Paper number:
H11B-0807

Testing MODFLOW-LGR for simulating flow around buried Quaternary valleys – synthetic test cases

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HYACINTS

Experimental background and perspectives

I

In Denmark the water supply is entirely based on ground water. In some parts of the country these resources are found in buried quaternary tunnel valleys. Intensive mapping has shown that the valleys typically have a complex internal hydrogeology with multiple cut and fill structures (Jørgensen and Sandersen, 2006).

The administration of groundwater resources has been based on simulations using regional scale groundwater models. However, regional scale models have difficulties with accurately resolving the complex geology of the buried valleys, which bears the risk of poor model predictions of local scale effects of groundwater abstraction. To enable effective administration of the groundwater resources new methods need to be investigated to improve simulation of local scale flow in buried valleys that interact with surrounding regional groundwater systems.

The purpose of this synthetic case study is to test the Local Grid Refinement (LGR) method developed for MODFLOW-2005 (Mehl and Hill, 2005) for simulation of groundwater flow in areas containing buried valleys. The tests are conducted as comparative analysis between simulations made with a globally refined model, a locally refined model, and a globally coarse model, respectively. Based on the results we will evaluate how to use the method to refine a regional scale model covering an area north of the town of Aarhus, Denmark. The area, which contains several buried valleys, is marked with a red square on the map.

The HYACINTS project (www.hyacints.dk):
The study is part of the **HY**drological **M**odelling for **A**ssessing **C**limate **C**hange **I**mpacts at differe**NT** **S**cales (HYACINTS) project and is financed by the Danish Coucil for Strategic Research and Aarhus Water and Wastewater. The aim of HYACINTS is to develop new methodologies and tools to enable easier and more accurate use of regional scale climate and hydrological models to address local scale water resources problems. Further Information can be found at www.hyacints.dk.

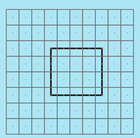
The MODFLOW - LGR method: Description and figures based on Mehl and Hill, 2002

II

Model setup

Parent Model

Child Model



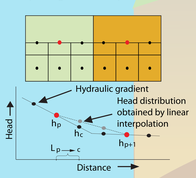
Child model area

shared nodes

Cells are truncated at the edge between the child and the parent model.

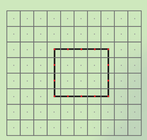
The method is an iterative method where simulated heads and fluxes are balanced at the interface between the parent and the child model The method allows refinement in 2D or 3D.

Darcy-weighted interpolation (DWI):



$$h_c = h_p - \frac{Q_{p \to p+1}}{K_c} \frac{2L_{p \to c}}{\text{thick } w}$$

Iteration process



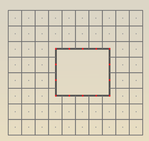
Begin with independent parent model simulation.

Simulated heads from the parent model are used to interpolate constant head BC's for the child model. Interpolation from shared nodes are made with DWI.

Constant head nodes

The child model is run with constant head BC's on the edge.

To obtain the specified-flux BC along the parent-grid interface, a mass balance is performed on the group of child cells that border each parent cell.



shared nodes

The parent model is run using the specified flux BC at the parent-child interface. The area cowered by the child model is omitted from the simulation.

Constant head nodes

Subsequently the heads derived from the parent model are used to interpolate new constant head BC's for the child model.

The iteration process continues until a specified closure criteria is fulfilled.

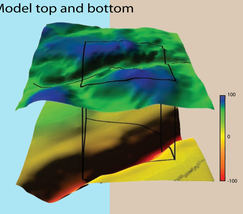
Model setup: complex model structure with multiple layers and vertical refinment

III

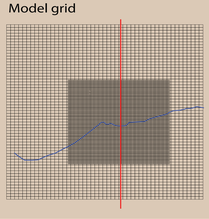
Figure 1 shows the contour map of the model terrain and the model bottom. Both surfaces express a valley structure. The locally refined area is shown with the dark square and the local stream is shown with a dark line. The next figure shows the grid composition with the locally refined area, the stream, and the red profile line of the cross sections. Last, the cross sections of the five setups are shown.

Figure 1: Model setup

Model top and bottom

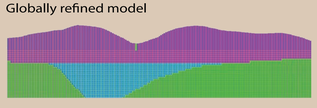


Model grid



Cross sections (location marked with red on grid):

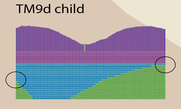
Globally refined model



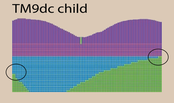
Globally coarse model

TM9 child

TM9d child



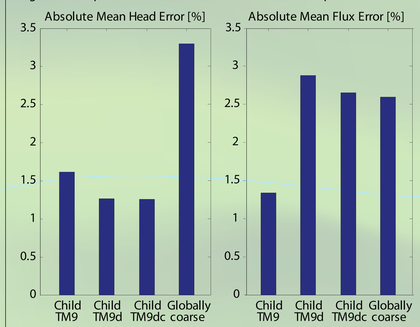
TM9dc child



Results: Complex model structure with multiple layers and vertical refinement

IV

Figure 2: Comparison between different child model setups

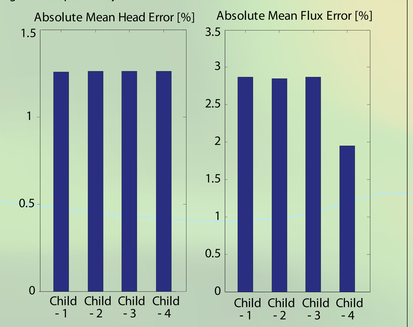


	Globally refined	Child TM9	Child TM9d	Child TM9dc	Globally coarse
Execution time	1 Min, 52.356 Sec	8 Min, 28.113 Sec	9 Min, 26.567 Sec	8 Min, 39.271 Sec	0 Min, 1.141 Sec
LGR damping factor	-	0.2	0.2	0.2	-
LGR head closure criteria	-	5e-4 m	5e-4 m	5e-4 m	-
LGR flow closure criteria	-	1e-7 m^3/s	1e-7 m^3/s	1e-7 m^3/s	-
PCG head closure criteria	1e-8 m	1e-8 m	1e-8 m	1e-8m	1e-8 m
PCG flow closure criteria	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s
PCG max iterations	25	25	25	25	25

- For heads, all child models perform better than the globally coarse model
- For fluxes, only the TM9 model performs better than the globally coarse model, but the TM9dc model comes close.
- Runtimes for the locally refined models were 4 to 11 times longer than for the globally refined model.

The results were obtained using recharge correction method e (explained in Figure 4).

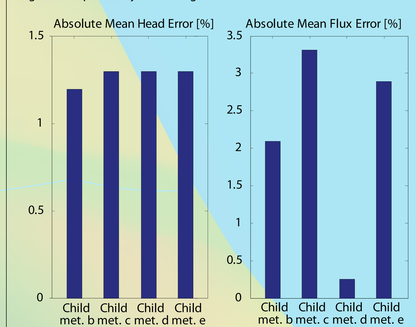
Figure 3: Dependency on closure criteria



	Globally refined	TM9d Child - 1	TM9d Child - 2	TM9d Child - 3	TM9d Child - 4
Execution time	1 Min, 52.611 Sec	8 Min, 28.254 Sec	6 Min, 2.143 Sec.	4 Min, 15.236 Sec	2 Min, 23.064 Sec.
LGR damping factor	-	0.2	0.2	0.2	0.05
LGR head closure criteria	-	1e-4 m	1e-2 m	1e-4 m	1e-2 m
LGR flow closure criteria	-	1e-7 m^3/s	1e-2 m^3/s	1e-7 m^3/s	1e-2 m^3/s
PCG head closure criteria	1e-8 m	1e-8 m	1e-8 m	1e-4m	1e-3 m
PCG ow closure criteria	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s	1e-7 m^3/s	1e-3 m^3/s
PCG max iterations	25	25	25	25	25

- Simulated heads are insensitive to changes in the closure criteria (mean error ≈ 1.25%)
- Simulated fluxes are fairly insensitivite to closure criteria. The smallest flux error was achieved with the most relaxed closure criteria.
- Simulation runtimes proved to be highly dependent on closure criteria.

Figure 4: Dependency on recharge correction method



	Globally refined	Child met. b	Child met. c	Child met. d	Child met. e
Execution time	1 Min, 52.356 Sec	15 Min, 31.219 Sec	15 Min, 30.031 Sec	4 Min, 0.875 Sec	15 Min, 30.156 Sec
LGR damping factor	-	0.05	0.05	0.05	0.05
LGR head closure criteria	-	1e-2 m	1e-2 m	1e-2 m	-
LGR flow closure criteria	-	1e-2 m^3/s	1e-2 m^3/s	1e-2 m^3/s	-
PCG head closure criteria	1e-8 m	1e-8 m	1e-8 m	1e-8m	1e-8 m
PCG flow closure criteria	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s	1e-8 m^3/s
PCG max iterations	25	25	25	25	25

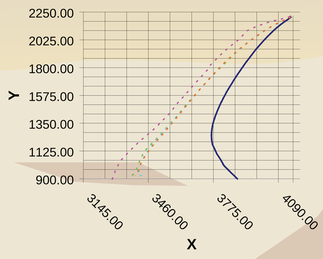
- Simulated heads proved to be insensitive to the recharge correction method.
- Fluxes proved to be sensitive.
- Using method d gives a runtime which is 3.9 times faster than when using the other correction methods.

Recharge correction methods (see Mehl and Hill, 2005, pp. 5-7):

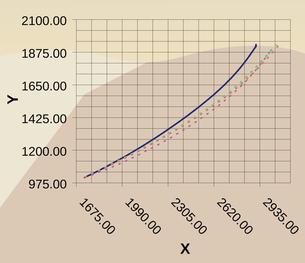
Method b.	No correction made to the original boundary conditions.
Methdo c.	Reduce the stress in the parent cells at the interface.
Method d.	Reduce the stress in the parent cells at the interface but also add to account for the loss of recharge within constant head child cells.
Method e.	Reduce the stress in the parent cells at the interface, and increase stress in child cells neighboring constant head cells.

The difference between TM9d and TM9dc can be seen from Figure 1. The TM9d model uses a fine geological resolution in its entire child domain, whereas the TM9dc model uses a coarse resolution at the parent-child interface (to obey the assumption of the DWI, box II) and a fine resolution in the interior child domain.

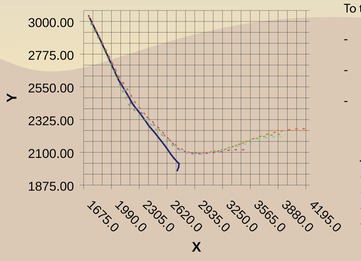
Particle 1 - reverse tracked



Particle 2 - forward tracking



Particle 3 - forward tracking



To the left traces of three different particles have been simulated.

- For all three particles the simulated traces deviate from the the real traces.
- For two particles the child model simulations are more accurate than the globally coarse model simulation.
- For the third particle the globally coarse model simulation is the most accurate.

Reality (simulated with globally refined model)
TM9 Child
TM9d Child
TM9dc Child
Globally Coarse

Conclusions:

V

Using MODFLOW-LGR to locally increase the geological resolution resulted in improved simulation results.

Runtimes for the tested LGR-models were much longer than for the globally refined model. Limited testing shows that the long LGR-runtime is partly due to the complex geology, and partly due to the fairly large parent-child grid-size ratio of 4:1.

Optimal tuning of MODFLOW-LGR was time consuming because the damping factor were hard to estimate in advance; it had to be optimized by trial and error.

The optimal choice of correction method appears to be very case dependent. Guidelines given by Mehl and Hill (2005) only partially applied here, where testing showed that correction method d gave the most accurate results.

The LGR closure criteria could be relaxed without deterioration of the simulation results.

The study of traces of just three particles gave ambiguous results. A more comprehensive study is necessary.

References:

VI

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Mehl, S. and Hill, M.C. (2002). Development and evaluation of a local grid refinement method for block-centered finite-difference ground-water models using shared nodes. Advances in Water Resources. 2002; 25(5): 497-511

Jørgensen, F. and Sandersen, P. (2006). Buried and open tunnel valleys in Denmark — erosion beneath multiple ice sheets. Quaternary Science Reviews 25: 1339–1363