Domain Decomposition in Shallow Water Modelling of Dutch Lakes for Multiple Applications

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1 Introduction

1.1 Area of interest

Lake IJssel, Lake Marken, and Veluwerandmeren originated from the construction of dams and land reclamation of an inland sea in the Netherlands (see Fig. 4). For Lake Marken and Veluwerandmeren the dynamic behavior is mainly governed by wind driven waves and flow of water. For Lake IJssel also discharge of River IJssel (in the south) and flushing of water towards the Wadden Sea (in the north) play a role. Proper computational modelling of the dynamics of waves and flow of water is a challenge. This is of importance for different societal aspects of these lakes: in safety assessments of the primary water defences, operational forecasting of flooding [1], and water quality and ecological studies.

1.2 Previous approaches

Previously, for modelling the hydrodynamic flow in the lake, two shallow water solvers were used: Delft3D-FLOW and WAQUA [2]. Delft3D-FLOW is the depth averaged (2DH) and three-dimensional (3D) shallow water solver in the modelling suite Delft3D [3]. Delft3D is open source and used worldwide. WAQUA is the 2DH shallow water solver in the modelling suite SIMONA. SIMONA is maintained for Dutch public works and only applied to the Dutch main waters (coastal area, rivers, and lakes). The computational kernels of Delft3D-FLOW and WAQUA are quite similar: both use the same ADI (Alternating Direction Implicit) time integration method on a staggered curvilinear computational grid.

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In first instance, for Delft3D-FLOW focus was on modelling flexibility and for WAQUA on good parallel performance. Parallel implementation of WAQUA was developed [4, 5] based on domain decomposition with an overlap of one subdomain. In the same period, non-overlapping domain decomposition with optimized coupling/absorbing boundary conditions was considered for Delft3D-FLOW [6, 7, 8]. Ideas of the latter were adapted for incorporation in WAQUA to enable more modelling flexibility and further improvement of the parallel performance, see [9]. For application of this approach to operational forecasting of flooding on Lake IJssel and Lake Marken, see [10]. The WAQUA shallow water solver is suitable for safety assessments of the primary water defences and operational forecasting of flooding. Water quality and ecological studies require more advanced modelling flexibility from Delft3D-FLOW (see for instance [11] for a typical application in Lake Marken). However, Delft3D-FLOW does not have such a good parallel behavior like WAQUA. This is a bottle neck for applications that require highly detailed modelling.

1.3 New approach

Currently there is a transition from Delft3D-FLOW and WAQUA/TRIWAQ to the shallow water solver for unstructured computational grids in the Delft3D FM (Flexible Mesh) suite [12, 13]. To enable the use of unstructured computational grids, the computational kernel of Delft3D FM is different from Delft3D-FLOW and WAQUA/TRIWAQ.

Delft3D FM solves the shallow-water equations with the spatial discretisation being achieved by a staggered finite volume method on an unstructured mesh of cells of varying complexity (triangles to hexagons). The discretised shallow water equations for the water levels are solved implicitly in time, with momentum advection treated explicitly. The velocities and fluxes are then obtained by back substitution. After linearisation of the temporal discretisation, the resulting systems are solved with a semi-implicit method. This involves a linear system which is currently solved by a minimum degree algorithm to reduce system size and a Conjugate Gradient iterative solver with block Jacobi preconditioner and ILU(0) factorization on the blocks as implemented in PETSc [14]. (Note that for this new simulation software for shallow water we are still working on major improvements, Delft3D FM is open source to enable collaboration world-wide.)

Because of these differences, a novel approach is required for model development and model application with Delft3D FM [12, 13]. In this paper we illustrate this for the new shallow water models of Lake IJssel, Lake Marken, and Veluwerandmeren. The aim is an integrated approach in which the Delft3D FM models can be used as a basis for the different societal aspects of these lakes. For that purpose we want to take advantage of the enhanced modelling possibilities of an unstructured computational grid. Therefore focus is on the computational grid and we developed a strategy to generate this, as outlined in section 2. For the different applications on the lakes,

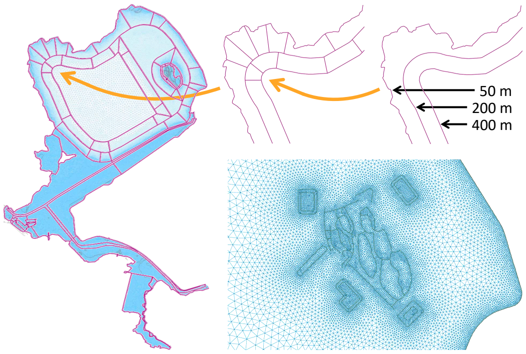

Fig. 1: On the top an illustration of the generation of the boundary fitted computational grid for Lake Marken. With 50 m triangular grid cells near the coast and 400 m triangular grid cells in the middle of the lake by using polygons. On the right bottom a local update of the computational grid near Marker Wadden.

section 3 illustrates how domain decomposition in Delft3D FM enables parallel computing for practical use. We end with some concluding remarks in section 4.

2 Computational grids

Lake IJssel, Lake Marken, and Veluwerandmeren are quite shallow lakes with local depth varations (due to navigation channels, pits for sand mining or that remained from the old inland sea, land reclamation for housing or nature). For accurate modelling the flow of water, these local depth variations and structures like dams and sluices should be incorporated properly. Also projection of topography on the computational grid needs special care. The required accuracy can differ in the application to different societal aspects. However, our aim is an integrated approach in which the model can serve as a basis for different model applications.

Key idea is to have enough grid resolution with 50 m triangular cells near the dikes (important for dike safety assessments and operational forecasting) and a coarser grid resolution with 400 m triangular cells where possible in order to save computational time (important both for operational forecasting and water quality studies). For this we used polygons to force the required local resolutions. See the top of Fig. 1 for an illustration for Lake Marken of the strategy to generate the computational grid. From an initial pilot we learned that we can make a Delft3D FM boundary fitted triangular grid that has similar accuracy as a uniform boundary fitted grid with 50 m triangular cells but with more than three times less grid cells and, as a consequence, computational times that are more than three times lower. With the grid generation strategy we were able, next to a proper fitting of the grid to the boundary, to incorporate important details of new land reclamation projects,

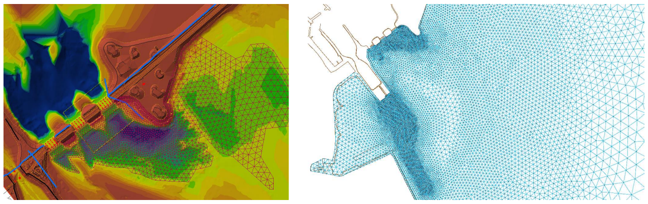

Fig. 2: Example near the discharge sluices of Den Oever (in north west part) of taking into account for the grid generation the erosion pits near the Afsluitdijk (left) and the resulting highly detailed parts of the grid (right).

like IJburg for housing and Marker Wadden for nature in Lake Marken. See Fig. 4 for the resulting computational grids.

Furthermore, the strategy enables the local adaptation of the computational grid later on. For Lake Marken this is important as several infrastructural projects are still running or being started in the near future. On the bottom right of Fig. 1 an example of such an adaptation for Lake Marken is shown. It shows the local update of the computational grid near Marker Wadden by following the local structures for the most recent outline of the islands (which are being built between 2016 and 2019) and pits around the islands (topography obtained from recent surveys with high resolution multibeam depth samples). This update is important for modelling (in combination with in situ measurements and remote sensing images) the effect of Marker Wadden on sediments in Lake Marken in water quality and ecological studies. For Lake IJssel the computational grid was locally adapted near the Afsluitdijk in the north for salt intrusion via the locks from the Wadden Sea. That resulted in highly detailed parts of the grid covering deep pits and navigation channels to better represent steep gradients in the topography, see the example in Fig. 2. Fig. 3 shows model results for Lake IJssel for the 2018 drought. Then, very little fresh water entered the lake from River IJssel. Therefore, it was not possible to flush the more saline water that accumulated in the deep pits to the Wadden Sea. As a consequence chloride spreaded all over the lake and chloride concentrations exceeded average norms at drinking water intakes in the mid west of the lake. To monitor this situation during the 2018 drought many measurement campaigns were performed on Lake IJssel. These measurements were used to validate the model, they are plotted as bullets on the model results in Fig. 3.

3 Domain decomposition for parallel computing in Delft3D FM

The new shallow water models with Delft3D FM of Lake IJssel, Lake Marken, and Veluwerandmeren incorporate important details by local grid refinement.

As a consequence, compared with the previous shallow water solvers, for Lake IJssel and Lake Marken the corresponding horizontal computational grids are about a factor 4 larger. The WAQUA model of Lake IJssel contains 111 763 horizontal grid

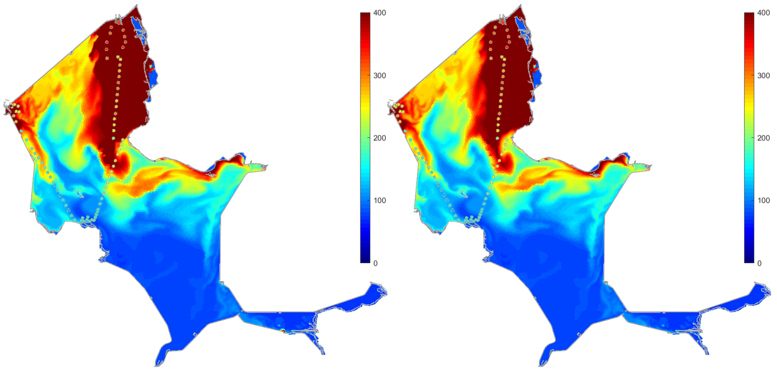

Fig. 3: Results of new model and measurements (bullets) during 2018 drought, chloride [mg/l] near bottom (left) and near surface (right).

elements, whereas the Delft3D FM model 369 683. For Lake Marken these numbers are 109 793 and 33 5141, respectively. The WAQUA model of Veluwerandmeren contains 64 616 horizontal grid elements, the Delft3D FM model 91 291. To be able to use these models for the different applications in practice, we want to apply parallel computing with Delft3D FM.

Current parallelisation of Delft3D FM is via domain decomposition with METIS [15] to distribute the computational work. At the interfaces between subdomains, halo regions are defined using degree 4 neighbours for a proper representation of discretised stencils (see [12, 13] for more details) at the interfaces and communication between subdomains via MPI [16]. On the right in Fig. 4 an example is shown of such a decomposition for the shallow water model of Lake Marken.

The shallow water models of Lake Marken and Lake IJssel were two of the real life testcases to study the current parallelization of Delft3D FM in two PRACE projects. These projects investigated possible improvements, amongst others strategies for automatic partitioning into subdomains, for more details we refer to [17, 18]. In the present paper we show results for the current parallelisation in the standard version of Delft3D FM.

To investigate the parallel performance of the new Delft3D FM shallow water models we run tests both in depth-averaged mode (2DH) and in three-dimensional mode (3D). For Lake IJssel in 3D the model was run with both hydrodynamics and salinity for a part of the drought period in 2018 with 5 boundary fitted layers in the vertical. For Lake Marken in 3D the model was run with hydrodynamics for the second half year of 2011 with 7 boundary fitted layers in the vertical. In 2DH the Lake IJssel and Lake Marken models were run with hydrodynamics for a storm in January 2007. For Lake Veluwerandmeren the model was run with hydrodynamics for a storm in December 2013 both in 2DH and 3D with 5 boundary fitted layers in the vertical. Tests were run at the Cartesius supercomputer with 2 Intel Xeon E5-

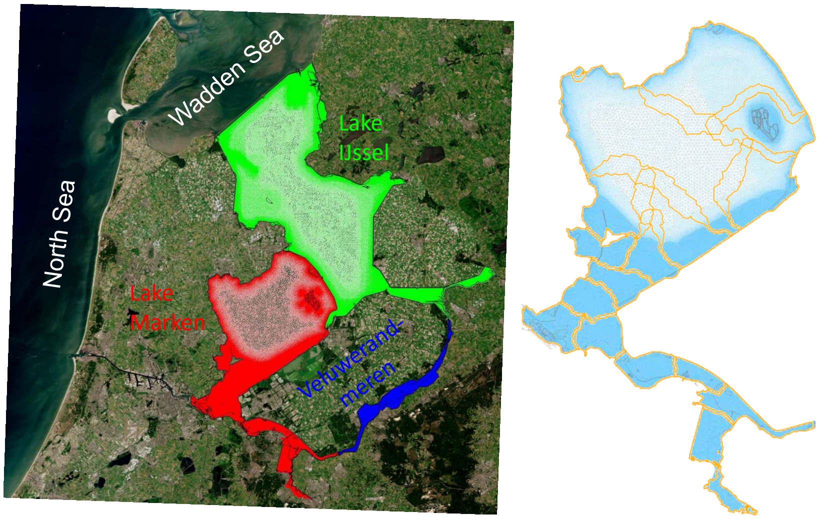

Fig. 4: On the left the area of interest with the computational grids of the lakes projected on a satellite image (by Copernicus Sentinel-2 from ESA at June 30th 2018, https://scihub.copernicus.eu/dhus). On the right an example for Lake Marken of automatic partitioning by domain decomposition with METIS into 16 subdomains. The overlap/halo regions are highlighted by orange lines (light gray in black and white print). Note that gridcells are 400 m in the middle of the lake and 50 m near the borders of the lake.

2697A v4 processors and 32 cores per node and InfiniBand and Intel MPI between the nodes (Bull B720 bullx system, SURF, the Netherlands).

Fig. 5 shows the speedup compared to computations on 1 node. The Veluwerandmeren model is relatively small. In 2DH parallel scaling stops after about 4 nodes (with 128 cores), for 3D there is more computational work per horizontal grid point and computational times can still be lowered by incorporating more nodes/cores. The Lake IJssel and Lake Marken models have comparable horizontal grid sizes and speedup also shows similar behavior. In 2DH parallel scaling stops at about 16 nodes (with 512 cores), for 3D parallel scaling continues even beyond 16 nodes. This last observation is important for application in 3D for real life problems in these lakes with salinity, nutrients, sediments, and algae. The current numerical implementation of Delft3D FM uses a time integration method with automatic time stepping. The time step (that is used for the whole model domain) is determined with a local CFL criterium for which small grid cells may result in relatively small time steps. The computational grids for Lake IJssel and Lake Marken contain highly detailed parts which may lead to such small time steps. To finish the required simulation periods, which may be typically a year for applications in water quality and ecology, this accumulates to a lot of time steps to be taken. But as the scaling in 3D is still good, computational times can be further lowered by incorporating more nodes/cores. Note that, because of complexity due to different processes modeled and the automatic time stepping approach, it is hard to present generic and characteristic numbers that relate problem size and computational performance. For a model that only involves the shallow water equations, about 40 % to 60 % of the wall clock time is due to the solver part, see [17] for more details. This contribution is much lower when incorporating additional processes like salt intrusion for Lake IJssel, profiling results for this and other models (amongst others for the North Sea with transport of nutrients and algal blooms) are currently being analyzed in a running PRACE project.

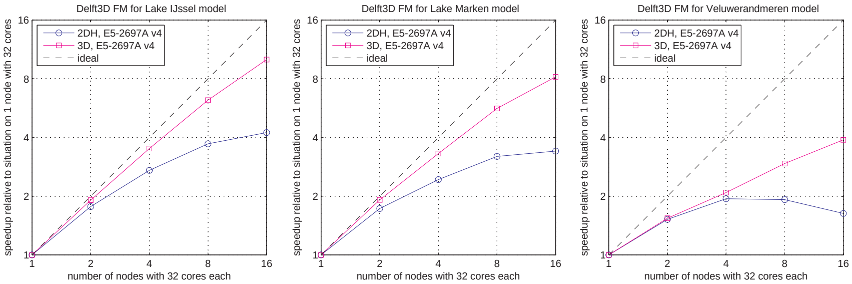

Fig. 5: Speed up of Delft3D FM shallow water models for Lake IJssel (left), Lake Marken (middle), and Veluwerandmeren (right) compared to computations on 1 node on Cartesius supercomputer of SURF.

4 Conclusions and outlook

In this paper we illustrated the development of new shallow water models of Lake IJssel, Lake Marken, and Veluwerandmeren with Delft3D FM. The aim is an integrated approach in which the models can be used as a basis for the different societal aspects of these lakes: in safety assessments of the primary water defences, operational forecasting of flooding, and water quality and ecological studies. For that purpose domain decomposition in the current numerical implementation of Delft3D FM enables parallel computing for practical use. However, the time integration method used with automatic time stepping may become a bottleneck in the near future for these models due to the highly detailed parts in the computational grids. Therefore, a next step would be to make a more implicit time integration method available in Delft3D FM. That may also require more advanced non-overlapping domain decomposition techniques with optimized coupling/absorbing boundary conditions, as applied before in the previous shallow water solvers for these lakes.

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