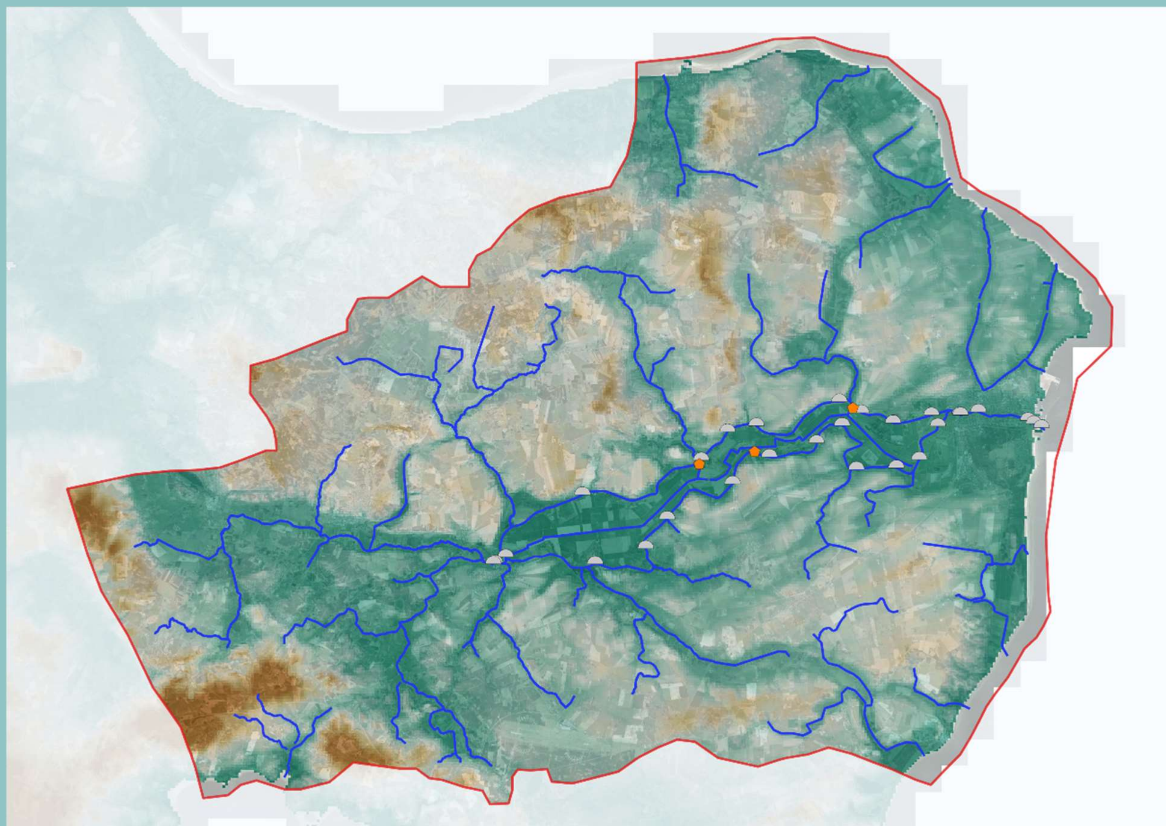

3Di model Grenaa

Modelling principles and assumptions

Syddjurs and Norddjurs Municipality

10-5-2021

3Di model Grenaa

Modelling principles and assumptions

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Projectgegevens

Dossier	:	W0026
Datum	:	10-5-2021

1 Introduction

The Grenaa catchment is situated In the Eastern part of the Danish mainland (Region Midtjylland) (Figure 1). The catchment has an area of about 745 km^2 and is situated in the municipalities of Norddjurs and Syddjurs. In the village of Grenaa the river enters the sea (Kattegat).

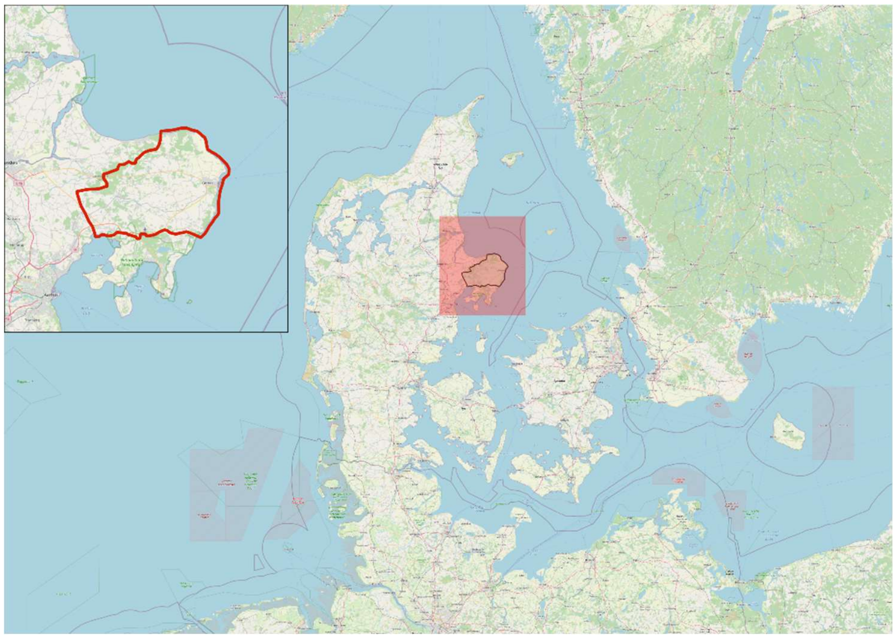

Figure 1 Location of the catchment within Denmark.

In the middle of the catchment a polder is located. The polder lies below sea level and is prone to flooding. Flooding can also occur at other places along the rivers. Flooding will occur with extreme rainfall and/or high sea levels.

The Geological Survey of Denmark and Greenland (GEUS) has made a hydrological model using the Mike FLOOD model software. The model consists of surface water, terrain and groundwater. GEUS has problems with extracting the water level/water depths images out of the model. It is hard to tell which areas exactly are vulnerable to flooding, where flooding starts and how flood scenarios develop over time.

GEUS has asked Nelen & Schuurmans to convert the Mike model into a 3Di-model. GEUS will run the 3Di-model itself with the assistance of Nelen & Schuurmans. We also suggest the involvement of Norddjurs and Syddjurs Kommune project leaders in the 3Di development and testing. With the 3Di model developed and combined with running “scenario” simulations via the live site will offer long-term value for any future projects in this area where a flood risk assessment is needed.

Most of the data for the model has been sent from GEUS related to the surface water system and terrain including the digital elevation model, impervious surfaces and parts of the Mike model. This document describes which data will be used, how it will used in the model and what assumptions will be made. A summary of the datasets available and received are provided at the end of the document.

This document describes the components of the model and the assumptions that will be made based on the data available and the agreements reached with GEUS and the municipalities. The document consists of 5 chapters. The first chapter is the Introduction. The second chapter will elaborate on how the model is built-up and the model components used. The third chapter includes a detailed elaboration on the terrain model discussing the grid, the rasters, obstacles and boundary conditions. Streams and surface water are discussed in chapter 4. Finally, an overview of the received data is given in chapter 5.

Modelling principles and assumptions

Table of contents

2 Model components

3Di is a process-based, fully-distributed hydrodynamic model. Since it is a fully distributed model, spatial data is used intensively in different components of the model. The 3Di model for Grenaa consists of a 2-dimensional component in which the terrain is modelled which interacts with the a 1-dimensional component in which surface water is modelled.

The terrain model is built using a height model, land-use maps and soils maps, levees and water levels and discharges. Using the data mentioned above the following model components are constructed:

- Digital elevation model
- Friction raster
- Infiltration raster
- Levees (as obstacles)
- Boundary conditions

The surface water model is built using detailed information about the channels such as cross-sections, profiles and locations of channels. But also, locations and operational information of pumpstations and bridges. Using this data, these components will be constructed:

- Channels
- Pumpstations
- Orifices

Finally, external forcing can be added to model a specific scenario such as precipitation, lateral discharges and wind.

3 Terrain

The terrain is modeled in a 2-dimensional form (2D). Based on the grid cell size and grid refinement the calculation grid is constructed using the quad-tree method (see section 3.4 for details). The grid consists of calculation points and flow links between those calculation points. After the grid is constructed, 3di will store the relations with water level and cross-sectional areas and volumes from the terrain (infiltration, height, friction). For every water level different volumes and cross-sectional areas can be used in the calculation using this sub grid method. The obstacles which are added to the model will close flow links to ensure no flow. This will be the case for instance along the locations of the levees. Finally, during the calculations flow limiters are used to ensure proper cross-sectional areas even if the slope is very high.

3.1 Digital Elevation Model (DEM)

For the calculation of overland flow, a Digital Terrain Model (DHM/Terræn) is used which has been sent by GEUS. The digital terrain model (DTM) consists of data indicating the elevation of the terrain, ignoring trees, buildings, etcetera.

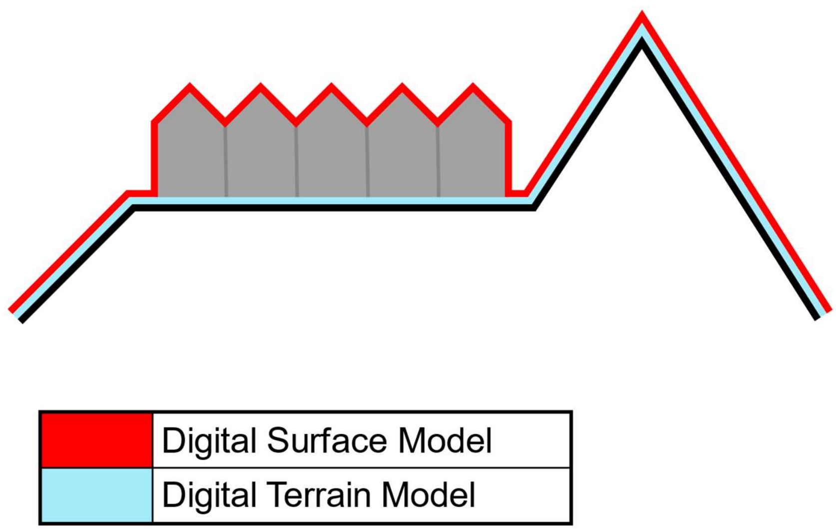

Figure 2 Differences between a DTM and DEM.

The raw data is an ASCII raster file with a resolution of 1.6 m. The raster will be cropped to the extent of the Mike model. Also, the raster will be made 3Di compatible by converting it to a GeoTIFF format, changing the data type (float32) and changing the no data value to -9999.

The DEM raster is the base raster of the 3Di model. All other rasters will have the same extent, resolution, data/no-data pixels and similar no data values, data type and format. The resolution that is applied on the 3Di model is 1.6 meter. In case higher resolution data is available for a smaller area, that can also be coupled to the 1D model (see section 3.8 for limitations related to the amount of data).

3.2 Infiltration

An important hydrological process is the surface infiltration. The maximum rate of infiltration (mm/day) is mainly determined by the soil type. In 3Di there are multiple forms of infiltration (figure 3):

- The full surface area option uses infiltration at all cells with data.
- In the wet surface area option, every cell infiltrate which is lower than water level.
- In the surface area depends on rain option, every cell infiltrate if rain is present at that particular cell.

For the model of Grenaa, the latter infiltration method is chosen, as it is closest to reality: “surface area” .

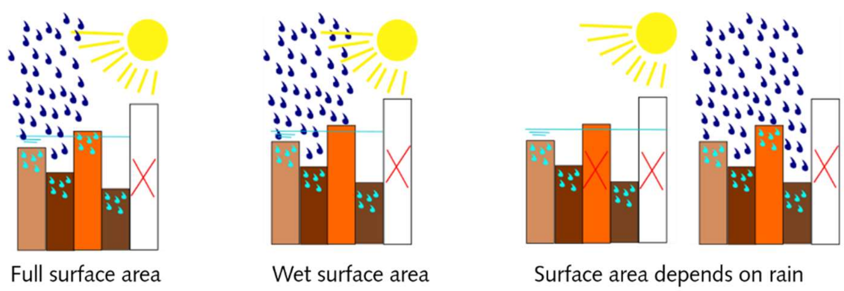

Figure 3 Different forms of infiltration. ‘Full surface area’ infiltrates in all cells, ‘Wet surface area ‘infiltrates in submerged cells, ‘Surface area depends on rains’ infiltrates in cells which have rain.

The infiltration raster is based on the soil map Danmarks Digitale Jordartskort (1:25.000) from De Nationale Geologiske Undersøgelser for Danmark og Grønland. This map describes 1 or 2 soil types in the topsoil. The JSYM1 data column of the map contains an abbreviation of the covering soil type, which is most important for the infiltration rate. The shapefile is rasterized to the same extent and resolution as the DEM, and given the following infiltration rate based on the abbreviation in the JSYM1 column (see table 1)

Pervious and impervious layers are also received from Scalgo. We will multiply the result of the converted infiltration raster with the pervious/impervious. Hence, we will have infiltration if the soil is pervious and no infiltration where the soil is impervious (including lakes).

Table 1 Soil infiltration conversion table

Abbreviation	Soil type	Maximum infiltration rate [mm/day]
BY	Town/impervious	120
DG	Meltwater gravel	480
DI	Meltwater silt	120
DL	Meltwater clay	120
DS	Meltwater sand	480
ES	Aeolian sand	480
FG	Fresh water gravel	480
FJ	FK -Tufa, bog-and lake marl	0
FL	Freshwater clay	120
FP	Freshwater gyttja	120
FS	Freshwater sand	480
FT	Freshwater peat	480
FV	Alternating thin freshwater beds	0
HAV	Sea	0
HG	Saltwater gravel	480
HL	Saltwater clay	120
HP	Saltwater gyttja	120
HS	Saltwater sand	480
HT	Saltwater peat	480
KML	Limey till, clayey	480
KMS	Limey till, sandy	480
KMG	Limey till, gravely	480
LRÅ	Abandoned pit	120
MG	Gravelly till	480
ML	Clayey till	480
MS	Sandy till	480
O	Rubbish dump	480
PL	Seladian clay	120
RÅ	Pit	120
S	Sandy till	480
SO	Freshwater	0
TG	Meltwater gravel	480

TL	Meltwater clay	120
TS	Meltwater sand	480
X	Bed unknown	0
ZK	Danian chalk / chalk and flint	0
ZL	Glaciolacustrine clay	120

3.3 Friction

A base friction raster is constructed using the pervious and impervious areas from Scalgo and the classifications presented in table 2 below. We will enhance the base friction raster with land-use data downloaded from GeoDenmark (classification used in table 3). The final raster is combined with the base friction raster. Different manning values are assumed for different land use and pervious/impervious classes.

Note that the pervious/impervious raster will only be changed if the classified land-use is available at that certain location. The land use map consists of multiple classes. For the model we will only use two as is shown in table 3.

Table 2 Pervious/impervious friction conversion table

Pervious/impervious	Manning's n-value s/m$^{1/3}$
Pervious	0.030
Impervious areas	0.130
Lake	0.026
Buildings/roof	0.058

Table 3 Enhancement to the friction conversion table

Enhancement with Land use (GeoDenmark)	Manning's n-value s/m$^{1/3}$
Forests (SKOV)	0.058
Water (SOE)	0.026

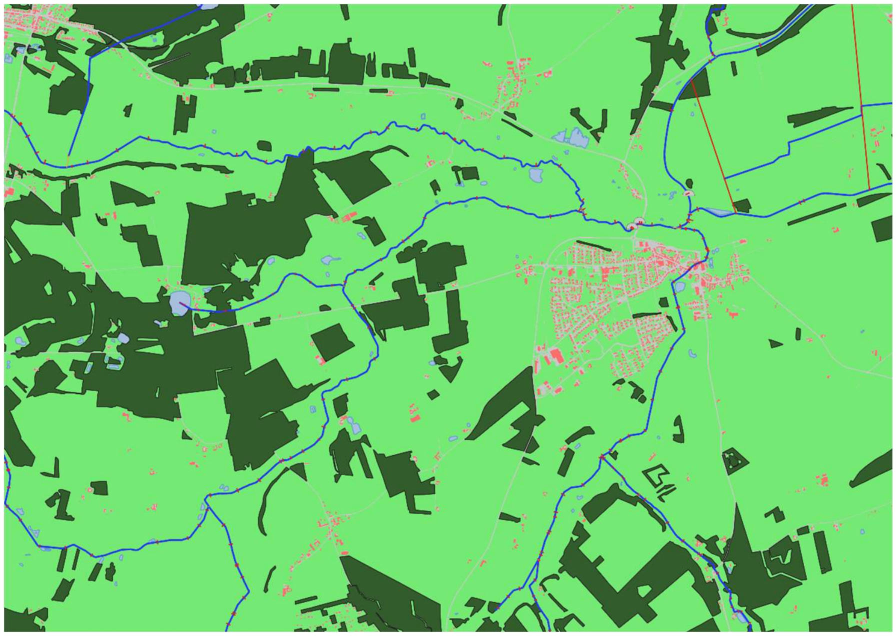

Figure 4 The pervious/impervious map enriched with data of Geo Denmark.

3.4 Calculation grid and grid refinement

One of the major advantages of 3Di is the elevation data can remain with a high resolution while the computational grid is larger (see Figure 5).

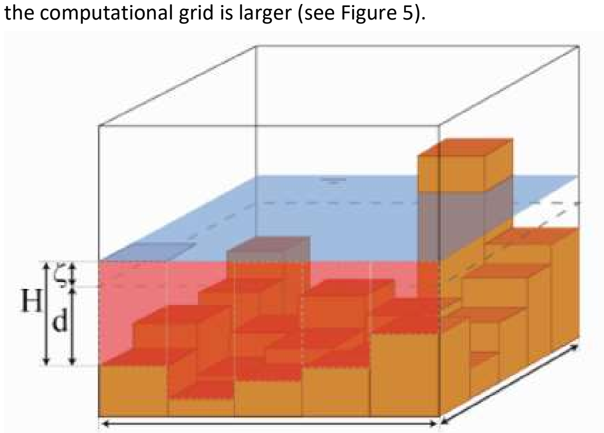

Figure 5 An example of a computational cell with a bathymetry defined on the subgrid

The 3Di calculation grid consists of calculation points and flow links. The grid can be locally refined using the quad-tree method (see figure 6). Choosing the size of the smallest and largest grid cells and where to add refinement to the grid depends on the size of the model, the desired accuracy and the desired speed of the model. The larger the grid size, the faster the model, but the lower the accuracy and vice versa. The grid size has to be a multiplication of the cell size of the rasters. The largest cells will be in the order of magnitude of 80 meter, this will be further finetuned in the finalization of the model. We suggest to apply a minimal grid size in the order of magnitude of 16 meters.

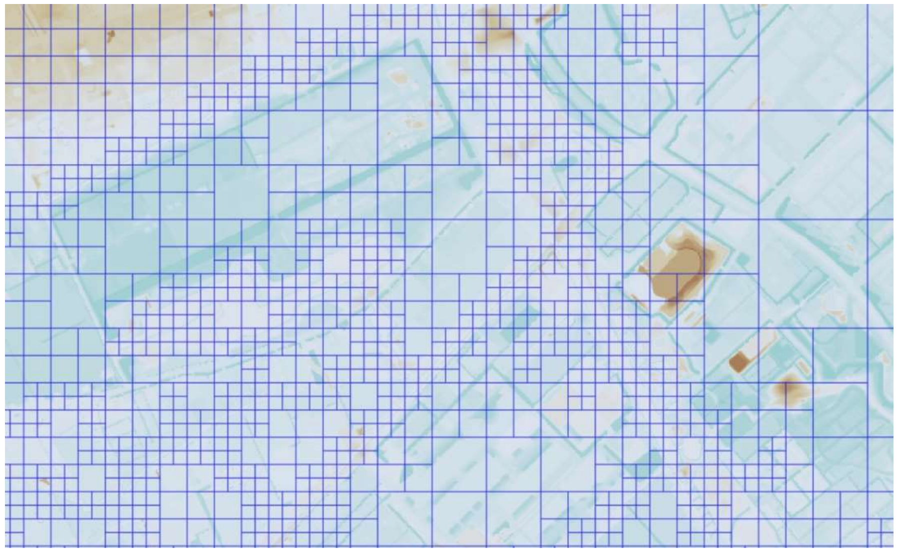

Figure 6 Example of the 3Di calculation grid using the quad-tree method.

Grid refinement is applied:

- Around streams to be as accurate as possible related to the inflow of surface water into the streams. Especially paying attention to sharp corners in the streams.
- In urban areas where a detailed calculation is needed to model the urban water flooding.
- Midterkanal, since this is an important flood-prone polder.
- When obstacles are missed during a test simulation. Then they are either added as obstacle or as grid refinement.
- Around levees to increase accuracy in the volume distribution around the levee.
- Grid cell size also have to be optimized to the calculation points in channels since they are embedded.

3.5 Sub grid

In every calculation cell, 3Di assumes an equal water level. When a new water level is introduced, the water level will be corrected using the sub grid. Depending on the water level it can be defined which bathymetry cells are wet and which are not. If the bathymetry cells are wet, 3Di will use these cells to calculate the water level based on infiltration, friction, volume and cross-sectional areas. This water level will be used in the next computational step. The figure below shows a computational cell with the same water level. Sub grid provides different friction, infiltration, volume and cross-sectional area even if it has the same water level as other models.

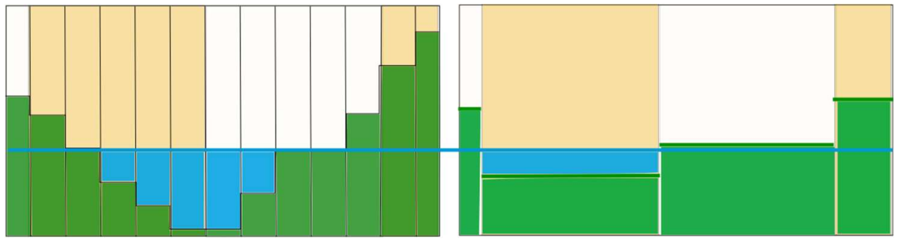

Figure 7 Computational cells with sub grid (left), without sub grid (right).

3.6 Slope limiters

3Di is able to handle water levels in hilly areas properly, using slope limiters which are able to vary per timestep and per slope steepness. Within 3Di the water level in calculation cells is assumed homogeneous. In steep areas however, water levels may vary within a calculation cell. The wet cross-sectional area at the downstream border of a steep cell, is larger than in reality. A large cross-sectional area results in less friction and thus more discharge from the cells when compared to a thin layer of water.

With limiters 3Di calculates the cross-sectional area of such a cell as follows (note the figure below). A “thin water layer definition” is defined (for example 10 cm). The thin water layer definition is always relative to the lowest pixel of the upstream calculation cell.

If the water level falls below the thin water layer definition in cell 26, a limiter will be activated. The limiter divides the water depth with the area of the calculation cell to provide an accurate cross-sectional area at the downstream border of the cell. If the water level rises above the thin water layer definition, the limiter is deactivated. Deactivation takes place due to limited differences at high water levels between the limiter method and no limiter method. Within the thin water layer definition, the cross-sectional area is interpolated between the limiter result and the no-limiter result. Using this method 3Di handles flow through slopes differently per angle and per timestep. The methodology is show in the figure below.

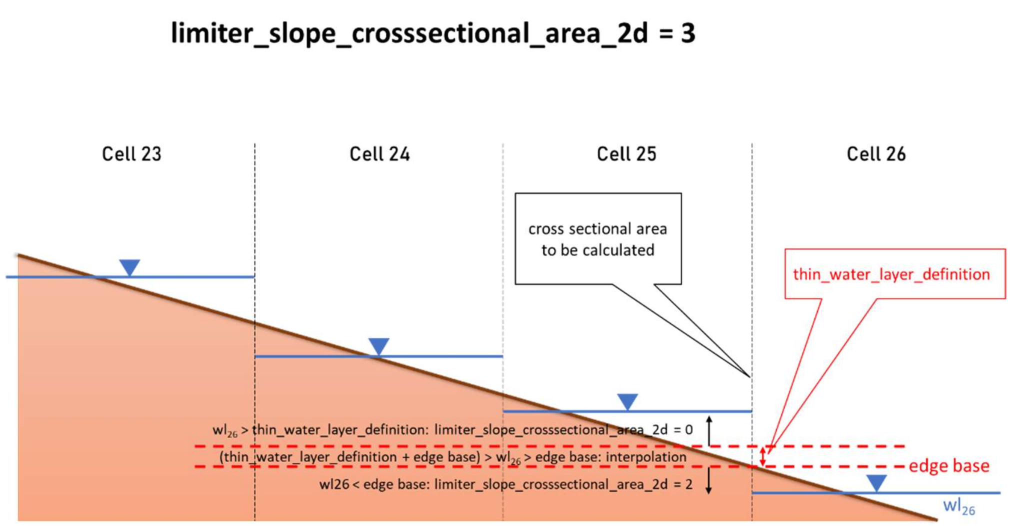

Figure 8 Calculation of water level in cell 26 using a limiter.

The slope limiter can be applied in 1d and 2d. The thin water layer definition will be defined at 10 cm for the start. During the test run, the water levels, discharge and flow velocity downstream will be checked for fast changes. The thin water layer definition will be changed accordingly.

3.7 Levees

When water ‘flows’ through a calculation grid, small obstacles might not be detected. Levees for example are mostly detected by the calculation grid. If, however, a calculation cell fully covers a levee width, water will still be able to flow from one calculation node to another. If the levee height is present on the cell edges, this will cause the flow to be disrupted. For very small levees however, this is not the case. To make sure the model does not leak, an 3Di obstacle is placed on such levees. If an obstacle is placed, the calculation which cross the obstacle will be set to the height of the levee.

An example of a levee would be around the polder area, which is presented in the land use dataset GeoDenmark as DAEMNING.

Figure 9 shows the levees present around polder. Levees have two fields, a location and a height. Location is present in the GeoDenmark dataset and for height we will use the Digital

Figure 9 Levees around the main polder in the catchment.

Elevation Model.

3.8 Terrain limitations

3Di is limited to 1 billion pixels for all rasters combined. By using the current model area, with a resolution of 1.6 meters, these limits are exceeded. There are two options for resolving this problem:

- Resample the entire area to 2 meters.
- Reduce the modelling area in order to keep the 1.6-meter resolution in the polder area.

In agreement with GEUS, it is decided to resample the entire area to a pixel size of 2meters.

4 Streams and surface water

Surface water and streams are represented in the model in the form of channels and structures. The channels are modelled in 1D networks. Flood plains such as the polder area are modelled in 2D, since the flow can be present in multiple directions.

For the channels an initial water level, a base flow (if available) and boundary conditions upstream and downstream will be added. Furthermore, structures as sluices, pumpstations and bridges are added in the model as well.

4.1 2D and 1D considerations

Streams which are present in the original Mike model are added as 1D elements. In general, 2D shows the natural characteristics more due to the differences in bathymetry and 1D provides fast and precise calculations. We have chosen to model the channels in 1D due to following reasons:

- The model is quite data demanding and covers a large area. To model 2D flow in streams correctly one must have a lot of high-resolution calculation cells in channels, which will increase the computational nodes and will make the model somewhat slow.
- The lower part of the bathymetry (DEM) is not similar to the profile's information used in the model from MIKE. Since profiles are only applicable in 1D, this is a better option.

Given that the polder area is the area of interest, we will model the main polder in 2D and use a grid refinement.

4.2 Connected and embedded channels

Due to the choice of 1D, the channels have to be coupled to the 2D grid cells. For this, we have multiple options: connected double connected or embedded (Figure 10)

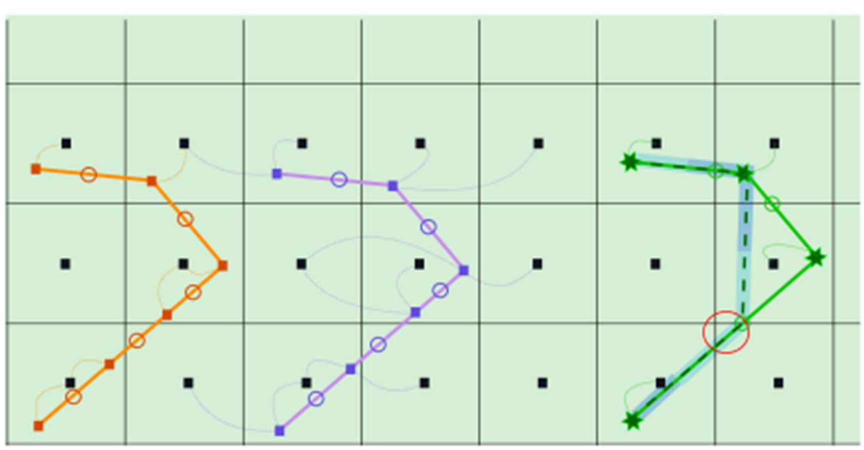

Figure 10 Calculation types from left to right, connected, double connected and embedded.

A connected type calculation can cause a double counting of volume if volume is both present in 1D and 2D. This is usually the case when the profile of the channel is also (partly) present in the height model. In Grenaa this is the case. Hence, embedded is the best option. This means that water level is shared, flow speeds are based on 1D and cross-sections and storage are dependent on both 1D and 2D. Please refer to the documentation for further information about the calculation types https://docs.3di.live/b_1dtypes.html.

In the channels, a calculation point distance has to be defined. When using an embedded calculation type, there can only be one calculation point in one grid cell. Hence, we are going to optimize the calculation point distance and the grid refinement until an appropriate cell size is found.

4.3 Branch connections

From the model schematization in the Mike software the branches of the channels are available in a shapefile. These branches are separated from each other. In order to use them in 3Di they need to be connected first. We will connect the branches by looking at the closest distances between the branches and extending the smaller branch to the main branch. In 3Di, streams are connected to each other by adding connection nodes at the start and end of every stream and at each confluence.

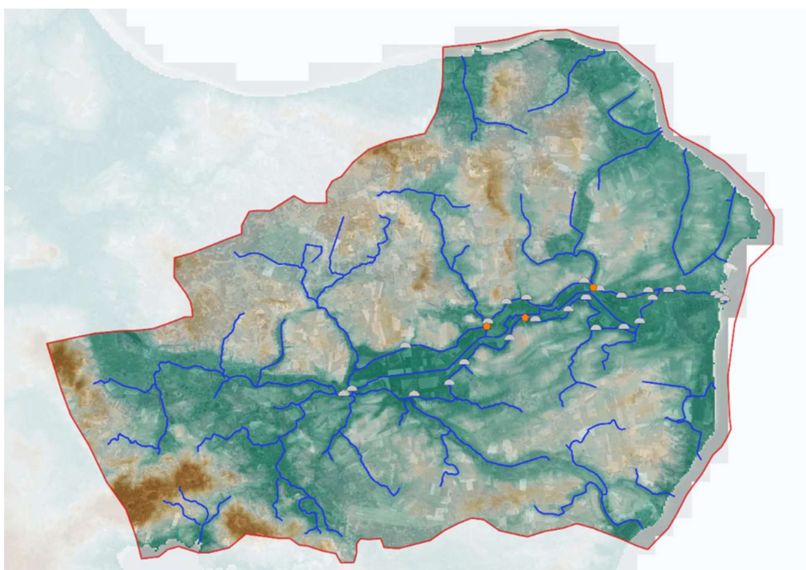

Figure 11 Streams which are modelled in 1D.

4.4 Profiles

The profile definition files (.txt) describe the cross section of the rivers and streams. Within the files there are multiple cross-sections defined along the river. Each definition describes the name of the stream, the location (from the start/end of the stream). Next there is an YZ definition defining the bottom level (Z) at different distances (Y) from the bank.

3Di does not work with YZ-profile definitions but with tabulated trapezium definitions. A tabulated trapezium definition defines the width of the stream at several heights above the bottom level. The profile definition is clipped on the lowest bank level in order to allow a discharge between the 1D and the 2D domain from that level on.

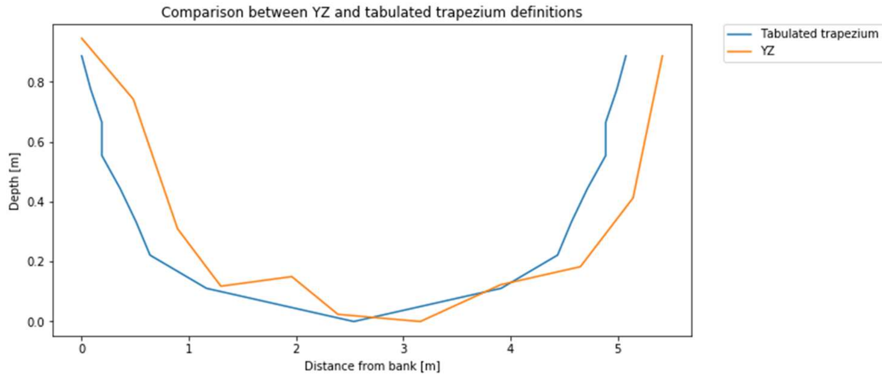

Figure 12 The original YZ profile (orange) and the 3Di tabulated trapezium profile.

The bottom level of each cross-section is defined as the lowest z value in the given YZ-profile. The left bank level is the maximum z value on the left of the lowest point, the right bank level is the maximum z value on the right of the lowest point. The general bank level (the level at which flow is possible between the 1D and 2D domain) is chosen to be the lowest of both bank levels.

The location of the cross-section definition is determined by using the lines from the streams and the point locations along these lines with the distance markers.

3Di interpolates the cross-section profiles between the defined locations over channel elements. However, a culvert or a tributary inflow results in a new channel element and there is no interpolation over different channel elements in 3Di. Because the profile measurements are rather dense and the difference between consecutive profiles in the same stream are expected to be low, the closest profile definition is used in case a channel element does not contain a profile definition.

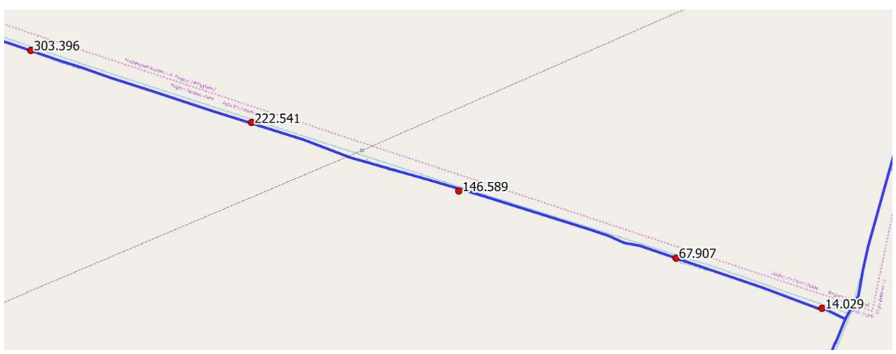

Figure 135 Visualization of the distance markers for determining the cross-section location.

Extra attention needs to be paid when the difference between left and right banks are very large. If such cases occur, the lowest bank level is used for the channel and an obstacle is placed on the highest bank. There are around 77 cases in the Grenaa Datasets where the left and right bank level have a difference which is larger than 1 meter.

In Mike the polder is modelled using large cross sections. In 3Di we will model the polder in 2D and the channels inside the polder will be modeled as 1D elements. In 2D, 3Di is able to calculate flow in a spatially accurate manner (spatially varying water level, wet cross-sectional areas, friction, obstacles etc.), hence a 2d approach is taken for the polder.

4.5 Initial water level

The channels will be initially filled with 1 meter of water. After the dry run including boundary conditions the model will come to a steady state. The output of the run will be the used as final initial water level.

In 3Di the channels are comprised of connection nodes and calculation points within those connection nodes. If an initial water level is given to the connection nodes, the calculation points will copy the initial water level of the nearest connection node. If the channel is very long, a problem might arise when an initial water level upstream is copied. This might result in high water level compared to the bank level and the surround terrain. To tackle this, the channel will be split when the gradient between two connection nodes is too large.

We will limit the height of the initial water level based on a threshold and adjust the channel length accordingly. The channel is adjusted using the following formula:

$$\frac{Threshold}{channel\ gradient} = new\ channel\ distance$$

E.g., if the threshold is 0.5 and the gradient is 0.05 the channel has to be split after 10 meters.

4.6 Boundary conditions

Boundary conditions will be added at the sections where water flow into the sea. Sea level measurements were received. Hence a boundary conditions with water level will be placed.

We will use the same average which is used in the Mike model for the sea boundary condition. Which is most likely the case in the average of a tide.

Some upstream boundaries have been received; however, we are expecting them for every channel.

Depending on the first model results a lateral baseflow to the channels can be added in order to simulate the ground water discharge into the streams, to prevent the streams from drying up too rapidly. This is useful for long calculations.

4.7 Friction

The friction of the channels is defined by a Manning's *n* value of 0.035 which is the average value for a main channel with some stones or weeds. If other friction values are present, we will use these values.

4.8 Sluices and orifices

The sluices block the flow of the sea into the stream. In the 3Di model these sluices are implemented as an orifice. The orifice is open towards the sea and closed towards the stream. When the water level in the stream is higher than the sea, water will flow towards the sea. When the sea water level is higher than the water level in the stream, there is no flow. Currently, no sluices are present in the model. But it is very likely that sluices will be added in scenarios in the future.

4.9 Pumpstations

Pumpstations pump water from one channel to another. In the case of Grenaa, the pumpstations pump from the polder to main stream which are headed towards the sea. In 3Di these pumpstation have a stop level, a start level and a pump capacity which have been received from GEUS.

Table 4 Information on the pumpstations

Pump name	Start level	Stop level	Discharge (m3/s)
Fannerup	-4.6	-4.95	2
Enslev	-4.15	-4.45	2.4
Allelev	-4.8	-5.1	0.6

4.10 Bridges

Bridges are present in the digital elevation model. This might cause back water flow, (water to be retained before the bridge) as the channels and terrain are embedded.

Hence, bridges will need to be removed from the height model. We will replace the bridge with the closest cross section.

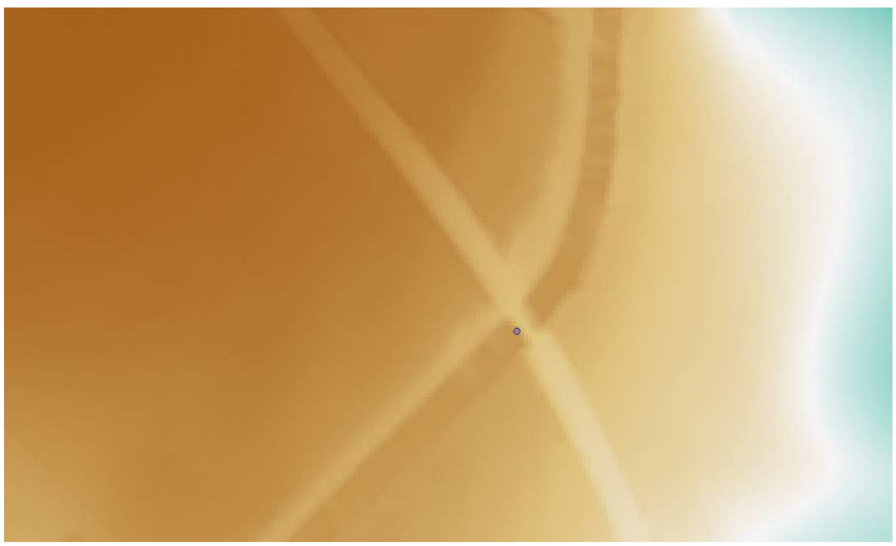

Figure 14 Example of a bridge present in the digital elevation model.

5 Data overview

A lot of data is used to produce an integrated 3Di model. Much of the data is already received/downloaded. However, we would like to receive some extra information for the boundary conditions at the tributaries. During the continuous communication with GEUS we will make sure the information is shared and included.

5.1 Rasters

Rasters are received from GEUS and downloaded from different sites. In summary, they are complete.

Model part	Source	Available
Dem	GEUS (dtm.asc)	Yes
Friction	Pervious/Impervious from Scalgo and GeoDenmark (landuse)	Yes
Infiltration	Soil map + pervious/impervious from Scalgo	Yes

5.2 Channels

Channels have been received in the form of multiple files: 'Branches.shp', 'BranchConnections.shp', 'Cross_section_geometry.txt'. If the profiles in 'Cross_section_geometry.txt' are in meters above sea level (datum), then they can be used to fill the reference level and the bank level of the profile. If this is not the case, then a datum should be present. They are present in the shapefile 'cross_section_location.shp' however some of the datums are 0. Assumption will also have to be made for friction as they are not available currently. The detailed description of the procedures that we will follow are given in section 4.2.

Model part	Source	Missing
Geometry	Branches.shp/ BranchConnections.shp	No
Cross section locations geometry	Cross_section_geometry.txt /Cross_sections.shp	No
Bank level (at every cross section)	Cross_section_geometry.txt	Yes
Friction (at every cross section)	Cross_section_geometry.txt	Yes
reference level (at every cross section)	Cross_section_geometry.txt	Yes
Cross section width, height	Cross_section_geometry.txt	No

5.3 Boundary conditions and structures

We have received some boundary conditions; however, we do not have upstream boundary conditions for every channel, which we would expect.

The boundary condition of the sea is a timeseries. If tides play a large role in the area, we might want to take an average tide.

Model part	Source	Available	Needed
Boundary conditions	GEUS	Yes, however not all.	Yes
Pumps	GEUS	Yes	Yes
Sluice	GEUS	No	No
Levee's	GEUS	No	No