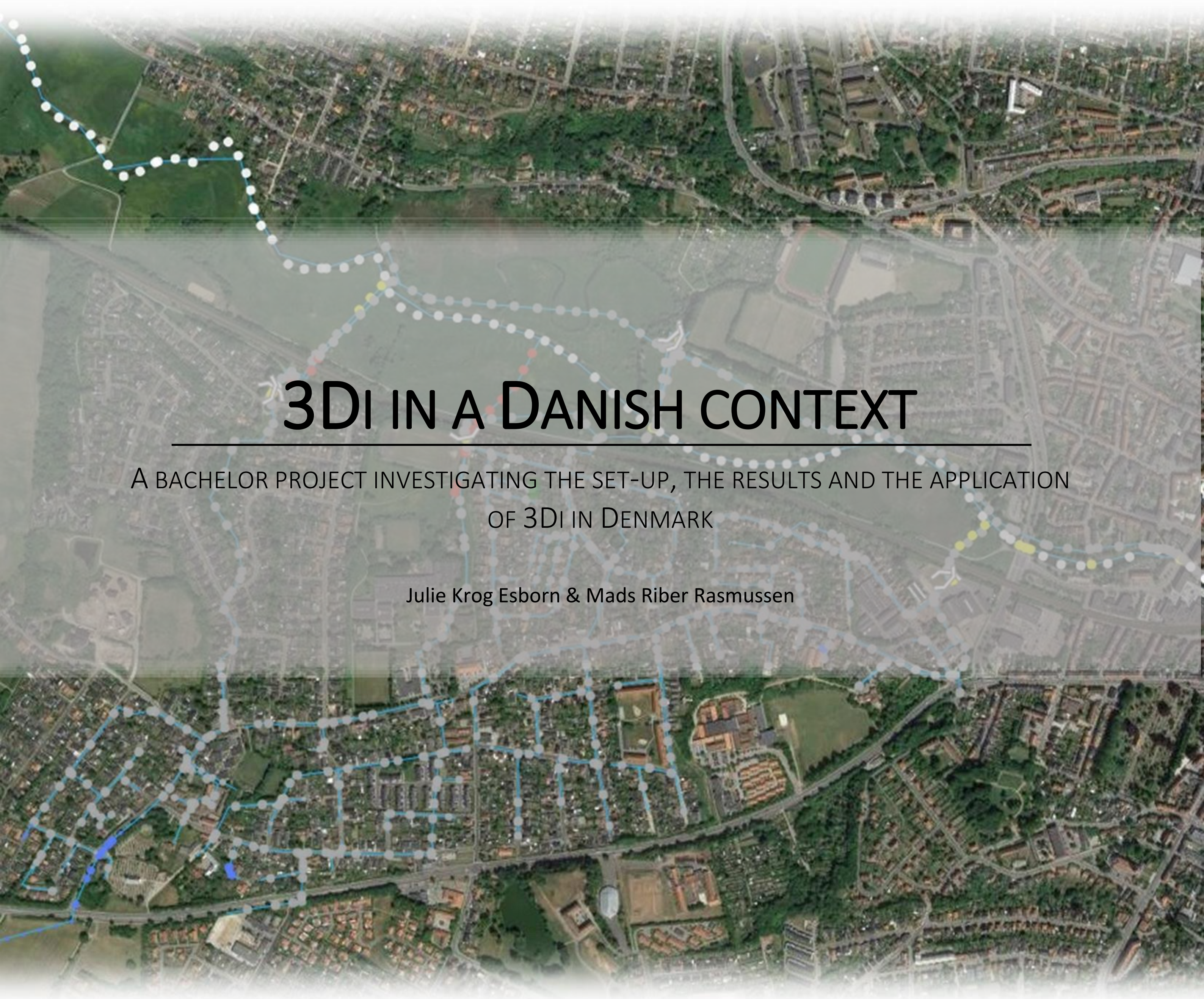

3Di in a Danish context

A bachelor project investigating the set-up, the results and the application of 3Di in Denmark

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Picture front page: Screen capture of the 3Di Live site

ABSTRACT

With the technological development, new possibilities within the modelling industry are arising. During the last couple of years, the digital elevation model has started to become part of hydrodynamic modelling and a greater interaction between the different components and new ways of offering a service have been seen.

The purpose of this report is to identify the differences in the setup in the Danish program MIKE URBAN which has been around for 20+ years and the newer Dutch program 3Di. In form of seminars, 3Di course, interviews with 3Di-users and hands-on work, differences in setup, application and results have been analysed and pinpointed. The report looks at how to set up a model in 3Di using Danish requirements differs and how Danish standards are implemented into its criteria. Lastly are the 3Di visual advantages discussed together with the amount of documentation that's behind the program. Through discussion, it has been found that costumers like municipalities are starting to request visual outputs and more control over the models themselves, while the lack of documentation might represent an obstacle for getting the consulting companies to include 3Di as a tool for hydrodynamic modelling.

PREFACE

The bachelor project has been composed in the period March-May 2019 and is based on our investigation of how and where the Dutch hydrodynamic software 3Di, can be applied in a Danish context. The purpose of this report is that it can be used as inspiration for professionals working with hydrodynamic models, both at consulting companies, municipalities and utility companies.

During the project a 1D 3Di model and a comparable MIKE URBAN model has been set-up. Besides the work with the hydrodynamic models, the project has included a trip to the company behind 3Di, meetings with municipalities and a presentation at EVA theme day.

1.1 CHAPTER OVERVIEW

The report can be divided into four main parts:

Chap. 1-2 Introduction to the project and the project area which has been modelled. The second chapter will describe some of the problems that the area is facing and how the different components interacts with each other.

Chap. 3-4 These chapters address the differences between the two models, based on the practical setup and the simulations performed in the project. The differences in setups have been tried to be pinpointed and afterwards looked at in contrast with the results coming out.

In addition to this, appendix A.1 and A.2 might be of interest for the reader, as they describe the set-up in each program in detail.

Chap. 5-6 Besides the comparison in chapter 3 and 4, the aim of the report has been to expand the view and look at the possibilities of 3Di in a broad perspective. In these two chapters some of the topics in relation to using hydrodynamic models in Denmark are discussed, drawn some perspectives to future use and a summary up of our recommendations for the use of 3Di.

Chap. 7-9 Memorandum of our “field” work, references and list of appendices.

1.2 READING GUIDE

Even though the report is written in English, decimals are used according to Danish notation. The “,” is therefore used a decimal separator, and period “.” is used as thousand separators.

References are listed according to the APA standard. Figures without references are created by the authors themselves.

The *Italic type* is used for indication reference to a function or technical term in the text.

1.3 Our expression of gratitude

The project has been realised by the help and engagement from several people and companies to whom we owe a great thank. Therefore, we would like to express our gratitude to the following:

- COWI for being willing to corporate with us on this project and for letting us use their license for 3Di, a special thanks goes to our supervisor Lars Frederiksen for being a great company on the course at 3Di and for his guidance and sharing of knowledge during the project.
- Nelen and Schuurmans / 3Di for letting us participate in the 3-days training course, for having us an extra two days and for helping us setting up the model. Several people have been involved from the company, but especially Bram de Vries has showed great patience and helped us in the understanding of 3Di.
- Lemvig Municipality, Pieter Mogree for giving a fine introduction to 3Di and sharing his experience with 3Di.
- Hedensted Municipality, Per Nørmark and Lene Nielsen for taking time out of their calendar to have a meeting with us where they told us about their use of 3Di at public meetings and their future plans with it.
- BlueKolding/Thomas Faarbæk for delivering a mdb-file of the sewer system of Kolding
- DHI for supporting us with licenses and software for the project.
- EVA for financially supporting our trip to Utrecht through their "studierejselegat". Another thanks for letting us share our experiences on the EVA-Theme day on the 9th of May, where we presented our thoughts on 3Di and MIKE.

1.4 Revision notice

The present document is a revised edition of the original report. Corrections has mainly been made to typos and rephrasing to improve the understanding. One major correction has been made to chapter 4.4. Figure 19 and the text regarding this figure has been updated to better express the difference of the outflow from catchments. In relation to new figures appendix A.12 has been added to the appendices.

"All models are wrong, but some are useful"

A note for whoever works with models,
quoted from statistician George Box

TABLE OF CONTENT

1. INTRODUCTION

1.1 MOTIVATION

The fact that the climate is changing has gradually become overall accepted. The extreme weather events that we see today, is no new phenomenon, but the increase in intensity of the events and the urbanization of the lands, has changed the picture. The cloud burst in Copenhagen 2011 was an eye-opener in Danish terms and put climate adaptions on the agenda in Denmark.
The climate challenges do not only include what comes from above, but also what comes from the sea(changes in mean sea-level and storm surge), rivers(expected increase of magnitude of extreme discharge events) and from beneath in the form of a rising groundwater table. In other words, a more complete picture has to be taken into consideration to describe the sometime complex relations of the water cycle.

The budgets for climate adaption projects are often in the scale of millions of kroners and for the project owner, most often the municipalities, there is a wish to be cost-efficient in the process. Furthermore, the expected lifetime for many of these projects are 50 to 100 years. Therefore, there is a need to make the decisions on a basis as solid and qualified as possible.

Luckily the possibilities and the power of computational software and digital description of our world has developed in a degree which makes it possible to calculate larger systems with greater precision on projects where this is needed. The toolbox for such calculations has for a long time consisted of DHI's product rage, which covers e.g. dynamic modelling of streams, sewer systems, surface flow and water distribution. Later on, SCALGO Live was introduced as an option for flood screening, flow patterns and analysis of the digital elevation model, based on static calculations.

As a part of EU-LIFE Project: *Coast2Coast Climate Challenge* the Dutch program 3Di was introduced in Denmark. The program is developed by Nelen & Schuurmans and has been used in the Netherlands for several years. The program was introduced as a fully integrated 1D and 2D model, with relatively low calculation time and a graphical user interface with the possibility of making changes "on the fly". At first hand these qualities seem very appealing, but:

- What can be gained from shifting to a new program like 3Di?
- How are the results compared to what know from e.g. MIKE URBAN?
- … and is it worth the effort in comparison to the existing software (DHI MIKE, SCALGO)

These questions we will address on a case study provided by COWI and BlueKolding (utility company of Kolding Municipality). The case consists of a sewer system in the inner city of Kolding, as well as a stream going through the city and into the fjord.

Beside conducting a case study, the aim is also to take a step up the ladder and with a broad perspective look at which parameters counts in the choice of the model. In order to do so, the report will try to address the question of usability, procurement of the results, the role of consultants and what (surplus) value the customer achieves from the model.

As part of the project work, it has been prioritised to spend some time away from the desktop and taking some out-of-the-house time to have a talk with some of the people who are already using 3Di in Denmark. The project also included a trip to Utrecht, the Netherlands, has been conducted to gain knowledge with the Dutch program. A memorandum describing the work of this can be read in chapter 7.

1.2 PROBLEM STATEMENT

Summarizing the above, the problem statement of this bachelor project can be formulated as following:

> *"How can 3Di be applied in a Danish context, are there any obstacles in the transition and are there any benefits?"*

1.3 DELIMITATION

The scope of this report is not to make an accurate 1:1 comparison between the computational engine of 3Di and MIKE. Instead the two models will be compared and evaluated according to the stated problem from a more practical point of view.

The project will not address the planned initiatives for the project area, as well as the models haven't been calibrated with any real-life data.

Lastly the report will only compare the two programs, based on a 1D-model of the sewer system. It would be a natural continuation of the 1D model, to add a surface layer and include the surface calculations as well. Due to a limited time frame for this project, it has not been possible to include the 2D comparison to this project.

2. PROJECT AREA

2.1 REASON FOR CHOSEN AREA

Kolding city has been chosen as project area because of the multiple challenges it is experiencing. Kolding Å (*stream*) is going through the city centre and has a catchment area of 277 km^2 where it runs out to Kolding harbour (COWI, 2008). The city is placed on the east coast of Jutland, which means it is in risk of storm surge. It is therefore not just heavy rainfalls that can become an issue for Kolding, but also rising sea level in Kolding Fjord.

The power of 3Di is that it can calculate on both pipe systems, streams/canals and surface runoff within the same model. It is based on different raster, most importantly the DEM.

The reason behind choosing this area is to look at an area that would normally require multiple models and different programs to create the same output as 3Di can in one model and in the same program.

2.2 THE CITY OF KOLDING

The municipality of Kolding is placed in the south/east of Jutland and has approx. 93.000 residents (Danmarks Statistik, 2019). Kolding city is the 7th largest city in Denmark and has origin back to 11th century (Visit Kolding, 2019). The city includes both an older city, shopping streets, new residential area and a harbour with industry. It is located out to Kolding Fjord which is connected to Lillebælt. Through the city flows Kolding Å, which in most of the inner city is channelized.

As many other cities in the eastern part of Jutland, Kolding city is placed in a river valley which can cause challenges in relation to the water. The upper part of the city is very robust in relation to water, while the lower and older part of the town is sensitive to both high discharges from the upper part of town and changes in water level in the stream during heavy rain or long rain events (Kolding Kommune, 2019).

Another issue for the city is in the event of change of wind direction during stormy weather. When strong and long term wind comes from west, great amounts of water is pushed into the Kattegat and The Baltic Sea. When the wind stops or even reverses, the water flows back causing a rise of the water levels in the fjords of Jutland facing east, including Kolding Fjord.

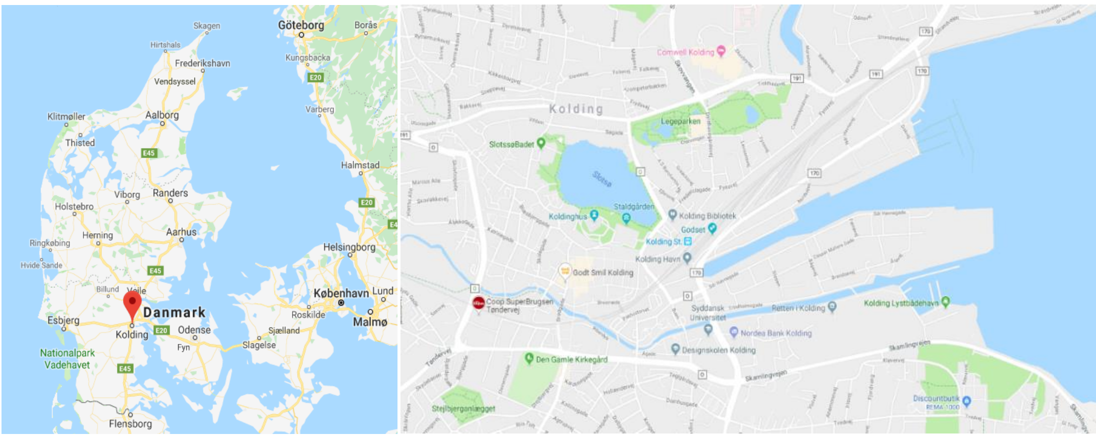

Figure 1 - The map on the left shows the location of Kolding. The map on the right shows Kolding city and Kolding Å going through the city and out to Kolding Fjord [Google Maps, 2019]

To help dealing with the consequences that rising sea- and water level can cause to Kolding city, the utility company has invested in a "sluice and pump"-solution. During heavy rain, the issues will normally appear as limited capacity of Kolding Å. Therefor the pumps pump water out of the stream and into the fjord to make space for the water coming from the catchment area. In the event of rising sea level, the sluice can hold back water. The project is expected to be completed in 2023 (Kolding Kommune, 2019).

2.3 Kolding Å

Kolding Å has a total catchment area of almost 280 km^2 where 178 km^2 of it is from the streams upstream Kolding Å. Kolding Å starts at the meeting point for Vester Nebel Å and Åkær Å and ends in Kolding Fjord.

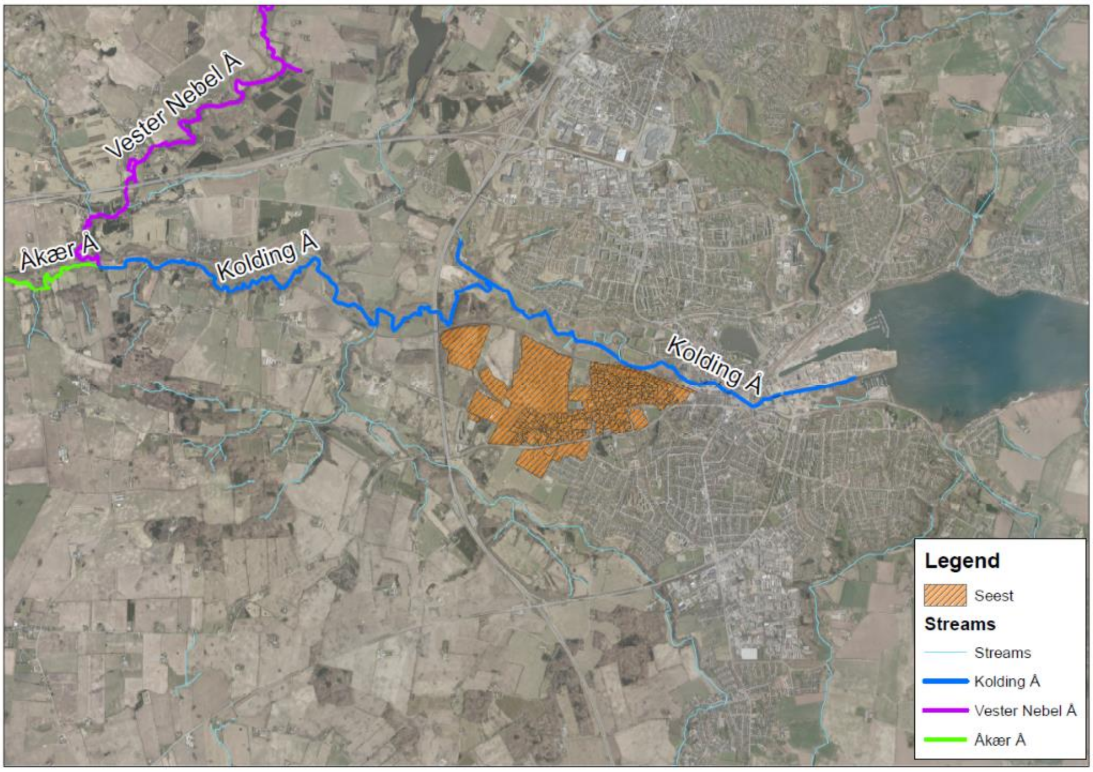

Figure 2 - The course of Kolding Å. It starts at the meeting point of Åkær Å and Vester Nebel Å and ends out in Kolding Fjord. The orange area is the area that has been chosen to model in this report. Full size map can be found as appendix A.3. [background layer; SDFE/Kortforsyningen]

During the summer period the run-off in Kolding Å will generally be lower than the rest of the year. Heavy cloudburst occurs during the summer period which can create a big pressure on the sewer system in Kolding city from the surface runoff. The sewer system in Kolding city has multiple outlets to Kolding Å, both as combined sewer overflow (CSO) and outlets from rainwater basins. Both must be able to have free discharge into Kolding Å, to avoid flooding in the streets and houses. During the winter period the run-off in Kolding will generally be higher due to long and/or repeating rain events. In that situation, there is a risk that the ground will be saturated leading a greater amount of surface run-off to Kolding Å.

2.4 KOLDING SEWER SYSTEM

The sewer system in Kolding consist of mainly a combined sewer system. The sewage from the smaller towns around Kolding all leads to the central part of Kolding, where the pre-treatment plant is located at Kolding Åpark. Afterwards it is transported in a 6.5 km long pipe out to the wastewater treatment plant in Agtrup outside of Kolding (BlueKolding, 2019). After treatment the water is led directly out into Lillebælt from the wastewater treatment plant in Agtrup.

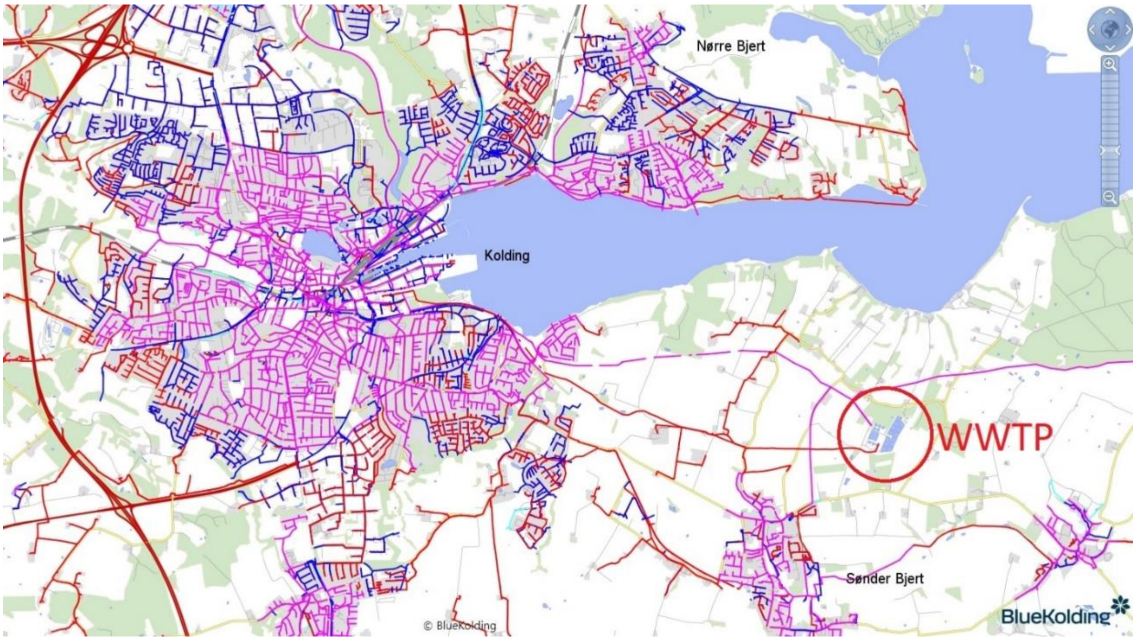

Figure 3 - The sewer system in Kolding and the surrounding cities. The red circle is the wastewater treatment plant in Agtrup where the sewage is pumped out to from the pre-treatment plant in Kolding city. [screenshot is from WEBGRAF Kolding, BlueKolding, 2019].

Because the sewer system is mainly combined, it is equipped with multiple basins and CSO which helps relieve the pressure on the sewer system during heavy rain. The positive side of this is that it creates a smaller possibility of flooding in houses, but the downside is that untreated water is led out to a recipient. As it is today, Kolding experience an average of 15 overflows a year (BlueKolding, 2019). This is influencing the water environment in e.g. Kolding Å.

2.5 SEEST - AREA OF FOCUS

The chosen area is an upstream suburb to Kolding city called Seest. It is mainly a housing area with smaller industrial and green areas. The sewer system consists of mainly combined systems and a smaller part of separated system. There is a total of five basins in Seest which are all sealed. Four of the basins are chained to another basin. This is made to reduce the load on the main pipe running out to the pre-wastewater treatment plant in Kolding city.

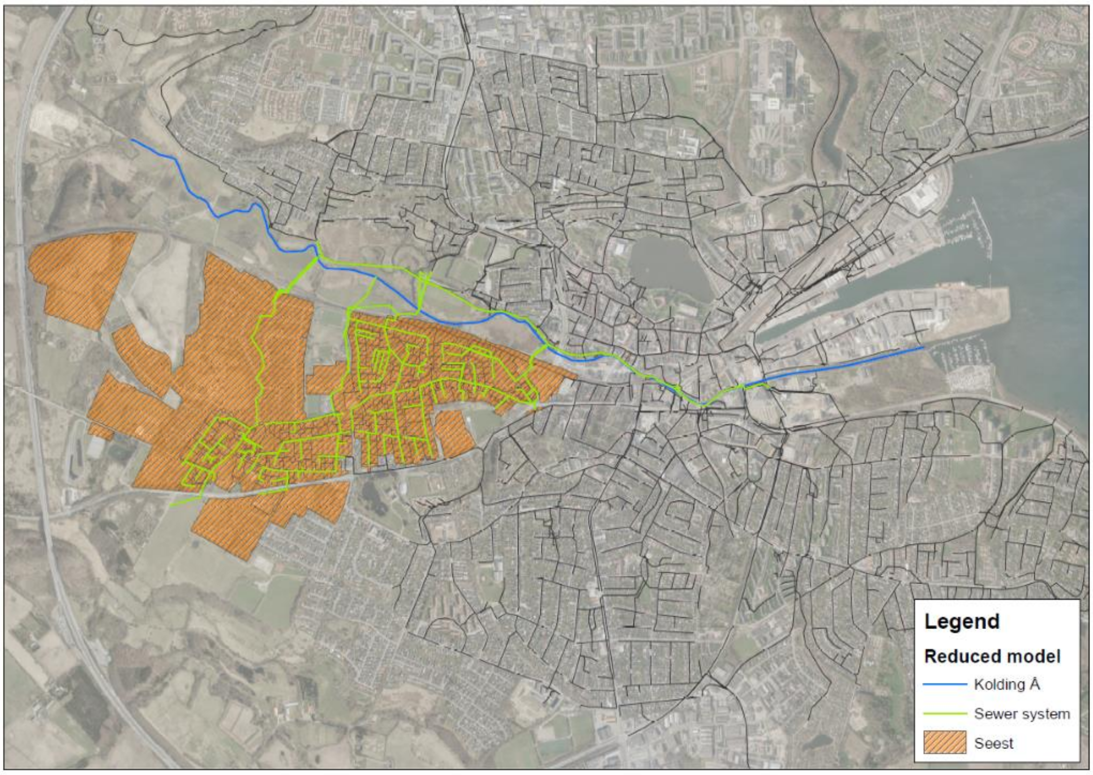

Figure 4 - The orange area is the area in focus. The black pipes are all pipes connected to the main-pipe that goes to Kolding wastewater treatment plant and part of the full MIKE URBAN model given by BlueKolding. [background layer; SDFE/Kortforsyningen]

The sewage is first led to one of the basins, where it can either be send to the main pipe or into the second basin through a regulated pipe. From the second basin the sewage can either go to main pipe or to an outlet letting it out into Kolding Å. The outlets are all regulated so they won't lead sewage to Kolding Å unless the pressure on the sewer system needs to be relieved. Letting sewage out into a stream can have consequences for the conditions in the stream and should therefore be avoided as much as possible.

3. SET-UP OF THE MODELS

3.1 INTRODUCTION TO CHAPTER

This chapter starts out describing the two programs 3Di and MIKE URBAN. Afterwards it goes through the general principles of the two models and where the general data are coming from. The following chapters are based on the differences in 3Di and MIKE URBAN and how data has been added to the two models. This concerns both input of data, defining the sewer system, modelling Kolding Å and how a simulation is launched and the presentation of the outcoming results.

The aim of the chapter is to give the reader an understanding of where the different input data has been added in each program and where the data input differs, while there is referred to the individual program's documentation for the full technical insight. In some cases, 3Di will be described more in-depth, hence MIKE URBAN is more well-known in Denmark.

3.2 PROGRAM INTRODUCTION

3.2.1 3DI

3Di has been developed by a Dutch consulting company named Nelen & Schuurmans, who together with other partners in a consortium created the program 3Di, that include both 1D, 2D and groundwater in the same model. The inclusion of these three modules in the same program, should provide a seamless calculation and by the use of 3Di's sub grid method the calculations should be executed at high speeds. The sub grid method is somewhat similar to the flexible mess (FM) module as used in MIKE, with the exception that it uses squared grids (quad-tree) instead of triangular grids.

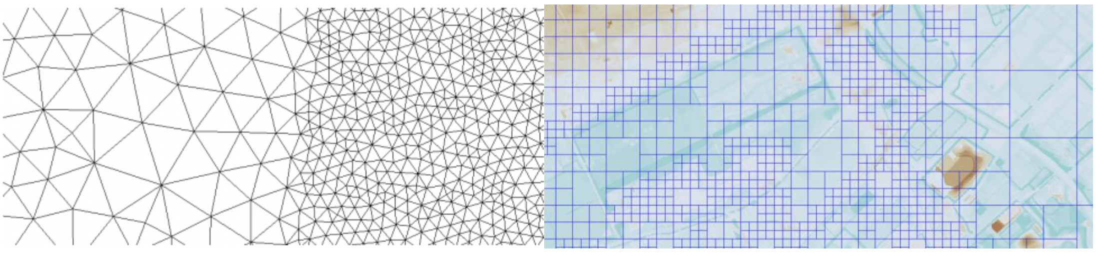

Figure 5 - On the left triangular mesh as used in MIKE FM. On right quadtree mesh as used in 3Di [figures from (Rambøll, 2019)/ (3Di/Nelen & Schuurmans, 2019)]

Oppose to the MIKE package, 3Di is partly an add-on to the open source QGIS and partly a server service. The add-on handles the editing of the SQLite database, while the calculations is performed by a server. Communication with the server can either be done from a web browser through the Live site, https://3di.lizard.net/, or from an API client (Application Programming Interface). Using the Live site, the simulation results can be seen as a very visual presentation at the speed they are performed. The Live site also allows the user to pause and make adjustments to the 2D model "on the fly".

The 3Di add-on provides the possibility to import sewer network data from the Dutch *sufhyd* standard. If data is not provided in this format, it is possible to program a script in python or make a SQL-call in order to have some sort of automation.

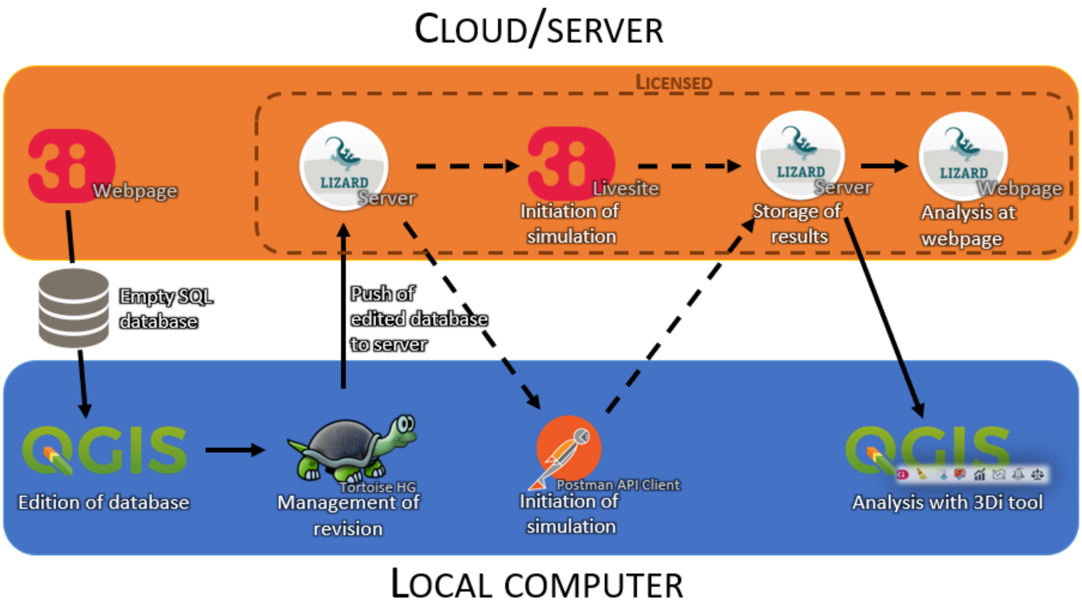

Figure 6 - Schematisation of the process of creating an analysing a model with 3Di. As illustrated only the simulation/post processing of the model is licensed according to the SaaS principle.

The services delivered from Nelen & Schuurmans is therefore not an editing program itself in traditional terms. Instead, Nelen & Schuurmans provides the server space for storage and computational power for simulation, as well as support and education. This form of service is also referred to as SaaS (software as a service) and a part of a more cloud based approach to software.

3.2.2 MIKE URBAN

MIKE URBAN is a modelling software created by DHI. It is frequently used in Denmark when working with sewer systems either dimensioning a new system or analysing an existing one. The model will often be based on a DanDasGraf file/database. This can be a file of the existing system, often delivered by the utility company, or a new system can be drawn in DanDasGraf and a capacity index of it can be made. It will afterward be imported to MIKE URBAN where a CDS, LTS or another rain events can be simulated, depending on the purpose of the project.

The model database is either edited through the user interface of MIKE URBAN, with an ESRI/ArcGIS underlay or it can be edited directly in the database table with e.g. Microsoft Access.

When there is a need for a simulation of complex river systems, surface and/or groundwater flow, additional module within the MIKE suite can be couple with the MIKE URBAN model. These modules are separate programs known as MIKE HYDRO Basin/River, MIKE FLOOD and MIKE SHE.

3.3 General principle of the model

Both the MIKE URBAN and the 3Di model have been built around two main structures, the stream Kolding Å and the sewer system of the city of Kolding. Both structures are included in the same model in each program, so there is a seamless interaction between the stream and sewer system. For 3Di the interaction between multiple components is a core product of theirs, while the MIKE package has different programs for different components

The base for the stream Kolding Å is a MIKE HYDRO River file delivered by COWI, which includes the full river system of Kolding Å and additional side streams. In the model the stream begins just downstream *Hartekanalen* and ends in the inner part of Kolding fjord. The flow in the stream is affected by the outlets from the sewer system, the specific flow from the upstream catchment area and the water level in the harbour, defined by Kolding Fjord. The last two serves as boundary conditions for the stream.

The base for the sewer system is a fully defined MIKE URBAN database, including the whole system connected to the wastewater treatment plant (WWTP) of Kolding. The database of the sewer system of Kolding was given by BlueKolding, the utility company of Kolding Municipality, and consists of a status model of the sewer system in Kolding as it is reckoning to be right now. This counts for both the regulations in the system, volumes of basins, dimensions of pipes and nodes, pump characteristics, overflow constructions and catchment data.

Containing not only the inner city of Kolding, but also the surrounding towns, the full model has been estimated to be too large for a comparison and would require long computational time for each simulation. Therefore, the model has been reduced to the area of *Seest* and the main pipe toward the pre-treatment WWTP. The full model has therefore been cut into a smaller area, where all the details have been kept. All the places where the model has been cut are illustrated on the figure below.

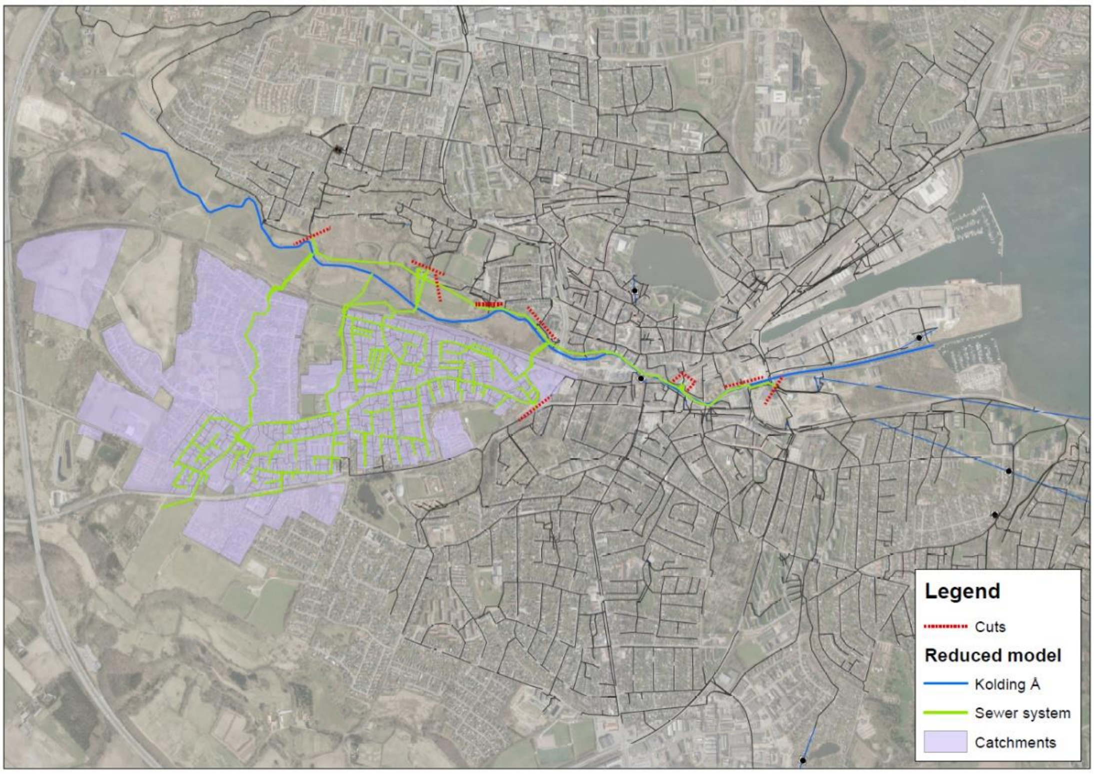

Figure 7 - The red dotted lines are where the model has been cut to create the reduced model. The green lines illustrate the pipes in the reduced model while the black lines illustrate the full sewer system model of Kolding. Kolding Å is shown in blue. Kolding Å is manually added to the reduced model. Full size map can be seen as appendix A.3. [background map from SDFE/Kortforsyningen]

All adjacent pipes to either the area of *Seest* or to the main pipes has been substituted with a discharge time series from a simulation of the full model with the same rain event as used on the reduced model. This has been done in order to add the contribution of the sewage load from the areas not included in the reduced model. Discharges have been added as network loads in MIKE URBAN and laterals in 3Di.

The scenario simulated has been chosen to be a rain event with a 10-year return period in combination with summer median discharge in Kolding Å and a safety factor of 1. The scenario describes a cloud burst in the summer period with a low flow in the stream as it could appear today.

3.4 Import of data

Since the MIKE URBAN model has been given as a complete model, additional data has not been added to it. If this hasn't been the case, the MIKE URBAN data would normally be imported from a DanDasGraf file. For this procedure each company, consulting or utility company, would have their own guide on how to import.

The procedure of importing the data to 3Di, starts by exporting data from the existing MIKE URBAN model into shape files/tables. These tables have then been used as a source for an SQL-call. An example of such is shown below.

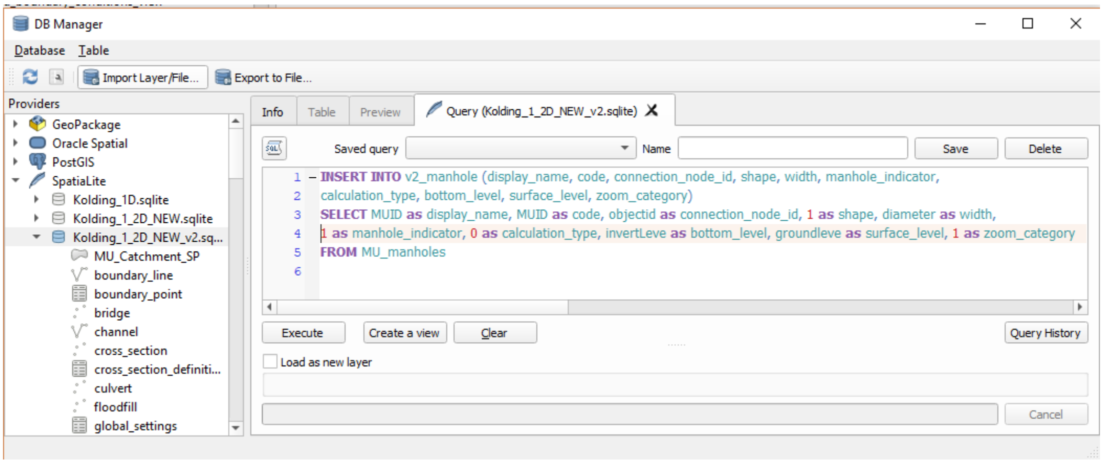

Figure 8 - Screen capture from the QGIS database manager. The SQL-call insert data INTO the v2_manhole table, using the FROM exported MIKE URBAN table [screenshot from QGIS].

For the example above, manholes are defined. The amount of definitions imported differs from table to table in 3Di. Most of the references refers to the MIKE URBAN table, while some, e.g. *connection_node_id*, refers to a table in the SQLite. In some cases, information has been edited afterwards either by manually changing the field in the table or by using the field calculator. Additional information to the tables has been added by joining the table by referring to e.g. the MUID.

The process of importing can also be automated by a python script, which would be an obvious choice if there were several models that had to be set up.

3.5 Set-up of the sewer system

The model of the sewer system of Kolding was given as a mdb-file by BlueKolding and it has been assumed that the data given in the mdb-file are accurate. After running the full model, the model has been reduced to the area Seest in MIKE URBAN like mentioned in chapter 3.3. The reduced model of the sewer system has afterwards been exported to 3Di. When running the reduced model some of the nodes have had their *Covertype* changed. This is because they are placed in Kolding Å and it has therefore been assumed that they are sealed, which was confirmed by Thomas Faarbaek, BlueKolding. Otherwise the MIKE URBAN model has been assumed to be correctly set up an no further changes to the sewer system has been made.

The sewer system in 3Di is based on the reduced MIKE URBAN model. It is built on a SQLite-file extended with a SpatiaLite library. Because the SpatiaLite library does not match all the tables in a MIKE URBAN database table, some adjustments must be made. This is because there are different practices internationally for how to do these calculations, and therefore which data are needed. For this reason, some adjustments had to be made to make the two models comparable.

3.5.1 Nodes

One of the places where the two models are not compatible is nodes/connection nodes. In MIKE URBAN a node can be defined as *Manhole*, *Basin*, *Outlet*, *Storage node* or *Soakaway*. In 3Di a connection node can be coupled with the Manhole or Pump table. In MIKE URBAN a node can be defined as a basin with a basin geometry connected to it, which is based on an elevation (H), surface area (As) and wetted cross-section area (Ac). To create a basin in 3Di you can either create the volume of the actual basin in a pipe section or by making a node with the same volume as the basin. In this model it has been made as a square node with the same storage volume as the basin. This is illustrated on the figure below.

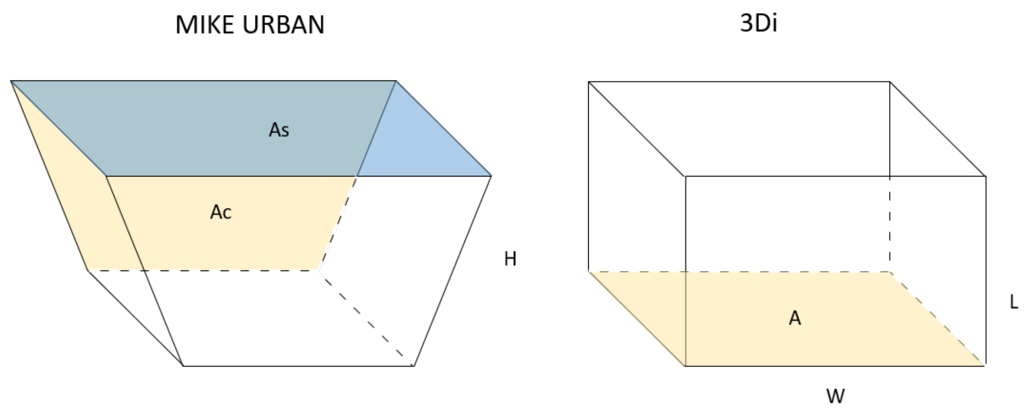

Figure 9 - Left: Basin in MIKE URBAN is defined by a cross sectional area and surface area at a specific height, which gives the possibility to define a basin to great detail. Right: Basins in 3Di are defined by a manhole with the same size as the original basin. Height of the basin is defined by the top and bottom level of the manhole. Volume wise both models can be accurately defined.

Both MIKE URBAN and 3Di defines the bottom level of the basin as the bottom level of the node. In 3Di the top level is likewise defined from the information added to the node, while the ground level of the basin in MIKE URBAN depends on the data added to the *basin geometry*.

Connection nodes can't be defined as outlets in 3Di either, like known in MIKE URBAN. To get water out of the model a boundary condition can be set up or a pump can be placed. For the "end-node" in the reduced model of the sewer system a pump has been chosen. The max capacity of the pump has been set to 2 m^3/s based on the flow found in the full MIKE URBAN model.

As with the detail of basins, the same goes for the detail of single head losses in manholes. In MIKE URBAN the head loss is by default calculated by F.A. Engelund (DHI, 2016), but with the possibility of choosing other formulae or disable head loss completely for a specific node. According to the 3Di documentation (3Di/Nelen & Schuurmans, 2019) and answer by mail, head losses are taken into consideration when solving Saint-Venant momentum equation, where inertia, advection and friction is included. The advection part in the equation can be turned off, but not for a specific node.

Since head losses in some cases will have significant importance to the water level, this might be a point where the two models have divergence.

3.5.2 PIPES

Opposite to MIKE URBAN, 3Di does not define pipes with its own geometry, but as a connection between two connection nodes. In practice this have very little impact, since most pipes in sewer systems goes in a straight line from manhole to manhole. In the case of a change of direction, a manhole must be placed in 3Di. For the model in this project it has not been relevant to make such modifications.

An additional note for the pipes is that the roughness in 3Di in defined as Manning n [$s/m^{1/3}$] and is directly related to the pipe, where MIKE URBAN defines it as Manning M [$m^{1/3}/s$] and as default embeds it in the material definition, which can be defined as preferred.

3.5.3 WEIRS

In the original model of the sewer system there are several weirs placed. In most cases these weirs serves as control between two basins. In MIKE URBAN the weirs are defined by a crest level, crest width and a discharge coefficient. The same goes for 3Di, which also defines the weir by these parameters. An important point in relation to this is that, even though both programs operates with a discharge coefficient and uses it for calculating the natural depth over the ridge, the coefficient is not transferable.

Default values for discharge coefficients are 0,35 in MIKE URBAN and 0,8 in 3Di. Both programs can define the weir as closed for backflow. Furthermore, does MIKE URBAN have the possibility to define the angle of the ridge in relation to the flow direction, as well as defining a Q-H relation for the specific structure.

3.5.4 HYDROLOGICAL REDUCTION FACTOR

Hydrological reduction factor is a very well-used parameter in Denmark and defines how much of the rain that falls on the impervious part of a catchment that ends in the sewer system. Often it is stated for the given area by the utility company, but the most accurate number is found by doing an actual test on the area. This can be costly and takes time which is the reason why it is often given with the assignment or an assumption is being made by the consulting engineers. The hydrological reduction factor has a great influence on the amount of rain that is expected to go into the sewer system. Choosing 0,9 or 0,8 gives a difference of around 12% on the amount of rain when dimensioning a pipe. There is no table for the hydrological reduction factor in 3Di. To include it, it can be multiplied on the rain or on the area. Because Kolding has defined different hydrological reduction factors in different areas of Kolding, the hydrological reduction factor has been multiplied to the imperviousness area and the actual amount is not stated directly in the 3Di model.

3.5.5 CATCHMENTS AND CONCENTRATION TIME

Concentration time in MIKE URBAN is set to 7 minutes by default. At some companies there is a practice of changing the concentration time for roads to e.g. 1 minute and keep the rest of the catchment areas set to default. In 3Di the discharge can be controlled by the outflow delay setting. The figure below describes the principle of the outflow delay. A more accurate comparison between outflow delay of 1, 0,5 and 0,33 can be found in appendix A.4.

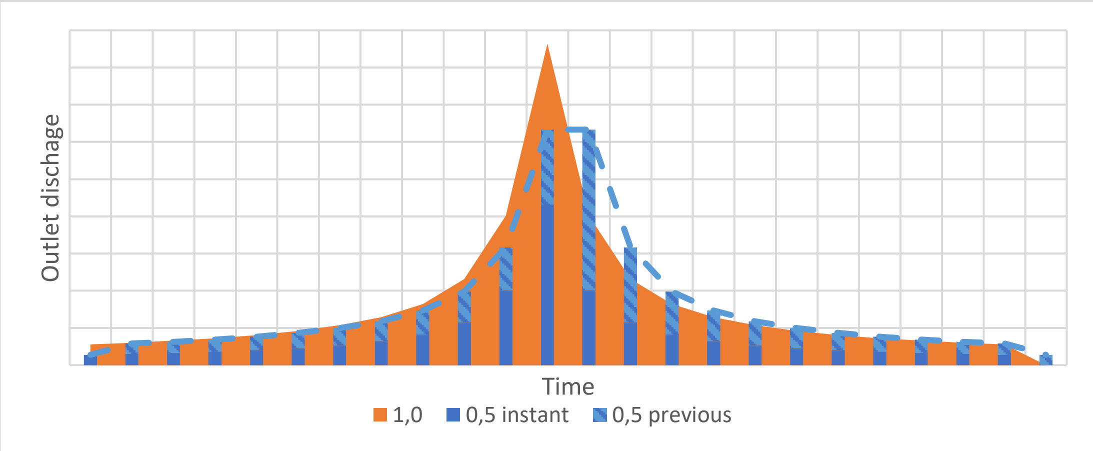

Figure 10 - Principle of outflow delay. Turning down the outlet coefficient some "buffer" capacity is assigned the catchment, resulting in a lower peak value and by that a longer discharge time. A graph based on actual simulation can be seen in appendix A.4.

Since the intention of 3Di is to also simulate surface flow, the Danish set-up with one or more cadastres defined as one catchment is not directly translated into the common set-up in 3Di. In 3Di the normal setup would be to use a DEM without buildings as a layer for surface flow, while the contribution from the buildings would be defined as 0D-areas. The 0D-areas will then be directly connected to the sewer system, while the surface runoff is added to the sewer system by the road drains.

In order to be able to compare the outcome of the two models, the “catchment-method” from MIKE URBAN has been transferred to 3Di, so it includes catchments with the same imperviousness percentage and area. The outflow delay has been set to 1, while the concentration in MIKE URBAN is set to default value of 7 minutes, except for one catchment where the value is defined by the utility company to 9 minutes.

3.5.6 TIME AREA CURVES

In addition to the previous section about the catchments, another difference in the way catchments are defined is that MIKE URBAN is able to define the discharge from the catchment in relation to one of three discharge curves, depending on the shape of the catchment. With that being said, a linear relation is most commonly used, hence it is the default value.

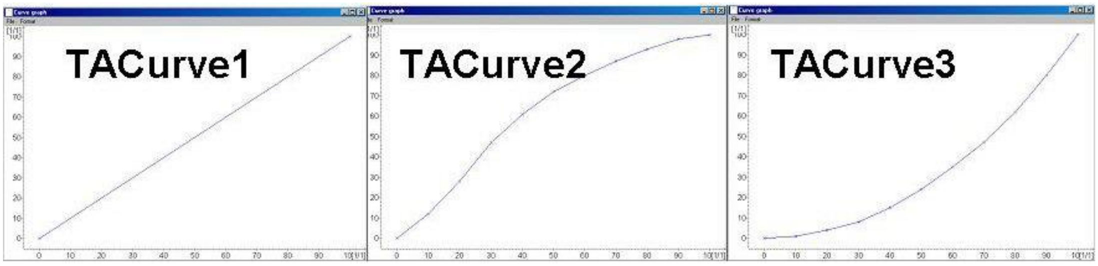

Figure 11 - Time-Area curves as they are defined in MIKE URBAN. The curves show the relation between the contribution from the catchment and time. From left the curves represent rectangular, divergent and convergent catchment profiles. [figure 4.5 in (DHI, 2017)]

3Di does not operate with these definition, most likely due to a different view of leading the water into the sewer as described in the previous section. For the two models, the TA-curve is not estimated to have any influence, since they all are defined as linear relation.

3.5.7 RAIN EVENTS

In Denmark a local rain event with a specific return period is normally generated in a *SVK Regneark*, an Excel document by The Water Pollution Committee of The Society of Danish Engineers (Spildevandskomiteen or SVK in Danish) that can generate a CDS rain event based on a geographical placement, a safety factor and the wanted return period. The return period used is normally based on the type of sewer system, combined or separated. The utility companies are required to live up to the service level set in *Script 27*. The safety factor is based on three different factors: uncertainty (*Script 29*), city development and climate change (*Script 30*), which are multiplied with each other to give the actual safety factor. The scripts are documents written by SVK and is considered to be best practice in Denmark. In MIKE URBAN the safety factor will normally be defined in the model as a scaling factor or it can be multiplied on the rain when generating it.

Another well used rain event in Denmark, is a LTS rain (Long Term Statistics), being a historical rain. This is generally used to simulated accumulated rain events and checking basins or combined sewer overflow (CSO) for return period for overflows and number of overflows e.g. per year. Previous to the simulation a set of parameters are set, e.g. only rain event with an intensity or a duration over a defined value is included, allowing the simulation time to be reduced significant.

In 3Di, a rain event can be defined by four options; constant, design, radar or custom rain. The constant rain is like the name indicates a constant intensity during a specific time. The design rain is defined according to Dutch national standards and can include both constant and varying intensity. Radar rain is based on rain measures, which beside varying in duration and intensity, also can have a spatial variation. The use of radar rain is also used for models in MIKE URBAN. The custom rain can be defined by the intensity to a timestep. At the Live site it is also possible to make a local cloud, with the purpose of adding additional rain during a live simulation.

For the simulation used in this project a custom rain has been created. At first the T10 CDS rain was defined directly into the API client, which made the computational time exceeding what was expected. In dialog with 3Di the CDS rain was created as a unique rain and upload to their Lizard platform. The result was a reduction of the computational time to a more acceptable level.

The used rain can be found in appendix B.4.

3.6 Set-up of Kolding Å

As earlier described, the base for modelling the stream is a MIKE HYDRO River model. The MIKE HYDRO model includes cross sections of the stream and its structures, e.g. bridges and culverts. MIKE HYDRO is a part of DHIs MIKE suite and can simulate complex river system with a wide selection of functions and tools for defining a dynamic river model.

For the case of the MIKE suite, the stream could be simulated in MIKE HYDRO River. In order to keep the two models comparable, Kolding Å has been defined as a natural channel in MIKE URBAN, which is more or less equal to the way the channel is defined in 3Di.

3.6.1 Flow, water level and roughness

Based on statistical analysis of Kolding Å performed by COWI (appendix A.5), a constant discharge into the stream has been set to 1,56 m^3/s, which is equal to a summer median situation. In both programs the discharge has been added as a boundary condition and is assumed to be the only contribution to the stream besides the outlets from the sewer system. Hence this, surface discharge along the stream, groundwater infiltration and drains are not included in the model.

Discharge	**Alpedalen** [m^3/s]	**Specific discharge** [$l/s/km^2$]	**Østerbrogade** [m^3/s]	**Havnen** [m^3/s]
Summer median	1,56	5,8	1,62	1,62
Summer media max.	6,7	24,93	6,96	6,98
Median max.	16,12	60,0	16,74	16,78
2Y event	15,93	59,3	16,55	16,59
5Y event	19,72	73,4	20,48	20,54
10Y event	22,25	82,8	23,11	23,17

Table 1 - Selected characteristic and extreme event discharge values. The first column contains data from a measuring station "Alpedalen", which is placed just upstream the staring point for the modelled part of Kolding Å. Based on the measurement specific discharge and discharge further downstream "Østerbrogade" and "Havnen" has been calculated. The catchment area for the measuring station is 268,7 km^2. [data from table 1-1 in appendix A.5]

Furthermore, the discharge starts at the same time as the rain event, resulting in a false storage capacity compared to the reality. In order to comparing the two programs in between, it is assumed not to have an impact.

The water level in Kolding Fjord, which makes the outlet boundary for the stream, has been set to 0,2 meter above mean sea level. The value has been chosen as a conservative value based on information provided by the utility company of Kolding, BlueKolding.

The roughness of the stream (COWI, 2008) has been set to 12 $m^{1/3}/s$, *Manning M,* or 0.0833 $s/m^{1/3}$, *Manning n*. For the simulation, only one roughness has been chosen, which is a simplification of reality. In reality the roughness would be changing along the stream. The upper part of the stream has a more natural cross sectional definition and more weeds to create an increase in the resistance. On the other hand, the lower part is more channelized and with less weeds allowing the water to flow faster due to lower resistance.

3.6.2 PRINCIPLE OF THE STREAM

Both 3Di and MIKE URBAN defines a stream by a line string/typography, to which cross sections can be added. In 3Di there are designated tables for the definition of a channel, while the stream in MIKE URBAN is defined as a natural channel.

The following figure shows the general structure of the two models.

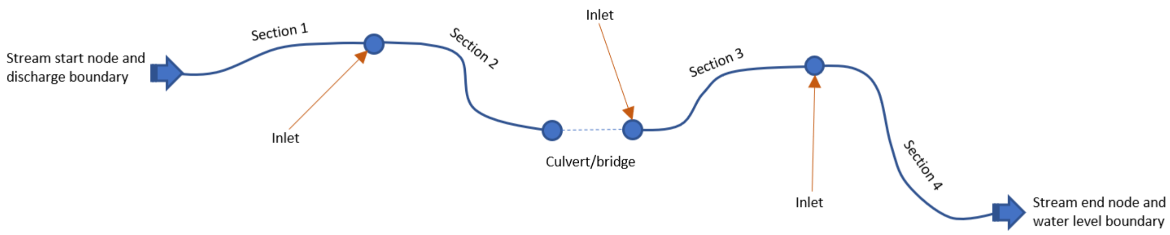

Figure 12 - Principle of the stream model for both 3Di and MIKE URBAN. Even though the definition of the channel has some differences in between, the overall principle is the same.

Even though the databases of the two models are different, the principle is to a great extend the same. E.g. is the shape of the cross sections in both models interpolated between two defined cross sections and extrapolated between a cross section and a node.

3.6.3 GEOMETRY AND CROSS SECTIONS

A line string defines the geometry, which runs between a start and end node (connection node in 3Di and manhole in MIKE URBAN). Along the geometry, cross sections are defined either by the chainage from the last upstream node (MIKE URBAN) or is bound up on a line vertex (3Di).

From the MIKE HYDRO River file, the cross sections are defined by a x,z-coordinate system, which is possible to define in MIKE URBAN, but not in 3Di. In 3Di the cross sections have to be defined either as a shape with constant height and width or as a tabulated height and width relation. The latter is also possible in MIKE URBAN, why this relation has been chosen.

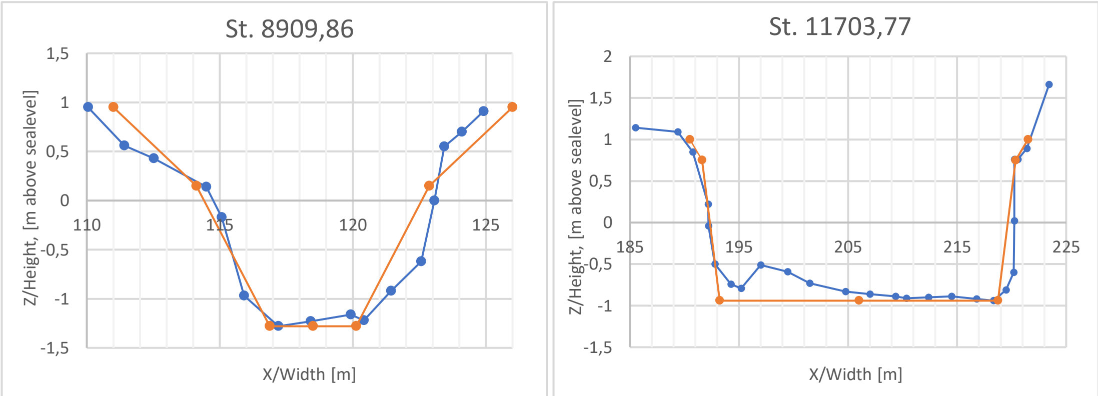

Figure 13 - Original MIKE HYDRO cross section (blue) in comparison with the tabulated cross section (orange), which has been used in both programs. The left is taken from the upper part of the stream where it tends to have a more natural shape. The right is from the lower part, where the stream is channelized. The tabulated cross section has a deviation of -4% for the left and +1% compared to the original. The original MIKE HYDRO cross section included the full river valley, which is why the abscissa starts at 110 and 185 m respectively.

The x,z defined cross sections have been transformed into height-width defined cross sections, which have approximated the same bottom level, profile and area. An overview of all the cross sections can be found in appendix A.6. In most cases the deviation in the cross sectional area is +/- 3-5% compared to the MIKE HYDRO area.

For MIKE URBAN counts that a natural channel can't have flooding. This means that if the water level in the stream rises above bank level, the simulation will stop. This has been fixed by creating a 1 meter vertical wall on the cross sections where the stream otherwise would experience flooding. This method is known from e.g. the Danish program VASP. In the 3Di documentation it is a bit unclear how it calculates when the water level rises over the banks in a 1D scenario. In a 2D scenario it will be able to spread onto the DEM raster depending on how it is set to interact (embedded, connected or isolated).

The culverts and bridges along the stream spans from smaller footbridges to larger bridges e.g. at *Vestre Ringgade*. The bridges included in the original MIKE HYDRO file is also included in the two models, as well as the roughness has been kept the same. Cross sections of the culverts and bridges are defined by the same principle as for the stream cross sections.

3.6.4 OUTLET FROM THE SEWER SYSTEM

Throughout Kolding city multiple outlets from basins are placed to reduce the load of the sewer system when heavy rains occur. To simplify the model without changing the impact on Kolding Å from the surrounding sewer system, all the outlets from the full model which are connected to Kolding Å has been kept. The discharge time series from the pipes where the model has been "cut", have been added to the reduced model to make the reduced model as accurate to the full model as possible. This has been done by running a simulation on the full model and exporting the discharge values of the specific pipes in MIKE View. These data represent the discharge in the specific pipes to the time series used in the simulation of the full model. The same time series have been used in the reduced model. This has been done by finding the time series for each outlet's discharge in the full MIKE URBAN model and adding it to the reduced model in both MIKE URBAN and 3Di.

In MIKE URBAN the discharge time series have been added to a node as a network load. Each network load has been defined as an *individual connection* type and linked to the specific node with the node load *Inflow Hydrograph.* The specific time series of the discharge has then been added as a .dfs0-file. In 3Di the outlets have been added as *laterals*, using the same timestep and intensity as in the dfs0-file used in MIKE URBAN.

An overview of time series can be found in appendix A.7.

3.7 SIMULATION

When running a simulation in MIKE URBAN a runoff and network file is generated. The runoff file defines the amount of rain falling on the model/catchments, while the network file calculates the sewage going through the sewer system. The network file can afterwards be opened in MIKE View, where it is possible to look at e.g. flooding in nodes, discharge in pipes, profiles of specific sections.

3Di has two options for initiating a simulation. The Live site provides a graphical user interface and allows the user to stop the simulation, add or subtract additional water and make changes to the DEM (2D) before continuing the simulation. The Live site can be accessed from a web browser on a computer, tablet or other mobile device. This option creates a good platform for a dialog, but due to the visual output, the calculation time is longer than using the other option, which is the API Client.

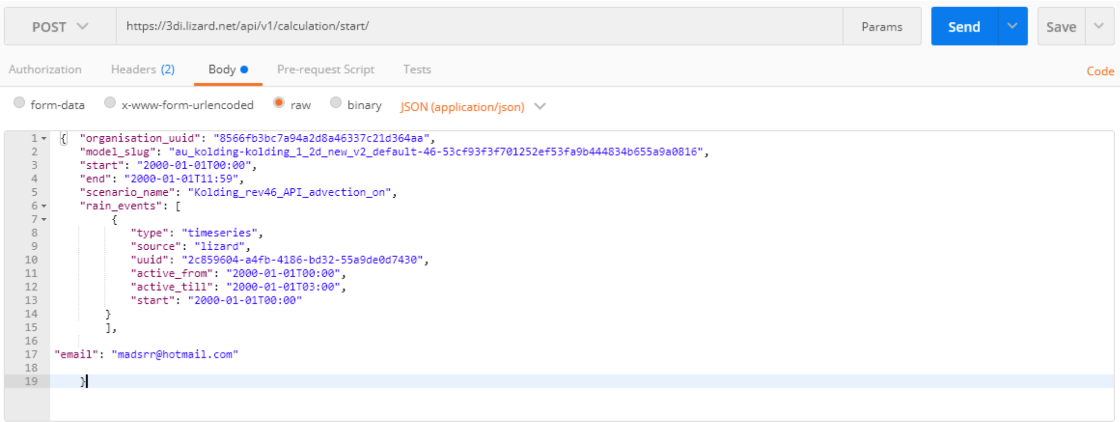

Figure 14 - The pricture shows the API Call a 12 hour simulation, with a 3 hour rain. Once the simulation is completet the results can be acces through the Lizard server or through the link received by mail. [Screen shot from Postman API]

Using an API client, e.g. Postman, the simulation is defined by a code send directly to the server and the user receives an email with a link for download of the result file, once the simulation is done. The results can either be further examined on the online Lizard platform or it can be opened and postprocessed in QGIS.

In QGIS the 3Di add-on includes different tools for extracting length profiles, discharge hydrograph and mass balances. Furthermore, the results can be presented as an animation of the different timesteps in the simulation. Maps, backgrounds and shapefiles can be operated as usual.

4. Comparison of simulation results

4.1 Introduction to chapter

During the analysis of the results from the 1D simulation in 3Di and MIKE URBAN it has become clear that there are some differences. This chapter looks at five different aspects of these and finalizes with a note on what general differs and what impact they have on the comparison. On the figure below is illustrated the placements of the different components mentioned in the following.

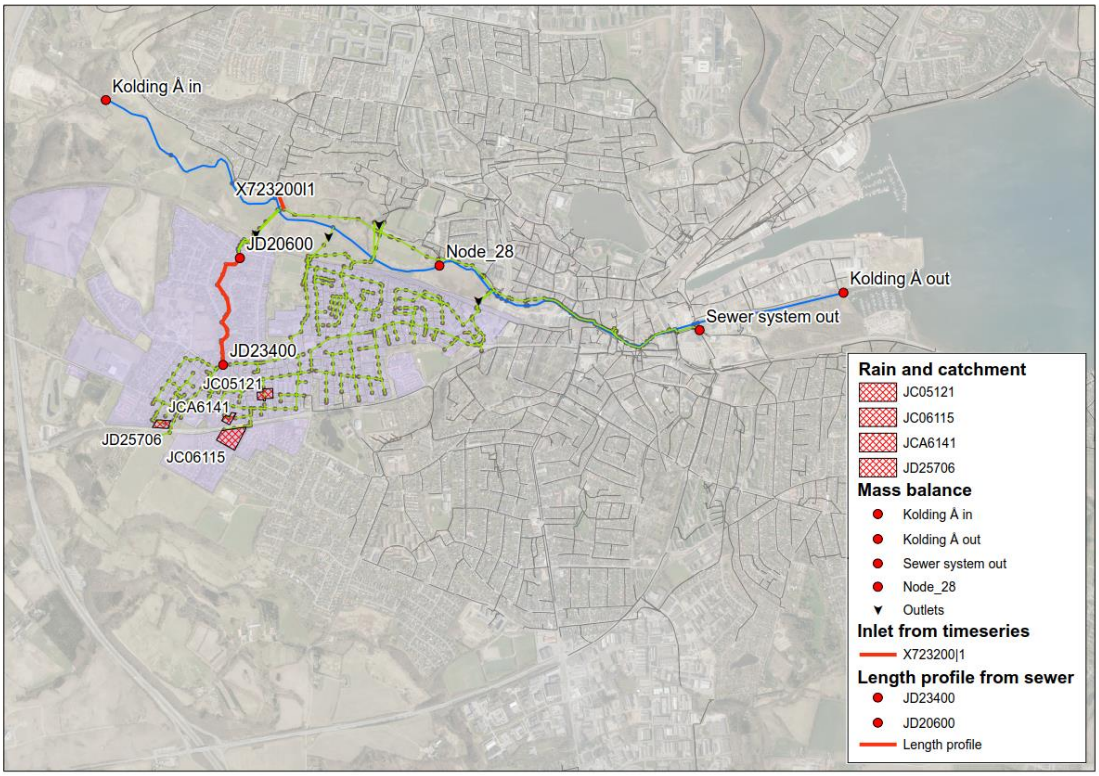

Figure 15 - Map of the components that will be mentioned in the following text. The figure can be found in the appendix for a bigger picture. Full size map can be seen in appendix A.3. [background map from SDFR/Kortforsyningen]

The raw data extracted from 3Di and MIKE URBAN and the associated graphs for the following graphs can be found as appendix A.8.

4.2 Mass balance

In order to see how the two models keep track of the water, a mass balance has been conducted. Besides showing if any water is “lost” in the model, the water balance will also indicate the interaction of water between the stream and the sewer within the two models.

The figure below shows the elements included in the mass balance, being in- and outlets of the stream, outlets from the sewer system, inlets from the rain event, external load (laterals or network loads) and lastly any leftover water in the system.

The total mass balance has been accessed by the build-in mass balance tool in 3Di's add-on in QGIS and from the network/summary report from MIKE URBAN. In order to differentiate the distribution of the outgoing water in MIKE URBAN, accumulated values from the discharge time series in MIKE View has been used to determine the outgoing amounts from the sewer system and the stream.

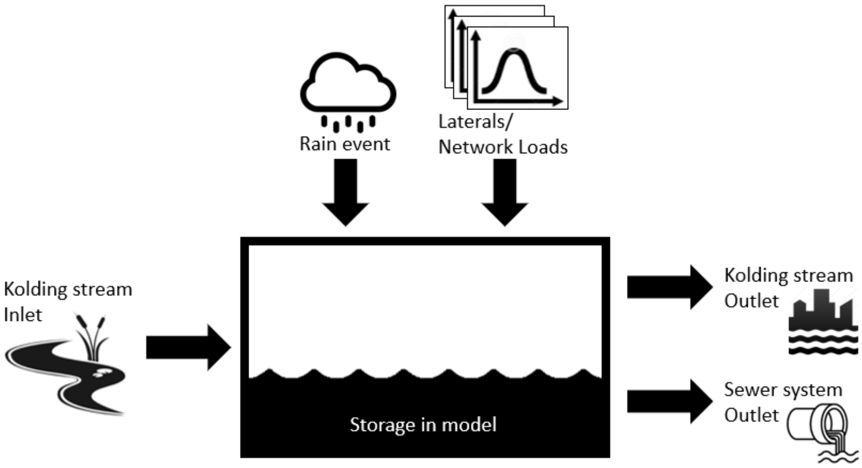

Figure 16 - Illustration of the elements included in the mass balance of the two models.

Subtracted from the full outflow volume, a volume of 640 m^3 is left unspecified in the MIKE URBAN model (0,4% of total outlet). One possible explanation for this could be an error related to instabilities in the channel, as seen on Figure 17. Beside this, it has not been possible to make any further investigation of this discrepancy.

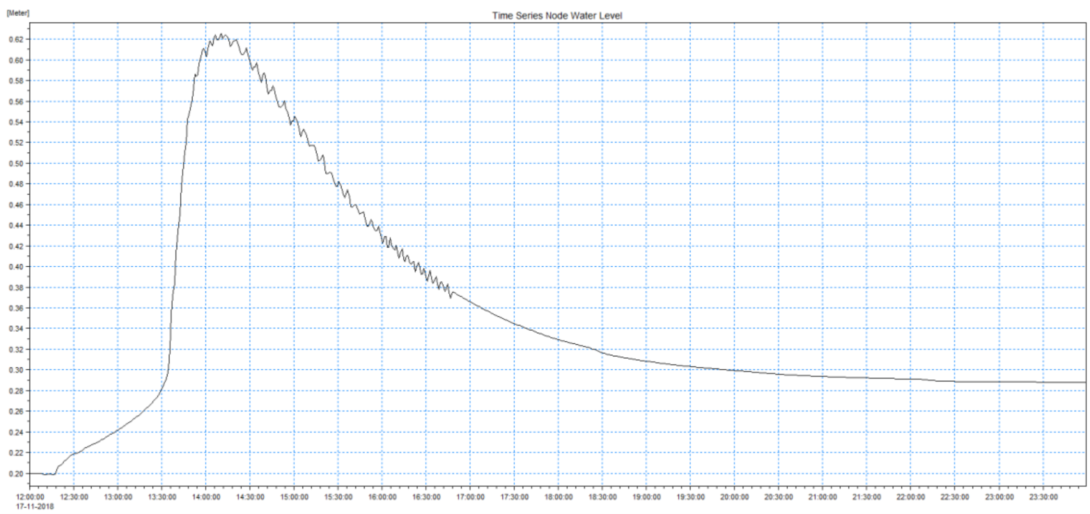

Figure 17 - Hydrograph of the water level in Node_28 in the model of the stream in the reduced MIKE URBAN model. From the peak and during the lowering some instability is seen, which could be a source for the discrepancy in the volumes.

The numbers from the mass balance indicates that the water balance of the two models seems to match within its own model. Comparing the two models in between, it is seen that the largest differences are found in the initial volume and the outlet from the sewer system.

		3Di	MIKE	+/-	Difference in % of MIKE
	Initial volume	78.334	86.480	-8.146	-9,4%
	End volume	88.781	94.519	-5.739	-6,1%
INFLOW	Inflow to stream	68.760	67.298	1.462	2,2%
	Inflow from rain	13.183	12.650	533	4,2%
	Inflow laterals/network loads	81.093	80.650	442	0,5%
	Non-specified inflows	0	345	-345	- %
OUTFLOW	*Outflow of stream	142.631	141.398	1.234	0,9%
	*Outflow from sewer	9.926	10.611	-685	-6,5%
	*Unspecified outflow	0	640		- %
1	Inflow	163.036	160.944	2.092	1,3%
2	Outflow	152.558	152.649	-92	-0,1%
3	Storage according to flow (2-1)	10.478	8.294	2.184	26,3%
4	Storage in model (End vol. - Initial vol.)	10.446	8.039	2.407	29,9%
	Water balance (3-4)	32	255		

*Table 2 - Mass balance of the two models. Values are in m³ and are accumulated over the full duration of the 12 hours simulation. *Note: the unspecified volume of 640 m³ occur when the total outflow of the MIKE model is subtracted the accumulated values of the outlet from the stream and the sewer is read off in MIKE VIEW. Percentage is the difference divided by the MIKE value. [Appendix A.8 - Mass balance]*

The initial volume of the two models is created by the initial water level of 0,2 meter in the stream (water level in Kolding Fjord). There might be some differences in the interpolation between the cross sections between the two programs and hereof there might be some differences in the stream volume. Furthermore, MIKE URBAN is, oppose to 3Di, not able to calculate with empty/dry pipes and therefore it adds an initial volume to empty pipes in order to maintain steady calculations. For the same reason the end volume also differs.

In general, 3Di has higher inflow values. For the rain the difference might be found in the translation from the CDS to the API rain or less so in the difference of the discharge from the catchment and into the sewer system. For the stream, a small drop in the inflow at the very beginning of the stream is seen in the MIKE URBAN model (appendix A.8 - Channel_start). The reason for this has not been determined.

Comparing the discharge from the outlets to the stream, some differences are seen. Comparing the two total volumes, the difference might seem insignificant. This picture changes when looking at the specific outlet, as the difference appear up to 13-15% +/-.

Outlets into Kolding Å	3Di	MIKE	Difference	
Outlet JD00200 - Pipe 1	1.712	1.668	44	3%
Outlet JD00200 - Pipe 2	1.712	1.654	58	3%
Outlet JC00100	2.114	1.966	149	8%
Outlet JA00200	3.219	2.810	410	15%
Outlet SB001X - Pipe 1	2.002	2.297	-295	-13%
Outlet SB001X - Pipe 2	2.002	2.239	-237	-11%
Total	12.761	12.634	127	1%

Table 3 - Outlet from the CSO connected to the sewer system in chosen area of Seest. The raw data and hydrograph can be seen in appendix A.8. [Appendix A.8]

The difference is assumed to be related to the difference in coefficient, as well as some could be related to the definition of the basins. Furthermore, it is estimated that the difference could be reduced significant if the translation between the discharge coefficient was fully understood.

As an end note, the difference can also be seen in relation to the total outlet volume. In that case 3Di and MIKE URBAN has the same division between the sewer system and the stream of 7 and 93% respectively. Finally, the two models individually seem to have acceptable water balances.

4.3 Inlet from time series

A large contribution of water to the models comes from the time series from the full MIKE URBAN model. In order to qualify this input data, pipe X723200l1 has been examined. This is an inflow pipe to the main pipe carrying sewage from the northern area to Seest. The discharge time series for the pipe has been found in the full model and added to the most upstream node in both models.

The discharge in the full MIKE model versus the reduced MIKE URBAN and 3Di model does not look alike. This can be caused by backflows in the system which will interact with the discharge of the chosen pipe even though it is an upstream pipe. When the system is interacting both back and forth, it is hard to create the same circumstances in both models. This can be the reason why the discharges don't look similar when looking at the negative values. The differences in the discharge in the full MIKE URBAN model and the reduced MIKE URBAN and 3Di model is illustrated on the graph below.

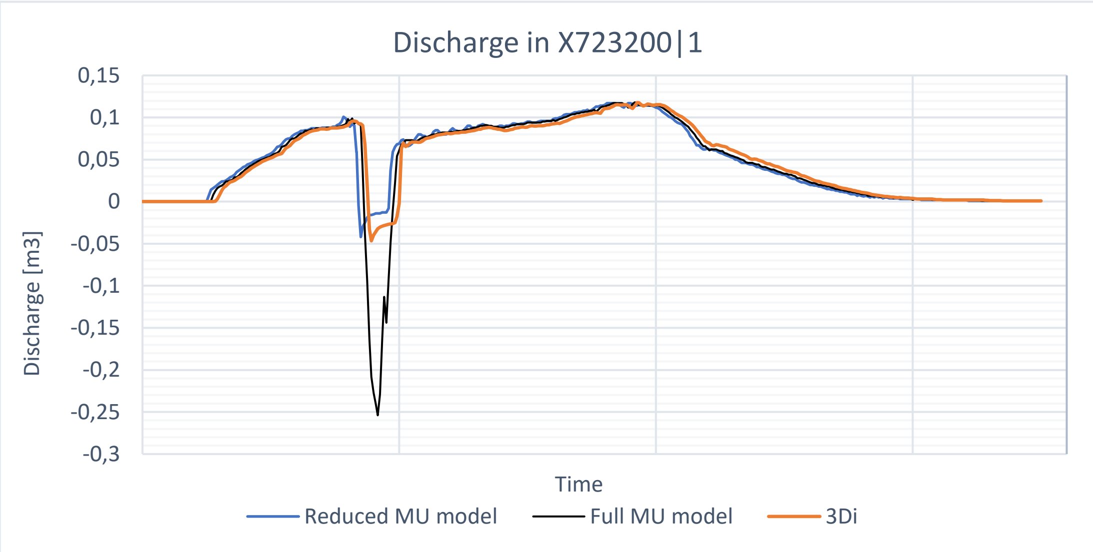

Figure 18 - Discharge graph of the pipe X723200|1 from the time 12:00 to 19:00 where the discharge goes to ~0. The only difference seen on the graph is the negative discharge in the full MIKE URBAN model which is sizable bigger than in the other models

Figure 18 shows, that the discharge in the upstream pipe X723200|1, where head losses, catchment areas, rain and like have had minimum influence, that 3Di and MIKE URBAN gets very similar results. The discharge is a bit delayed in the 3Di model compared to MIKE URBAN, but otherwise they look almost identical. This demonstrates that both programs handle and adds discharge values the same way or at least uses the data in the model a way that gives very similar results.

A realisation made in the end of the process was that there might be an important difference between defining input as laterals or boundary conditions in 3Di. According to the team behind 3Di, boundaries will beside volume also include momentum in the computation. A comparison of this hasn't been made but will be an obvious area for further studies.

4.4 Rain and catchment

The inlet from the time series is one source of water to the model, the rain is the other. In both models the rain falls on the catchment and the discharge to the sewer system is based on initial loss, hydrological reduction factor, imperviousness percentage and the definition of concentration time/outflow delay. A group of catchments placed in the upper end of the system has been chosen for comparison. Their positions in the system were chosen in order to reduce any interference with the discharge from other catchments, e.g. by backflow.

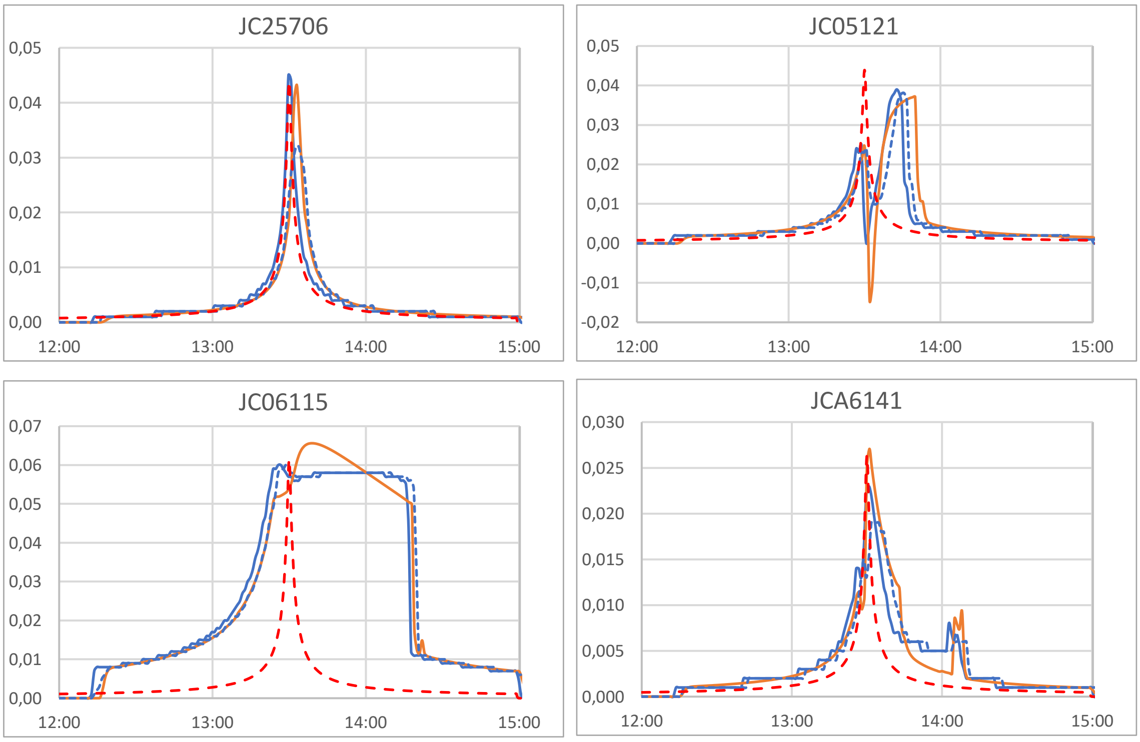

Figure 19 - Comparison of discharge from catchments in m3/s. 3Di is shown by the orange line and MIKE URBAN by the blue with concentration time of 0 and 7 minutes in solid and dashed respectively. The red dashed line shows the rain event, note that it is not in scale with the discharge. Accumulated values are shown in table below.

Catchment	Volume 3Di	Volume MIKE, 0 min	Deviation
JC05121	64	57	-13 %
JC06115	281	280	0 %
JCA6141	39	39	2 %
JD25706	41	40	2 %

Table 4 - Accumulated volumes of the discharge from the listed catchment. The data has been derived by the 3Di add-on in QGIS and MIKE View.

Figure 19 indicates that 3Di has no delay from the catchments, which was the expected result according to the set-up described in chapter 3.5. Comparing the results from MIKE URBAN, a concentration time of 0 min is quite similar to the 3Di. However, the default value in MIKE is 7 min, illustrated by the dashed blue line in figure 19. Using that default values outflows from the catchments are smoothened. This results in general lower peak values, which doesn't apply the same stress to the system as the undelayed outflow. Therefore, an active choice of the outflow delay coefficient is needed to be made in 3Di, just as it should be the case for the concentration time in MIKE.

4.5 LENGTH PROFILE FROM SEWER

A length profile from node JD23400 to JD20600 has been extracted from both models. The profile represents a steep part of the sewer system, average slope of 41 ‰, which theoretical should provide higher velocities and hereby higher head losses. The velocities for the length profiles range between 2,9-3,2 m/s in the upper part and 1,8-2,2 m/s in the lower part for the results from 3Di. In MIKE URBAN the velocities are more spread out, with velocities of 3,8-4,3 m/s in the upper and 1,2-1,8 m/s in the lower part.

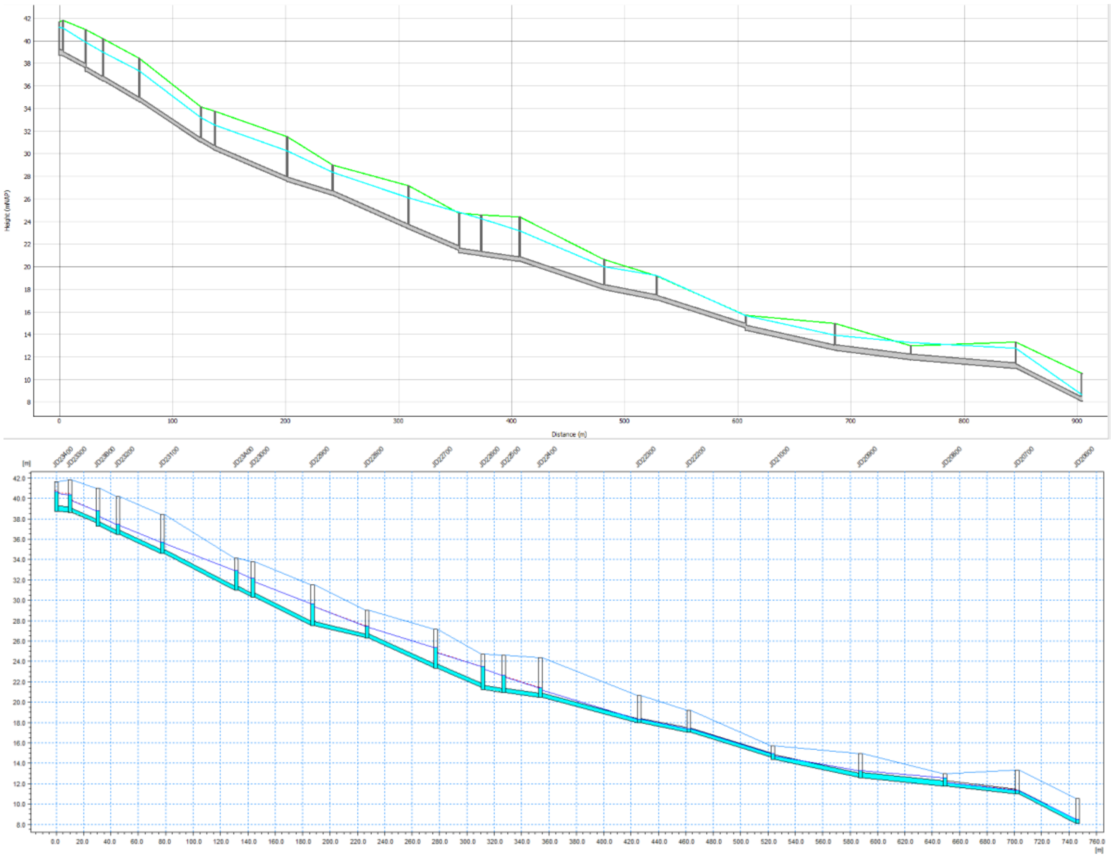

Figure 20 - Length profiles of the sewer section from node JD23400 to JD20600. Average slope is 41 ‰. Water level is indicated by a blue line/fill at the peak, which occurs at 1:45 (timestep 105) and 1:39 (13:39 o'clock) after the simulation was initiated for 3Di and MIKE URBAN respectively. Note that at the time the length profile was extracted, a bug with the map projection was present in QGIS which miscalculated the length. The result should not have been affected by this. Larger length profiles can be found in appendix A.9. Hydrographs for the top pipe can be found in appendix A.8. [Screenshots from QGIS and MIKE View]

Dimensions, roughness and geometry (slope and placement) are identical in the two models, which mean that difference must be found in the calculation-method and/or inflow to the model. As described in the chapter about rain and catchments, the discharge from the catchments in 3Di appears more rapid and with equal or greater peaks than seen in MIKE URBAN (when using default concentration time of 7 minutes). According to this the peak loads (flow and velocity) could also be expected to be higher in the 3Di model. When this is not the case, the difference most likely lies in the calculation or the numerical settings.

4.6 Simulation time

The simulation time for MIKE URBAN has in total been between 2 and 3 minutes for both the runoff and network simulation. The simulations in 3Di took in comparison between 20 and 30 minutes for the same simulation.

This difference can seem quite large, but there are some parameters that should be taken into consideration. One is the hardware power, where MIKE URBAN relies on the local computational power is the calculations in 3Di performed at 3Di's servers. The picture might therefor change as the complexity of the model goes up.

The other and perhaps more significant difference is that MIKE URBAN by default doesn't calculate pipe lengths shorter than 10 meters, whereas 3Di reduces the timestep instead. 18 % of the pipes in the simulated model is under 10 meters (107 of 585) and with 0,5 meter as the shortest and an average of 6,29 meter. According to the *timestep_reduction* file (appendix B.1) generated with the 3Di results, the lowest timestep used during the simulation was 0,83 seconds.

4.7 General note on the results

During the process of analysing the results of the two models it became clear that the difference in the computational core is of such significance that further analysis was needed. The documentation of 3Di (3Di/Nelen & Schuurmans, 2019) answers some of the questions, but not all. In order to clarify parts of this, the team behind 3Di was consulted.

The outcome of the meeting brought light to the questions at hand, but at the same time new questions occurred. The new questions were:

- What difference does it make between the models, that MIKE URBAN uses the "Preissmann slot" (DHI, 2016), while 3Di doesn't?
- What influence does it have that MIKE URBAN assumes a length of 10 m for short pipes, while 3Di reduces the timesteps? That is for both the water levels and discharges.
- How big is the difference on using laterals compared to boundary condition for additional inlets in 3Di?

Due to the scope and extent of this project, these questions are not answered in the report, but they could be subject for further studies.

Overall it is our judgement that the differences described in this chapter to a wide extend can be explained by the different definitions in the computational engine of the two programs. In order to have a better comparison between the two models they must, beside having the same input data, be calibrated to the same scenario. This emphasises the need of calibrating the model, in general, to fit actual conditions.

5. DISCUSSION AND FUTURE PERSPECTIVES

When discussing 3Di in a Danish context and its possibilities on the Danish market three questions have been found to be questioned throughout this project:

1) What has an impact on the choice of modelling tool?
2) Who is going to work with the model?
3) What does the future perspectives look like?

5.1 WHAT HAS AN IMPACT ON THE CHOICE OF MODELLING TOOL?

When looking at the reasons behind choosing a model, it is important to look at who the decisionmaker is. In Denmark, practise has often been that the costumer, e.g. the municipality, asks for a report on a certain issue and then the consulting company choose how the problem should be looked at and which program should be used. A report is made in the end accounting for which program has been used and how it has been used. Results will be pinpointed and explained for the reader in the report and (if part of the assignment) recommendations based on the results will be listed in a written language together with e.g. maps, figures and graphs.

What can be seen from the projects in Lemvig and Hedensted is that the costumer, in these cases municipalities, are getting more specific about what kind of model they want. For Lemvig Municipality's project applied that they wanted a model that was dynamic, visual and easy to make updates in – something they did not feel they were getting with the MIKE-solution they were offered. Instead they looked around for alternatives which were found in 3Di from Nelen & Schuurmans.

When looking at the visual aspect of the two programs, 3Di is numerous steps ahead of what DHI's products can offer when looking at appealing to people without previous skills. The visual part of 3Di that shows how the water will flow and accumulate with time in a depression creating flooding is illustrated very visually making it understandable, not to forget relatable, for most people. When looking at e.g. MIKE URBAN a normal way of delivering a visual product could be by making a map with red, yellow and green dots, illustrating which nodes will experience flooding at some point during the specific rain. It doesn't say anything about when it will flood during the rain, if it is flooding at the same time as the surrounding nodes or what the source of the flooding is.

In 3Di it is possible to see where the flooding is coming from and by that try to prevent it by pausing the simulation, adding suggested solutions to the model, and continuing the simulation afterwards. The possible changes and the process of making these changes on the 3Di Live site is close to what is known from SCALGO. This means that the user face in 3Di Live, when already having a full running model, is much more applicable for smaller changes than e.g. MIKE URBAN. This leads to the next question.

5.2 WHO IS GOING TO WORK WITH THE MODEL?

And who *should* work with the model? MIKE URBAN is complex modelling program that is made to be able to calculate on "*everything"*. By everything is meant that the program wants to offer the user the option to be able to customize the model and its components down to very small details and numbers. By giving the user a lot of options to modify, the program can seem complex with its many tabs, buttons, and not to forget a comprehensive definition in the formulas behind it. Therefore, most often people who has an educational background in hydraulic, and likely has been taught MIKE URBAN, will be the ones using the program. This is based on their knowledge about which elements that needs to be defined and what the different settings do to the model and how it relates to the results coming out.

For a costumer who receives a MIKE URBAN model without any background-knowledge, it can be very difficult to understand the data and make changes to the model. In that case the consulting company making the model is responsible for the parameters used, the results and the recommendation based on those. If the municipality wants to make changes to the model, they will have to send it out to a consulting company again, no matter if it is big or small changes. This makes the municipality very dependent on the consulting engineers in this example.

The normal procedure for setting up a 3Di model, is that Nelen & Schuurmans are paid to create the model. This has been the case for both Hedensted and Lemvig. Data of the sewer system is sent to Nelen & Schuurmans and all parts are translated into numbers and tables that 3Di understand. The costumer then receives a model back, but more important a login to the 3Di Live site. From this webpage it is possible to work with the model without working *in* the "*model behind*". The "*model behind*" consist of data like imperviousness, characteristics and dimensions of the system and other specified parameters like know from e.g. a MIKE URBAN model. On 3Di Live site it is not possible to make changes to the background data. Instead pipe and channel sections can be closed and opened, the DEM (2D model) can be edited and wind and rain can be added.

The difference between the actual model and the result processing in 3Di and MIKE can be illustrated like shown on the figure below.

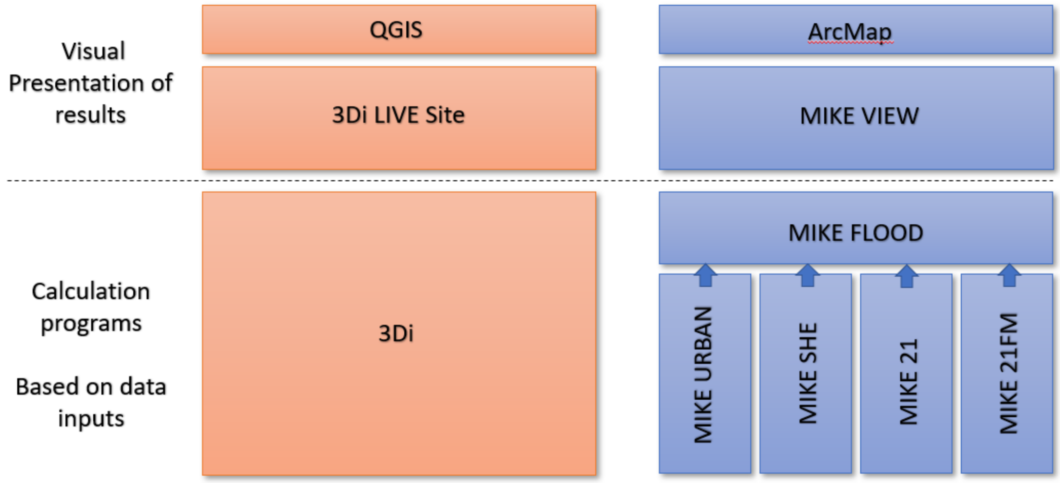

Figure 21 - On the figure to the left is shown an example of the programs needed in a 3Di solution while on the right is show a MIKE solution. The example is inspired by the project in Thyborøn for Lemvig Municipality.

When looking at postprocessing the results, DHI and Nelen & Schuurmans are offering very different outcomes. Like mentioned above, the 3Di Live site is made for the costumer to "play" with the results. For Mike View goes that it is most often only used by the same people who made the models. A visual part for the costumer is therefore not represented in the MIKE packet, which is where 3Di really seems to connect with its audience. Both programs have a GIS-program where results can be processed. An additional license to 3Di Lizard can also be used when postprocessing the results.

Underneath the dotted line in Figure 21 is the calculation programs that the results in the postprocessing are based on. These data are based on known data like dimensions of pipes, nodes and like, while other data might be a (hopefully) qualified assumption made by a person with hydraulics and hydrological knowledge. This could be the hydrological reduction factor, the scaling factor or imperviousness for an area. To be able to mingle around in all these different data and parameters, you have to know something about how they affect the results. MIKE is built on technical terminologies and to be able to use the program you need to know these as well. Because 3Di uses QGIS for setting up a model, tables define everything and changes to these can seem easier to some than in MIKE. When changing the data behind the model, one has to know that this can interfere with the validation of the model. The validation of the model is very important when actual recommendations and real-life decision are made based on the outcoming results.

When talking to the two municipalities, Lemvig and Hedensted, both showed an interest in being able to make changes to the actual model and not only the changes possible on the Live site. This makes sense regarding being less depended on e.g. consulting engineers, but it is important to be aware of what the model is going to be used for.

In Denmark the service level is a requirement that the utility company has to live up to since they are in charge of the operation of the sewer system while the municipality is in charge of planning how the sewage should be handled (Realdania, 2019). If the municipality wants to make changes to the model it could therefore make sense to partner-up with the utility company who often has engineers hired with knowledge about hydraulic models and therefore knows how changing the data will interfere with the results.

Since the utility company also are the ones who has to live up to the requirements, it makes sense that they are part of the modelling. Otherwise you might end up with two different models, one at the municipality and another model at the utility company. This can cause misunderstandings and collaboration issues between the two if the models show different results. This doesn't mean that the municipality and utility company can't have different models, because they use them for different things (planning and operation), but attention should be kept to the problems it can cause. This especially counts when working on areas that cross over each other's responsibilities/assignments.

A huge advantage when modelling in 3Di is the interaction between the sewer network, groundwater and streams and the DEM (2D) based option. In MIKE the models would not be coupled unless a MIKE FLOOD would be made from e.g. a MIKE URBAN and MIKE 21. If changes need to be made to the sewer system, a new MIKE URBAN needs to be made and coupled to the MIKE FLOOD. The interaction between the different components (streams, groundwater, surface run-off and so) seems therefore more complicated and not as smooth as seen in 3Di. It can be discussed how fair it is to compare the two programs on the interaction between the different components since MIKEs focus is on delivering different programs with great detail and which is specialized for a smaller specific project. The reason why the interaction still has been chosen to be mention is that there seems to be an increasing interest for it from the decisionmakers.

At the EVA Theme day 9th of May 2019, one of the presentations were "*Model consideration*" presented by Jonas Wied Pedersen and Nadia Lund from DTU (Lund & Pedersen, 2019). An important point from their presentation was the term *a good indicator*. A problem when modelling is often that the question asked is not the question answered, either because the question is misunderstood or because the data is not sufficient to answer the question. When having *a good indicator,* the chances for misunderstandings between the involved parties are reduced. Another gain from *a good indicator* is that it can help choosing the right modelling tool.

The importance of a good indicator can be seen in relation to the project in Thyborøn mentioned earlier. Lemvig Municipality had made a public invitation to tender where different consulting companies pitched ideas on how to approach the issue. Lemvig Municipality chose one of the companies and their MIKE solution, but later decided not to follow through with it because the actual product did not fit their expectations to the model and what they wanted to use it for.

This leads to the third question about what can be expected to be requested of the models by the costumer in the future?

5.3 WHAT DOES THE FUTURE PERSPECTIVES LOOK LIKE?

In an article authored by a hydraulic specialist from a Danish consulting company "*Modeller bliver lettere tilgængelige*" (Larsen, 2018), one of the highlighted issues with the models used today is the municipalities experiences. The municipalities pays a lot of money for models they can't use for anything else than the specific project. It is too expensive for them to have manpower and licenses to the programs to maintain them for later use and specialist knowledge is a requirement for using them.

When talking to Hedensted and Lemvig Municipality, one of the things they appreciate about 3Di is that they are able to try out their own scenarios on the model. The model can suddenly be used for different projects and different scenarios as long as it is within the geographical limits of the model built. This gives a great added value for the costumer which is not yet seen in DHI's products. So, for the visual part 3Di definitely have their hands on something very interesting, which the costumers have started to request. The customers want more "power" over the models they pay for and they want to be able to take use of them. This tendency is also seen to other products in the marked, among here also DHI who recently release their plans for going online with their *Cloud Bridge* (DHI, 2018).

Being a newer program also has its downsides. The documentation behind 3Di is still in development. The documentation on their webpage is in some area a bit scanty or not there at all. This counts for e.g. head losses in the nodes in the model. 3Di don't have a documentation page about how the program calculates these, even though it does take it into consideration when calculating. This can be an issue when trying to convince the specialist who on a daily basis builds models in programs like MIKE. For MIKE goes that they have been on the market for more than 25 years and have established great recognition and trust in their calculations amongst people within hydraulics. If in doubt about anything you can always click f1 which will bring you to MIKEs comprehensive documentation.

With technology changing new possibilities arrives. Like seen with 3Di and Danish SCALGO, the technology with the DEM has gotten much more precise and the grits sizes have gone down to a size where it can be used for modelling. The DEM is starting to find its ways into models when looking at surface water and this year SCALGO also implemented a stream-module to their model. This indicates a new way of modelling because real-life-data are accessible and in such a quality that it makes sense to use them in our models. With more data, the models also get heavier to calculate, but by doing like 3Di using a cloud system, modelling is no longer limited by the power on the user's computer. Instead it is sent out to a server with much higher power, which allows much more data to be processed.

So, trying to answer the question asked in the beginning, some of the things that can be seen in the near future is among other, program/software moves into cloud-based solutions. DHI have been out earlier this year to vent their plans with CloudBridge which is their version of what a server system will look like. This will, just like 3Di, make it possible for more people to access the model from different computers and without the program needed to be installed on either.

SCALGO have had great results in Denmark by basing their program on the DEM and are now slowly expanding their functions, e.g. a stream-module which have been added recently. SCALGO has managed to keep their simple user face through their development making it possible for most people to use their program. The simplicity in making changes and see how it affects the model is also one of the things which seems to be one of the key points for costumers like Lemvig and Hedensted Municipality. Making programs more user-friendly, both when creating the models but also for postprocessing seems to be something that is requested from the market, giving the models more value to the whole chain it goes through – from hydraulic specialist, to the costumer and citizens.

6. CONCLUSION

3Di brings something new to the water-modelling world we have in Denmark today. DHI's products have not experienced lots of competition on the Danish market, but it might change with a new player on the market like 3Di that comes with multiple new aspects on how a model should be. Instead of having multiple programs with different licences, 3Di has collected all the components in one model where licenses work as *license as a service* (LaaS). Instead of having to shift around in different models which can be coupled in the end, 3Di delivers one model with all components present at once. This means that they can simulate the interaction between e.g. a node flooding causing water to run on the surface to a new location causing flooding there, within the same model.

The setup of the model in 3Di is, to a great extend bases on the general principle, in relation to structure of the database. The main difference when comparing to MIKE URBAN is the lack of user interface and drop-down menus know from MIKE URBAN. This make the initial use of the program less intuitive, until the user has gotten familiar with the layout in QGIS. For the user with flair and skills within SQL and python the layout in QGIS might even be preferred.

Comparing results from a 1D simulation in 3Di and MIKE URBAN, both similarities and differences can be found. Some of the differences is assumed to be based on the different computational core of the programs, while others are based on the different definition of coefficients and geometry. Further studies with focus on these parameters could be conducted in order to clarify these points.

Though the programs will be able to calculate the same things, practise in Denmark and the Netherlands, is not the same. Neither are the standards, and a foreign model as 3Di is therefore not calibrated for Danish requirements. A Danish consulting company would be able to build a model in 3Di, but because of the insufficient documentation, it can be hard to verify for the company. This might be a hurdle for some consulting companies in Denmark from using the program, which will refrain them for using the new program and its possibilities. Nevertheless, having worked with it and seen the possibilities of defining setting in both MIKE URBAN and 3Di, is it our judgement that the use of 3Di, when calibrated, is equate to MIKE URBAN.

In Denmark the practice is often that a model is made by a consulting company. The strategy of 3Di propose that a model is built by the developer. This way the *consulting-company-step* we know in Denmark is skipped and the service becomes directly between the developer and the costumer. In Hedensted the municipality used the Danish consulting company NIRAS to verify and explain their 3Di model. This example could be a suitable solution for the transition into a new organisation.

Based on interviews with the municipalities of Lemvig and Hedensted it seems like the end-user of the model really like what 3Di is offering. For them it is a huge change to get a model that they can actual interact with and use for multiple purposes. Its visual aspect makes it possible to show at public meetings and meetings inside the organisation. The model allows changes to be made, meaning that organisations like municipalities can try out many different solutions and ideas before putting an assignment out for tender. These possibilities have Hedensted Municipality made use of at public meetings to engage the citizens and have had good experiences with this.

The new possibilities with the models have definitely lit a spark at the municipalities in Lemvig and Hedensted. Based on the experiences made throughout the work, interview and presentation conducted in this project, it is assumed that the enthusiasm for 3Di can spread to other municipalities, once they get to know more about the advantages in a 3Di model. 3Di's way of appealing to the costumer is very interesting and they seem to have success with it. More *value for money* is often a subject for conversation in Danish companies and in the public sector. Being able to reuse the same model for different purposes and projects can definitely create more value for money.

If 3Di can find their spot on the Danish market between costumers who has started asking more from the models and the consulting companies who often are in charge of the modelling, then more projects made with 3Di will be expected to be a reality in Denmark. The Danish practise of municipalities and utility companies using consulting companies to create and verify the models has become such a custom that 3Di has to convince the consulting companies of their product, before some of the costumers will follow. This could be overcome by developing the documentation and the user interface. In other words, the team behind 3Di need to determine what adds value to the consulting companies, the same way as they already have done it for the end costumers.

7. Memorandum on field work

7.1 Lemvig Municipality

20th of February, Pieter Mogree and Lis Ravn Sørensen, Lemvig Municipality

Lemvig Municipality is participating in the climate adaption project *Coast2Coast Climate Challenge* (C2C CC)which is led by Region Midtjylland and financially supported by the European Union's LIFE-program. The project is made for the city Thyborøn, which is in the northern part of west-Jutland. The city is positioned out to Limfjorden and is very flat, putting it in risk of flooding from most sides. Besides that, the ground is also sinking around 1 cm per year (Region Midtjylland, 2019).

On the 20th of February we had arranged a meeting with Pieter Mogree and Lis Ravn Sørensen from Lemvig Municipality to get to know more about the program 3Di, how they have used/uses it in Thyborøn and why they chose to go with something else than DHI programs.

Before getting an introduction to 3Di and the model of Thyborøn, Pieter talked about why they had chosen to go with 3Di for this project. Lemvig Municipality was looking for a solution where they could make easy changes, a dynamic model, and a visual model where they could use it when interacting with the citizens. They were offered different solutions by consulting companies and the project they went with first was a *classic* DHI solution. To make the model with all the components they needed they had to get a MIKE SHE, MIKE URBAN, MIKE FLOOD and MIKE 21 model. All four MIKE programs were needed if they wanted to get a model of both the groundwater, the sewer system, surface run-off and coast and seawater. If a change had to be made in e.g. the sewer system, a new simulation of all four parts had to be ran. This was not what they were looking for. Instead they chose to look for another solution with greater interaction between the different components. They found that in 3Di.

We were then introduced to the program QGIS and how the different elements were defined, 1D or 2D. Afterwards we were shown how to make changes on the Live site and how a simulation on the Live site works.

Lemvig Municipality use the Live site when talking to the citizens. For them the visual part of the program is a huge plus together with the ability to make changes to the model. They have had the people behind 3Di to build the model and they have afterwards made changes to it themselves. For Lemvig Municipality one of the biggest advantages about 3Di is the visual part of the program and that they can make changes to the model themselves. Pieter, who is the man in charge of the model, does not have an education within hydraulic but is able to make changes and add components in the model. The municipality therefore don't need to ask (or pay) a consulting company to make these changes for them.

7.2 3DI TRAINING PROGRAM

11th - 15th of Marts, Nelen & Schuurmans, Utrecht, the Netherlands

In corporation with COWI, we got the opportunity to participate in the 3-day 3Di training program, held by Nelen & Schuurmans in Utrecht, the Netherlands. The training program is an offer for both private and public companies that wants to know more about the theory behind the program and how to build and use a 3Di model. The goal with the course was to prepare us to build our own 3Di model as a part of our bachelor project.

On top of the training program we were offered to have an additional 2 days with one of their employees to be our buddy. His job would be to help us build the model after the course as well as supplying technical help when working on the model at home.

The training program was informative regarding the technical parts behind the program while the two extra days with "special help" from our buddy, Bram, really helped us with building the model. We had the data on the sewer system as a mdb-file, which needed to be imported to QGIS and the right tables. This was not part of the training program and the help was therefore essential for us to be able to make the model.

In the following time of the project, several e-mails have been exchanged plus a couple of Skype calls in the process of making the 3Di model. This process has been extremely positive and constructive, as well as the support has been fast and service minded.

7.3 HEDENSTED MUNICIPALITY

8th of May Per Nørmark and Lene Nielsen, Hedensted Municipality

Like the project in Lemvig, the two projects in Hedensted is also part of the climate adaption project *Coast2Coast Climate Challenge.* On the 8th of May we went to meet with Lene Nielsen and Per Nørmark from Hedensted Municipality. The questions prepared for the meeting can be found in appendix A.10.

Both Lene and Per had visited Nelen & Schuurmans as part of an excursion to the Netherlands with C2C where they were introduced to 3Di. For Hedensted Municipality the main reason for their choice of 3Di was the visual aspect of the program they had seen in the Netherlands. The program allows people without a degree in hydraulics to get an understanding of the issues and how climate adaption can help reduce the problems that would otherwise occur. The main purpose of the model is to use it with citizens, politicians and other people involved in the projects (NIRAS, 2018).

To verify the model Hedensted Municipality have hired NIRAS as their consulting engineers to look through the model, the data used in it and to make changes to the model. The municipality does not have anyone hired with a degree in hydrology, which is the reason why they have had NIRAS hired. Later in the process they had one of their own employees participating in the 3Di course training program, so they are able to make some of the changes themselves. At the moment they use the model at public meetings with the citizens and can see it used in meetings with the city's politicians as well. At the public meetings they point out different issues for the relevant citizens and let the citizens come with remarks regarding if the issues appearing on the model, also occurs in reality. The municipality use these data to calibrate the model. If the model fits reality, they talk to the citizens about suggested solutions which they can later try to implement to the model. It is implemented later to be able to do some quality assurance before showing it publicly.

Hedensted Municipality's impression of how the citizens react to the model, is that they find it very visual and therefor much easier to relate to the relevant issues, compare the model to reality and help finding solutions to the problems. By including the citizens this early in the process and doing it in a way where a common person can understand what is going on means that they see a much higher level of engagement and a sense of ownership in the project from the citizens. This makes the whole process much easier for the municipality, because misunderstandings and anxiety towards the project are swept aside, creating a much more positive atmosphere around the suggested initiatives.

7.4 EVA THEME DAY

9th of May, EVA Temadag, Odense

EVA, *Erfaringsudveksling i VAndmiljøteknikken*, is a part of the Water Pollution Committee of The Society of Danish Engineers, with the goal of exchanging experiences between its members, offer technical training and influence the development of the work within the sector of water environment. Three times a year they arrange a theme day, each treating a relevant theme.

As part of receiving the grant from *EVA-Studierejselegat* it is good custom that the donee make a presentation at a EVA theme day, presenting what the grant has been used for. For us it meant that we would do a presentation about 3Di together with Pieter Mogree from Lemvig Municipality and Bo Klinkvort Kempel from EnviDan. The theme of the day was "Which model, when?" which was very relevant for our project. The presentation was a joined presentation between all of us and we therefor had multiple Skype meetings leading up to the presentation. Pieter was going to talk about 3Di and why they chose to use it in Thyborøn, we were talking about our bachelor project and the differences we saw between MIKE an 3Di, while Bo talked about his perception about what he thinks modelling tools are going to be like in the future and what we as users and costumers want from them. The PowerPoint is attached as appendix A.11.

7.5 Overall outcome

Besides giving a lot of great inputs to the work with this bachelor project, the contact with the above-mentioned people and organizations, have given us a great and unique insight in the work with hydraulic models. The insight covers both the technical aspect as well as an understanding of how the models/results is received at the customer and vice versa, e.g. what parameters the customers attach significance to when they have to choose a model.

Having had the visit at Nelen & Schuurmans in the Netherland, have allowed us to expand our focus outside the boarders of Denmark when looking for solutions to and experience on how to solve future challenges. Having written the report and have conducted a lot of the communication in English, has prepared us for working with greater confidence in an international environment.

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9. List of Appendices

All appendices are handed in electronically in one folder.

No.	Name	Filetype
A.1	Model description, 3Di	.pdf
A.2	Model description, MIKE URBAN	.pdf
A.3	Overview maps	.pdf
A.4	Catchment outflow	.xlsx
A.5	Extract from COWI Report	.pdf
A.6	Cross section trapezium	.xlsx
A.7	Inlet values	.xlsx
A.8	Results comparison	.xlsx
A.9	Length profiles	.pdf
A.10	Questions for Hedensted Municipality	.pdf
A.11	Presentation for EVA Theme day	.pdf
A.12	Catchment outlet, revised	.xlsx

B.1	3Di Model and results	folder
B.2	Reduced MIKE URBAN and results	folder
B.3	Full MIKE URBAN and results	folder
B.4	MIKE URBAN miscellaneous	folder
B.5	MIKE HYDRO	folder

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