

Workbench Hydro-Structural Modelling (HSM) Guide

Create hydrostratigraphic models with a semi-automated workflow that combines borehole lithologies and resistivity information derived from geophysical data.

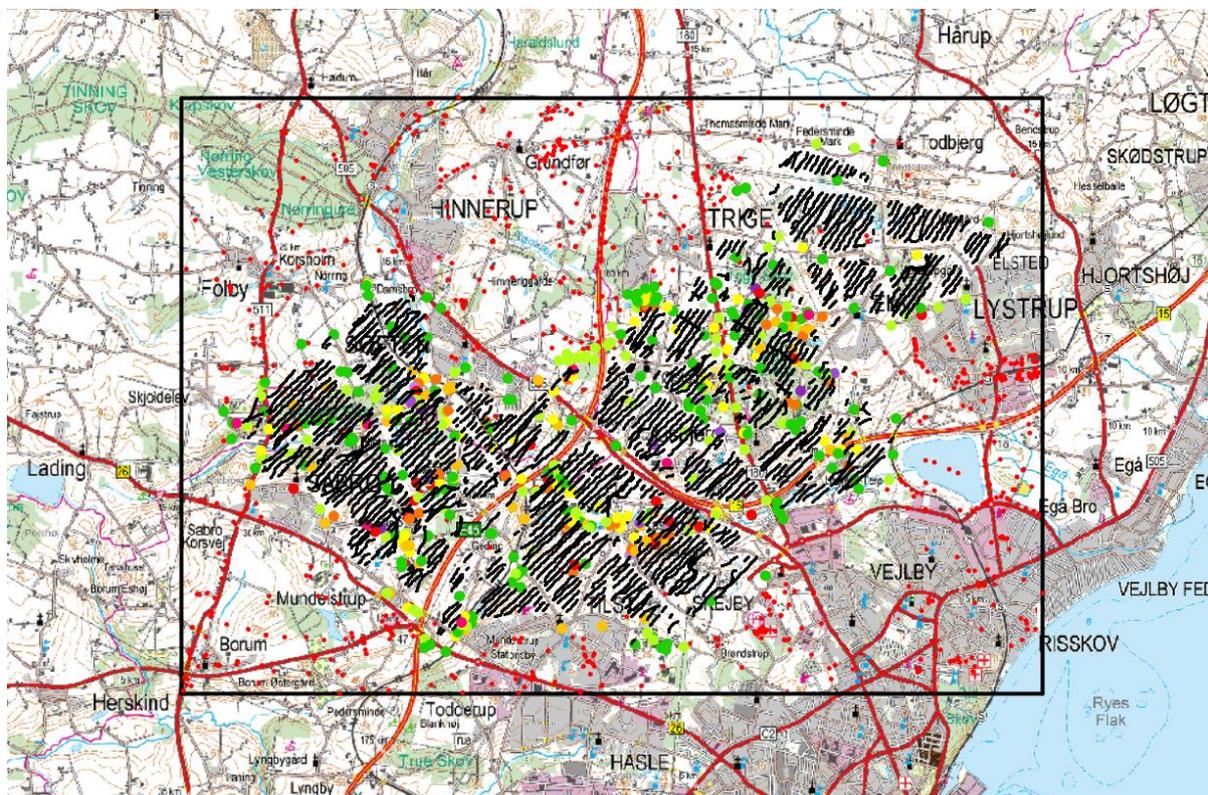


Figure 2 Data input to the HSM Tool

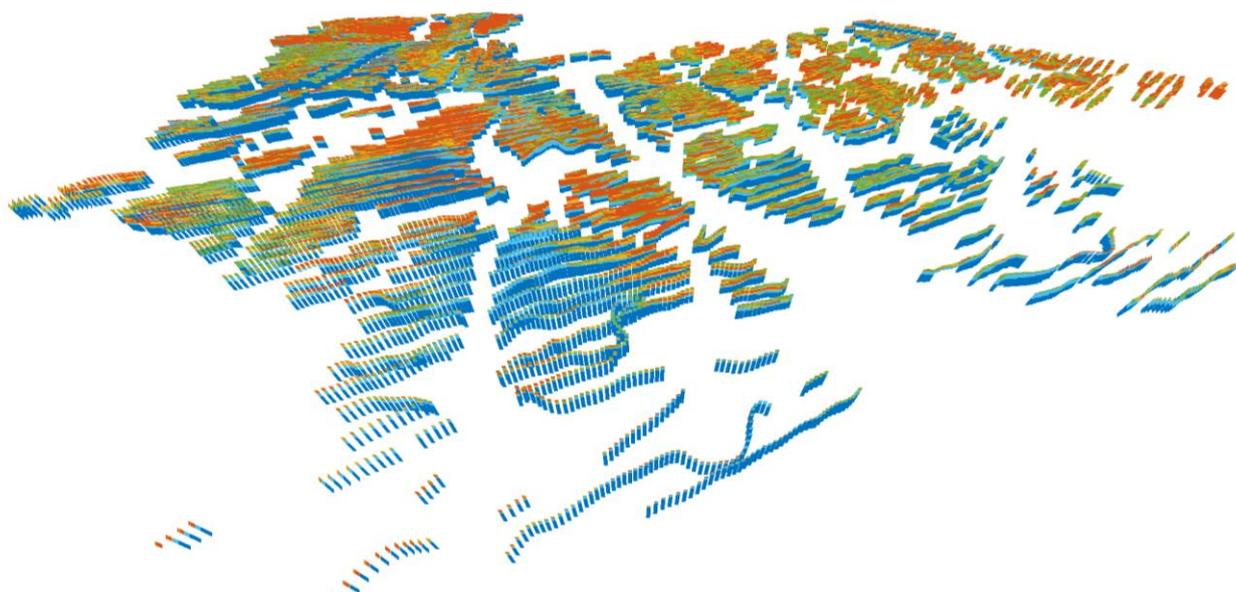


Figure 1 Cluster model from HSM Tool

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Introduction

Predictions made from groundwater models are very dependent on the uncertainty of the model inputs. Hence, the input variable uncertainties need to be carefully described to achieve predictions with relevant uncertainty spans.

One major cause of uncertainty in the predictions comes from uncertain knowledge about the subsurface structures, the hydrostratigraphy. The **Hydro Structural Modelling (HSM) module** is a transparent, objective, and data-driven workflow that creates exportable cluster models that can be used to create an ensemble of equally probable hydro stratigraphic models for groundwater modelling.

When used in conjunction with [Aarhus Workbench](#), this tool creates a new data driven workflow of using geophysical resistivity models and lithology logs as input to hydrogeological modelling.

The HSM module creates hydrostratigraphic models with a 2-step, semi-automated workflow that combines resistivity information from geophysical data and borehole lithologies.

- The first step uses Accumulated Clay Thickness (ACT) modelling to create a clay fraction model.
- The second step is a clustering routine that creates a zoned model, which is the hydrostratigraphic model when assigning hydrological parameters to the zones.
- The cluster model can be exported from the HSM tool and imported into third-party software, in which a third step can be performed using Multiple-Point Statistics (MPS) to create an ensemble of equally probable models, quantifying uncertainties of the hydrostratigraphic models.

The HSM module in Workbench includes the two first steps, ACT modelling and clustering.

ACT Modelling

In sedimentary environments, a general assumption is that low resistivities derived from geophysical data mainly correspond to clay or clay-rich sediments (aquitards). High resistivities mainly correspond to potential aquifer lithologies such as sand, gravel, or chalk. This general link is utilized by the Accumulated Clay Thickness (ACT) concept, linking the geophysical data and the borehole information to build a combined clay thickness (or clay fraction) model.

First, the available lithological borehole logs are divided into aquifers and aquitards (for example, sand and clay). Then a 3D model grid covering the area of interest is defined. A translator function is defined on each node in this model grid, which links resistivities and clay fraction. The translator function is described by two parameters – an upper and a lower resistivity value. Resistivity layers below the upper value will get a weight of 1 which means that the entire length of the resistivity layer is presumed to be clay. In contrast, resistivity layers above the lower value will get a weight of 0, corresponding to no-clay content (sand) for this resistivity layer. Mixed layers exist for values between the upper and lower value. By inversion, we find the set of parameters in the translator model (upper and lower) that best fit the borehole-derived clay fractions and the geophysical predicted clay fractions.

A vital aspect of this concept is that the translator function can change horizontally and vertically, adapting to the local conditions and borehole lithologies. Therefore, not one “global” translator

function is used for an entire survey, but a translator function that is spatially varying on the 3D model grid. The result is a 3D clay fraction model.

Cluster Model

The second step combines the clay fraction values from the ACT model and the geophysical resistivities in a k-mean clustering routine. As the clay fraction and resistivity models are correlated, the k-mean analysis is done on their principal components (PCA) to obtain uncorrelated variables. This produces a model reduced to several zoned clusters (typically 4-6), which can be used as hydro stratigraphic units in groundwater modelling when assigned relevant hydrological parameters.

Multi Point Statistics (MPS) for generating an ensemble of equally probable hydro stratigraphic models (not implemented in Workbench)

By using a MPS algorithm (direct sampling) and the cluster model as training image, we finally generate 100's or more equally probable realizations of the cluster model. The direct sampling method uses both hard data and soft data to guide the simulations into a relevant output. The hard data points in the simulation grid are the points that are set to a specific value and are constant in between the simulations. They are the anchor points of the simulation and are based either on measurements or on other data points that have a high probability. The soft data in the simulations are the cluster model. From these realizations the uncertainty of the cluster model can be estimated and used in the groundwater modelling, or the full ensemble of models can be used individually.

Workflow

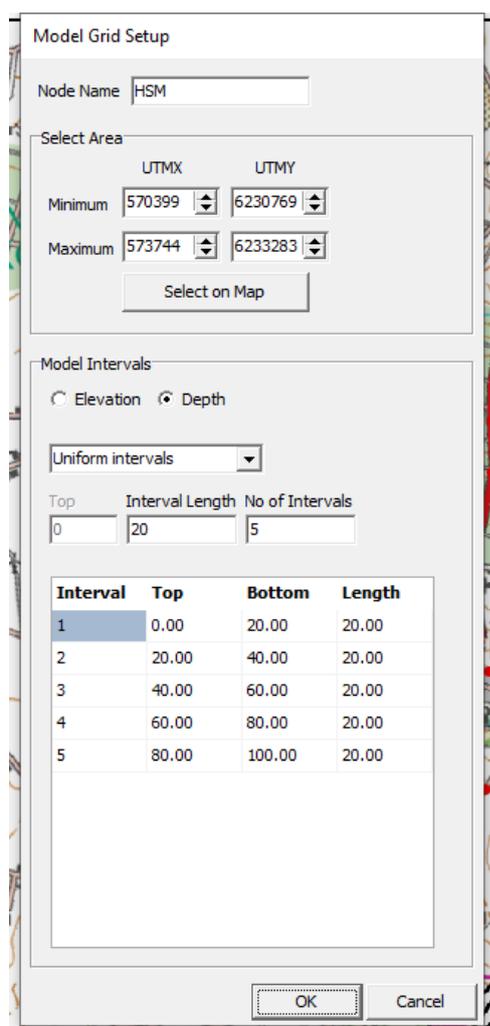
This workflow assumes that resistivity models from inversion are available in the Workbench workspace and lithology logs have been imported into Workbench.

For each window in the HSM tools, it is possible to press F1 and go to the help page for the specific open window.

The workflow will go through the setup for running ACT modelling and clustering.

Setup the Hydro Structural Modelling (HSM) node

First step is to create a model grid covering the area and depth of interest and setup a model grid for the area. This is done by going to the HSM tab and press “New”. The window below will appear.



Model Grid Setup

Node Name:

Select Area

UTMX UTM Y

Minimum:

Maximum:

Model Intervals

Elevation Depth

Top Interval Length No of Intervals

Interval	Top	Bottom	Length
1	0.00	20.00	20.00
2	20.00	40.00	20.00
3	40.00	60.00	20.00
4	60.00	80.00	20.00
5	80.00	100.00	20.00

- Node Name: Give the HSM node a name
- Select the area that the model grid needs to cover. This is easiest done by click “Select on Map” and draw a square on the GIS map covering the area.
- Setup the **model intervals** and depth. The model intervals can be set to run in depth or elevation. For elevation the topography should not be too varied as it will create many empty cells in the model grid.

The intervals of the model grid can be set to uniform or loaded from an external file (if they are non-uniform).

For a uniform model, select where the model should start (top for elevation), the length of each interval and number of intervals.

For non-uniform intervals, they can be loaded from an external text file. E.g., the intervals could follow the layers of the resistivity models and have a 1-1 correspondence between the model grid intervals and resistivity layer thicknesses.

The external file contains the number of layers as a header and the interval of each layer.

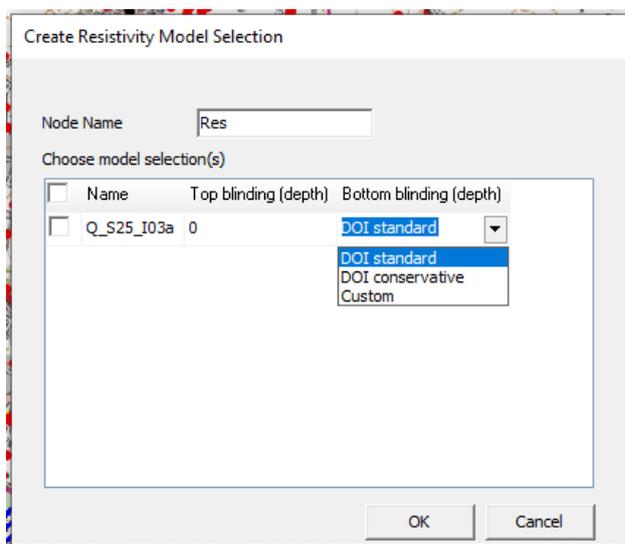
Example of the external model interval text file:

```
Number of layers=8
1
2
5.5
7
9.5
20
34
50
```

Click OK and the HSM node will be created in the workspace manager tree. It is possible to tick on the HSM node and the area will be displayed on the GIS.

Add resistivity models

The resistivity models used for the ACT run, can be added to the HSM node. Click “Add Models” in the HSM tab.

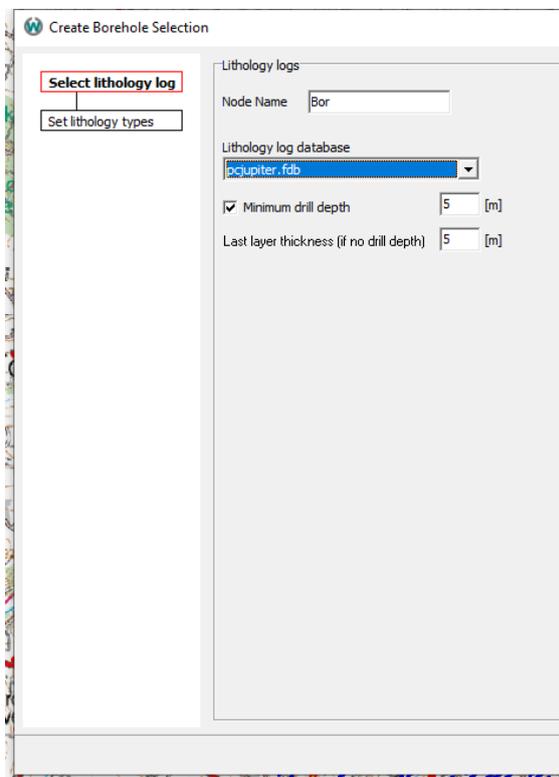


- Node Name: Give the resistivity node a name
- Choose the model selections with resistivity models that should be included. It is possible to include several model selections with resistivity models from different inversions or ERT / EM methods.
- Select if the resistivity models should be blinded in the top. This can be used if the models are not trusted within the first few meters.
- Select how the resistivity models should be blinded by depth. The calculated Depth Of Investigation (DOI) from the inversion can be used or a custom depth can be set.

Click OK and the model selections are added into a new sub node to the HSM node in the workspace manager tree. It is possible to tick on the resistivity node and the location of the resistivity models will be displayed on the GIS.

Add lithology logs

Here the lithology logs used for the ACT run, can be added to the HSM node. Click “Add Lithology Logs” in the HSM tab. This will first open the below window.



Node Name: Give the lithology node a name.

- Select in the dropdown the database with the lithology logs imported into Workbench.
- If needed, it is possible to set a minimum depth, if logs shorter than this depth should be excluded.

Some logs don't have the depth information, instead it is possible to set the minimum thickness for the last layer in the log.

Press next for the window where the lithologies needs to be split into 3 categories. The first list (Unknown lithologies) includes all lithologies and their description that have been imported. These lithologies should be sorted into these 2 categories:

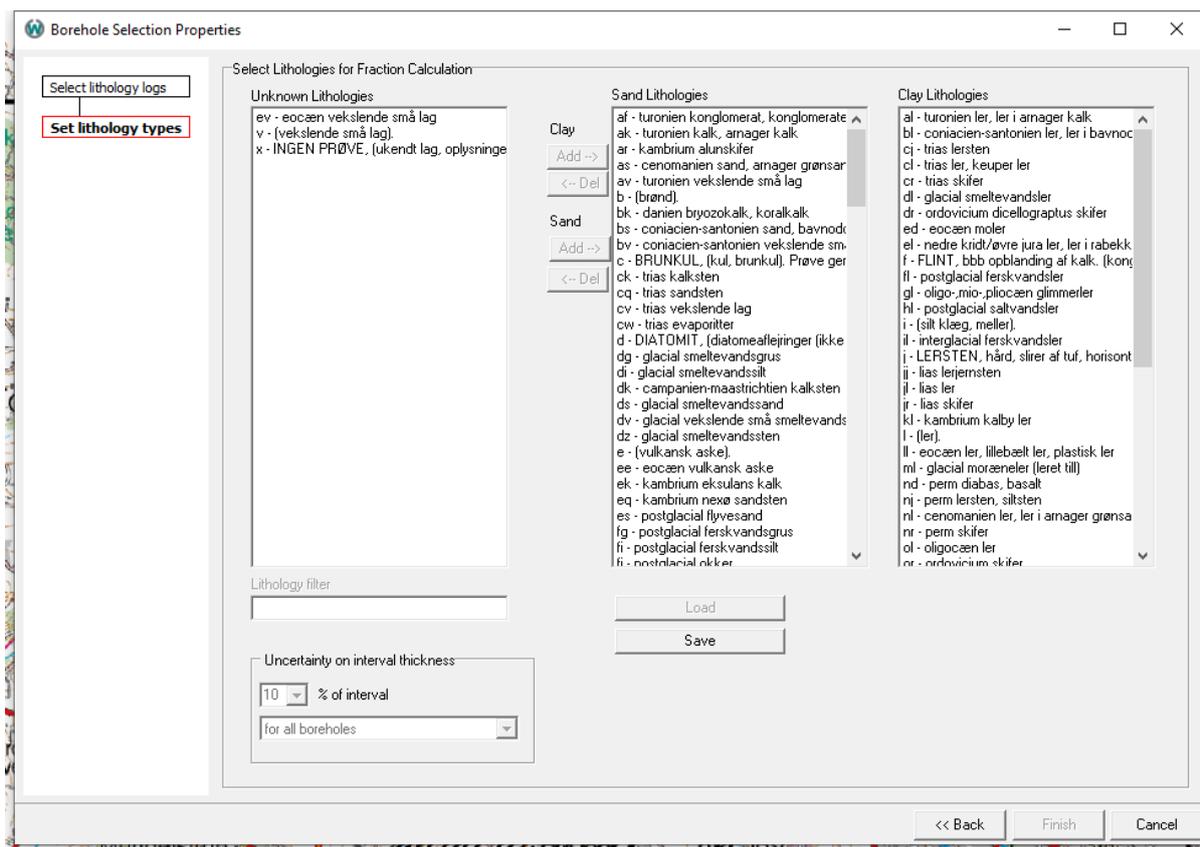
- **Sand lithologies:** this list should include all lithologies that acts like an aquifer, a sediment or rock that can contain groundwater.
- **Clay lithologies:** this list should include all lithologies that acts like an aquitard, clay, rock, or a sediment that restricts the flow of groundwater.

If some lithologies are unknown or should be excluded in the ACT modelling, they should be kept in the Unknown list.

It is possible to filter the list of Unknown Lithologies. This is useful if e.g., all lithologies that includes sand have an abbreviation for sand or the word “sand” in the description.

It is possible to select several lithologies by clicking and holding the mouse button down while dragging down in the lists.

Last the sorted lithology list can be saved into an external file. This file can later be loaded to avoid a new sorting.



Uncertainty of interval thickness

It is possible to set an uncertainty of the thickness of each interval in the lithology logs. There are 2 options:

- Set a % for all lithology logs (default).
- Only set a % if the lithology log doesn't have a quality rating imported.

During import of the .bor files, it is possible to add a quality rating to each log. The rating goes from 1-5 and describes the uncertainty of the intervals in the lithology log by:

- 1: 10%
- 2: 15%
- 3: 30%
- 4: 50%
- 5: disable interval

[See lithology log import file example her](#)

Click Finish and the sorted lithologies are added into a new sub node to the HSM node in the workspace manager tree. It is possible to tick on the lithology node and the location of the lithology logs will be displayed on the GIS.

Edit Intervals

For the Edit interval window, it is possible to use the GIS tool “Find nearest” from the GIS tab in Workbench. Enabling this tool and clicking on the GIS will make the Edit interval plot the nearest lithology log to the location of the mouse click.

Edit intervals before ACT run

Select a lithology node and click “Edit Data” in the HSM tab. The edit window will open. The window will have a list of all lithology logs and a plot with displaying:

- The Lithology log (left)
- The Clay Fraction (CF) for each model interval.
- The Standard Deviation (STD) for each CF in each interval. A STD of 1.1 corresponds to 10%.

By selecting a new lithology log, the plot will change its display to this lithology log and corresponding CF and CF STD.

A PDF Log report for each lithology log can be created displaying the imported information for each log. Click on the Log Report button to create the PDF report for the selected lithology log in the list.

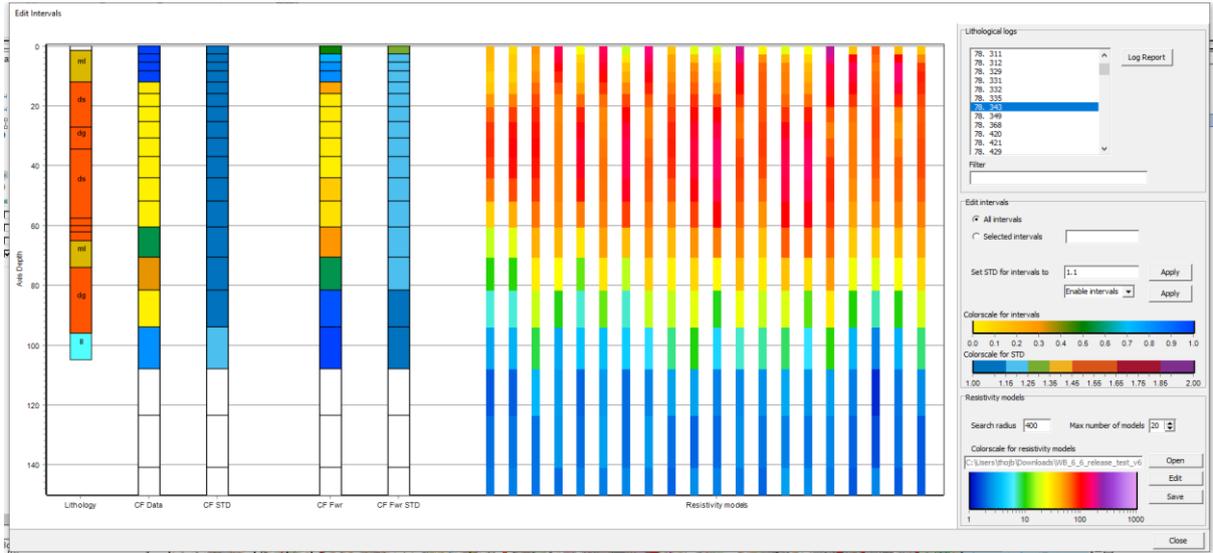
It is possible to disable CF intervals or change the uncertainty on the CF intervals. This is most useful after an ACT modelling has been run, where it is possible to look at which CF intervals does not fit with the resistivity models.

Edit Intervals after ACT run

Editing a lithology log node that has been used for an ACT run, will display several new information in the plot:

- **CF Fwr**: The resulting Clay Fraction from the ACT run for the selected lithology log.
- **CF Fwr STD**: The Standard Deviation for the resulting Clay Fraction from the ACT run for the selected lithology log.
- **Resistivity models**: The closest resistivity models used in the ACT run. In the newly added resistivity model section, it is possible to limit the number of models and search radius from the location of the lithology log. It is also possible to change the colour scale of the resistivity models.
Above each resistivity model in the plot, the distance to the lithology log is displayed

Having these results, it is possible to go through the lithology logs once more, look at where the **CF Fwr** and **CF Fwr STD** does not find, and take decision if the STD should be increased or intervals should be disabled before making a new ACT run.

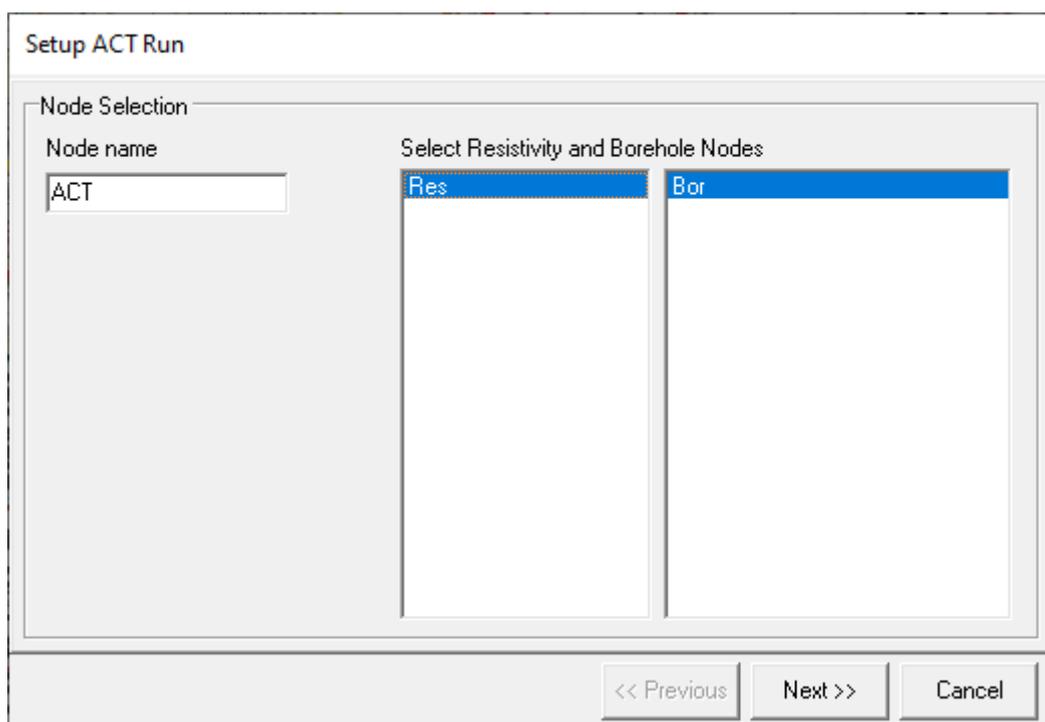


Run ACT modelling

Now that the HSM model grid, resistivity node and lithology logs are set, it is possible to run an ACT modelling by selecting the HSM node and click “ACT” in the HSM tab. This will open the setup for running the ACT modelling.

Setup ACT run

Give the ACT node a name and select the resistivity nodes and lithology nodes for the run.



Setup area and node distance

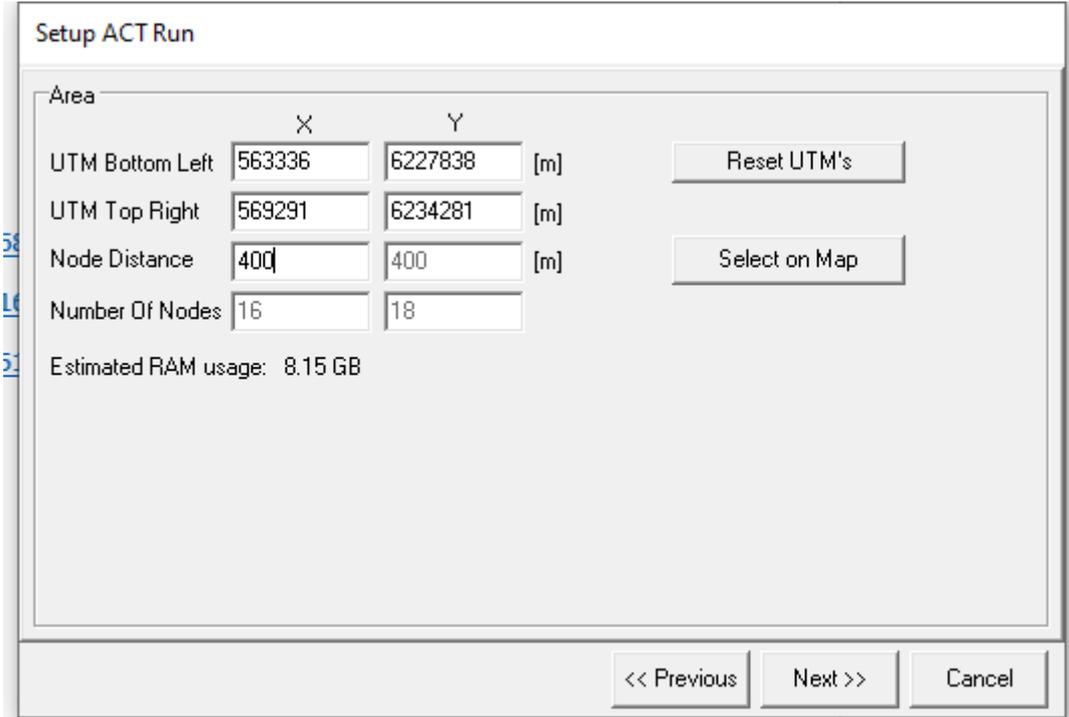
In the next window, it is possible to select a sub-area for the ACT run. The default area is the area of the HSM node, but it can be necessary to run several subareas due to memory limitations. The estimated memory usage displayed. The estimated memory usage will change depending on the size



of the area and

the Node Distance in the model grid.

The Node Distance can be set to minimum 50 meters, but most often needs to be larger. The node distance should be set to represent the variability in resistivity by distance away from the lithology log location. Setting a small distance will make it easier to fit each translator function but it will also give them more extreme and varying results which is not what is wanted. 500 – 1000 meters or even more will be a good starting point for the first ACT run.



	X	Y	
UTM Bottom Left	563336	6227838	[m]
UTM Top Right	569291	6234281	[m]
Node Distance	400	400	[m]
Number Of Nodes	16	18	

Estimated RAM usage: 8.15 GB

<< Previous Next >> Cancel

Setup the translator model

In the next window, the starting translator model for the inversion can be set.

The translator function is described by two parameters – an upper and a lower resistivity value. Resistivity layers below the upper value will get a weight of 1 which means that the full length of the resistivity layer is presumed to be clay, while resistivity layers above the lower value will get a weight of 0, corresponding to no-clay content (sand) for this resistivity layer. Mixed layers exist for values between the upper and lower value. By inversion we find the set of parameters in the translator model (upper and lower) which produces the best fit between the borehole-derived clay fractions and the geophysical predicted clay fractions. This inversion is done for a translator function in each point in the model grid.

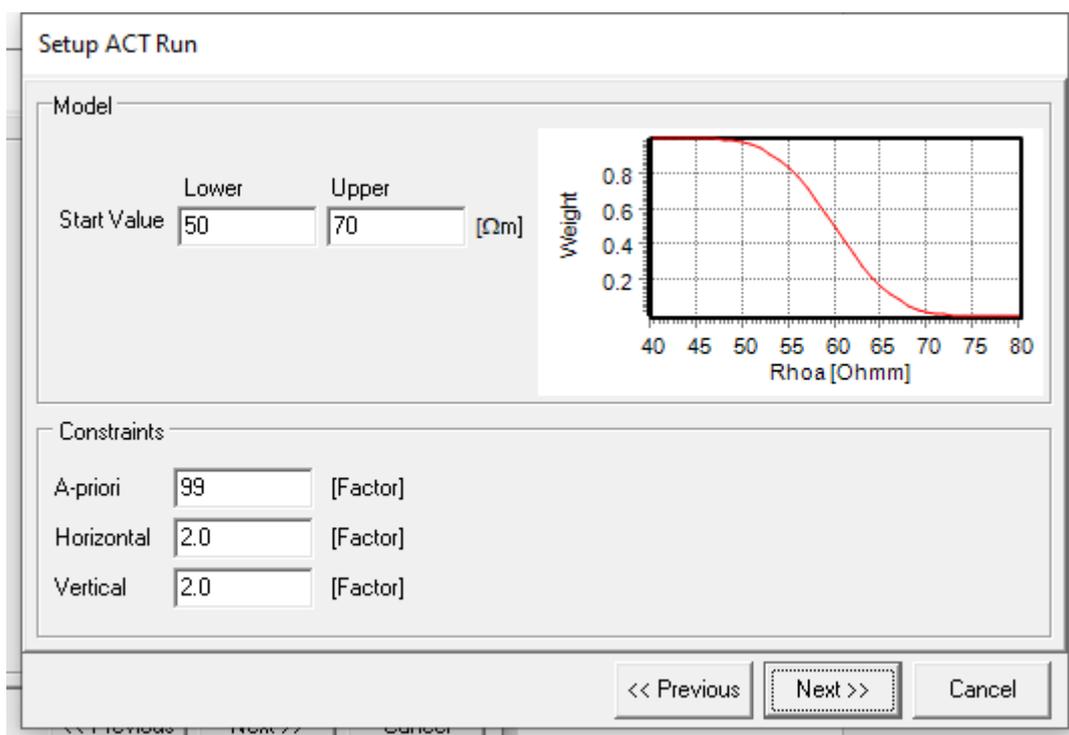
The upper and lower boundary can be changed, and the resistivity values should be set to estimated values for clay and sand. If any estimate of these resistivity is known from e.g., resistivity logs, it should be used to make the best start model possible. In areas where there are no lithology logs, the results will end close to the starting model.

Constraints

It is possible to set the constraints of the starting model and both horizontal and vertical between each translator model in the grid.

The **A priori** constraint sets how much the translator function can vary from the starting model. A factor of **99** means that the parameters can move freely. If the survey area is sparse of lithology logs, it is better to trust the starting model that is set with the best knowledge available and set the **A priori** factor to be between **2-5**.

The horizontal and vertical constraints is how much the translator function maximum can change to is nearest grid neighbors. A factor setting of 2 is a good starting estimate.



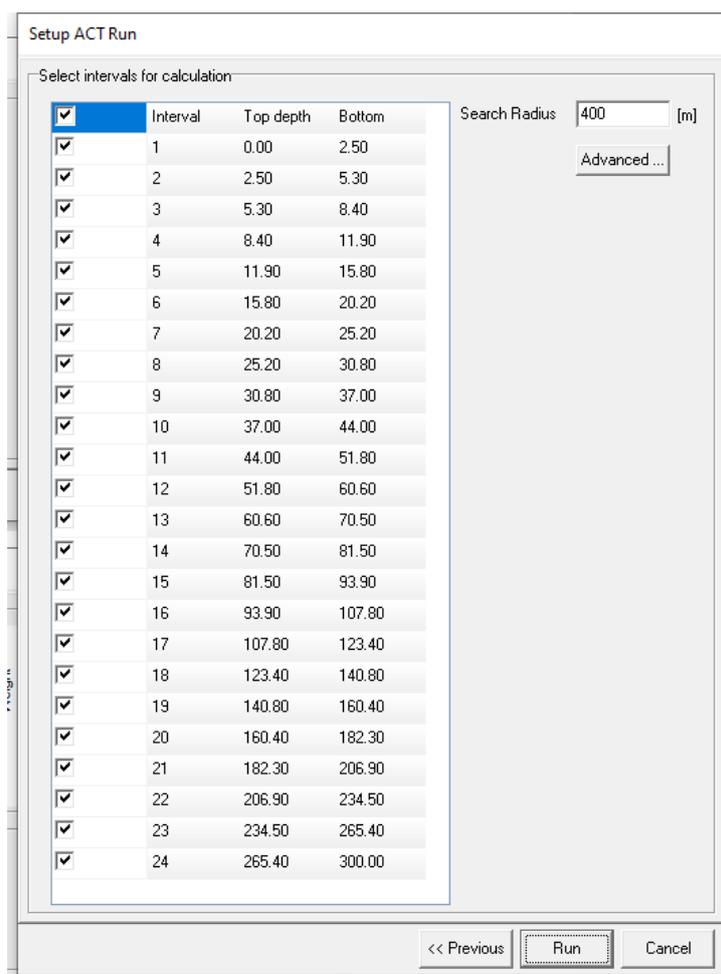
Select intervals and search radius

In the last window of the ACT run, it is possible to select only a number of the intervals in the model grid. This can be useful if e.g., there are no lithology logs deeper than 60 meters. Then all intervals below 60 meters can be deselected.

The search radius is in the Kriging interpolation used to interpolate from the lithology logs to the location of the resistivity models. Resistivity models closest to the lithology log will have a higher weight than models further away.

It is possible to set advanced properties for the variogram used for the Kriging interpolation. The ACT code automatically calculates the best variogram settings and the advanced setting will only be used if the automatically settings are not within accepted limits (e.g., close to the Depth Of Investigation (DOI) boundary where only little resistivity information can exist). The default settings are recommended.

Now the ACT modelling can run.



ACT results and visualization

The resulting Clay Fraction for each lithology log can be seen by highlighting the lithology log node used in the ACT run and click “Edit Interval”. See **Edit Intervals after ACT run** section above.

The ACT run results in a new ACT node under the HSM mode in the workspace manager. This ACT node includes 5 new sub-nodes:

- **ACT_ResPoint:** Clay Fraction values extrapolated to each resistivity model location. This node includes several parameters which all can be **plotted on a section**:
 - Resistivity model
 - Clay Fraction from ACT modelling
 - Clay Fraction STD from ACT modelling
 - Upper limit of translator model
 - Lower limit of translator model

- **ACT_LogPoint:** Clay Fraction values extrapolated to each lithology log location. This node includes several parameters which all can be **plotted on a section**:
 - Initial Clay Fraction
 - Initial Clay Fraction STD

- Clay Fraction from ACT modelling
 - Clay Fraction STD from ACT modelling
 - Absolute difference between Initial Clay Fraction and Clay Fraction from ACT modelling
 - DataFit
-
- **ACT_Trans_ModelGrid:** Upper, Lower and STD of the translator function in each model grid point. These can be visualized by adding them to the **3D Viewer**.

 - **ACT_DataFitSum:** The sum of all data fits at each lithology log location. This can help evaluate if many intervals do not fit to the individual lithology log, hence the description of the log could be of low quality. These results can be added to the **GIS for visualization**.

 - **ACT_DataFitAve:** The average of all data fits at each lithology log location. This can help evaluate if many intervals do not fit to the individual lithology log, hence the description of the log could be of low quality. These results can be added to the **GIS for visualization**.

Clustering

it is possible to use the clay fraction and resistivity models from an ACT run in a k-mean clustering routine. First the resistivity is standardized to values between 0-1 (to have the same range as the clay fraction). Then, the resistivity and Clay Fraction values are used to perform a PCA to minimize correlation. After this the clustering routine can be run.

The clustering routine produces a model reduced to a number of zoned clusters (typically 4-6), which can be used as hydro stratigraphic units in a groundwater modelling when assigned relevant hydrological parameters. It can be exported and used as training image for MPS to create realizations and estimate the uncertainty of the cluster model.

- **Node name:** Give the cluster node a name.
- **ACT runs:** Select the ACT run from where the clay fractions and resistivity models should be used for the cluster run.

Settings

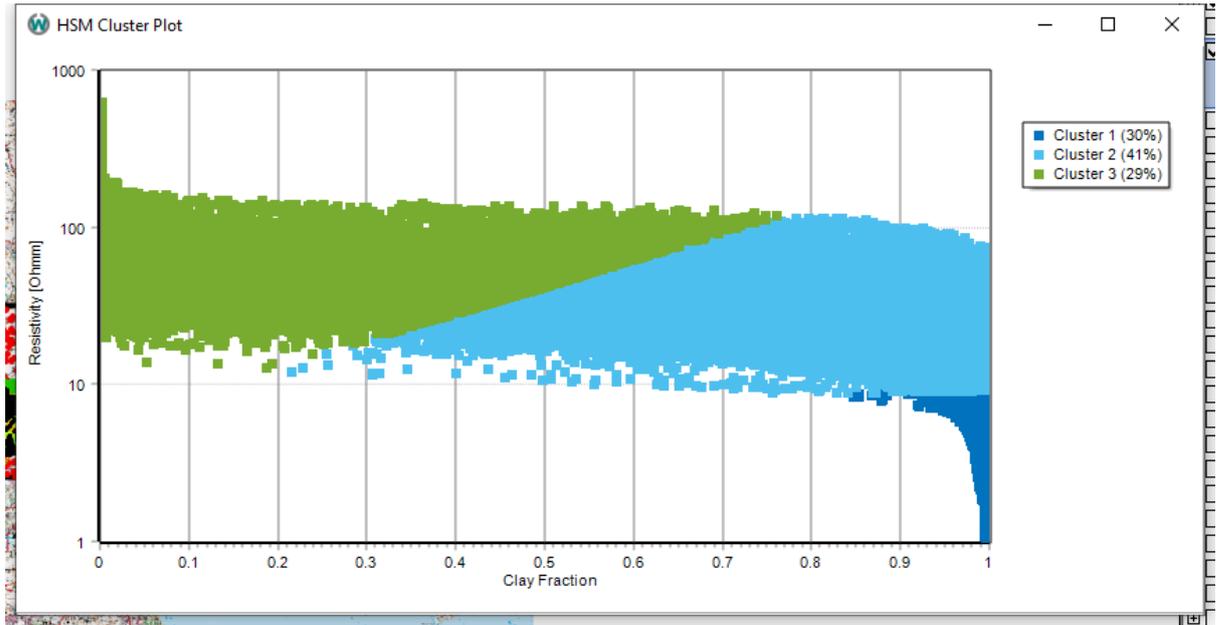
- **Number of Clusters:** Set number of wanted clusters.
- **Truncation:** Truncate the minimum and maximum resistivity values. Every value below the minimum setting will be set to this value. Every value above the maximum setting will be set to this value.
- **Resistivity and Clay Fraction weight:** If the clustering routine should weight either the resistivity or Clay Fraction higher, it is possible to add a higher weight to either of these. A weight of 2 means that the range (the range is between 0-1) is timed by 2.

Result and visualization

A new cluster node will be created under the ACT node in the workspace manager. The models with clusters in each resistivity model location can be visualize by:

- The HSM node has a cluster plot. This will create a 2D plot of resistivity vs Clay Fraction for all clusters. The legend will indicate how many of data there are in each cluster in %.
- Adding the cluster node to 3D viewer.
- Adding the cluster node to a 2D section.

It is also possible to export the cluster results into an XYZ file.



References

http://www.hgg.geo.au.dk/Papers_EndNote/1688970941/VILHELMOSEN2019.pdf

http://www.hgg.geo.au.dk/Papers_EndNote/0167303347/CHRISTIANSEN2014C.pdf

http://www.hgg.geo.au.dk/Papers_EndNote/1514882869/FOGED2014.pdf