Exploring Different Domain Decomposition Approaches for Enhanced Modelling of Real-Life Applications in Lakes

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1 Introduction

Several ongoing and planned developments in Lake IJssel and Lake Marken require impact assessments. For that purpose there is a need for computational models that can be applied in practice: with enough quality and resolution and for which computations are fast enough for the specific impact assessments (a.o. nutrient currents, water quality, ecology). Many developments consist of a local measure that may have effect on the global scale of the whole lake. Furthermore, a combination of different measures may have a stronger, cumulative effect. This asks for a model approach with high resolution in the vicinity of the measures and that takes into account the global system behavior further away from the taken and planned measures. Models for Lake IJssel and Lake Marken are based on knowledge of the underlying physical, chemical, and biological processes. This is essential because of the limited amount of available in situ measurement data. For impact assessments, the models simulate quantities related to water, temperature, and substances. A typical example is the silt model for Lake Marken [15, 2] (see [11] for a model application in integral impact assessments). Currently, practical applications with the silt model for Lake Marken are still with the Delft3D 4 software [7]. For Lake IJssel and Lake Marken there is a transition to the Delft3D Flexible Mesh (Delft3D FM) software [8, 14].

During a recent practical application of the Lake Marken silt model to an important real-life case, bottlenecks were encountered. It was not possible to perform simulations of sufficient quality and resolution required for the study of impact assessments around Marker Wadden within reasonable computational times. Therefore the current possibilities in the Delft3D 4 software on modern hardware were explored for more quality/resolution and faster computations. This paper focuses on the shal-

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low water solver in Delft3D 4 for currents, one of the two computationally most intensive components. For results of the other component, SWAN [3] for waves, we refer to [9]. In addition, for the same model application to Marker Wadden, we also explored the current possibilities of the shallow water solvers in Delft3D FM and SIMONA [1]. We compare the computational time (purely solver times without I/O) for the flow part (only shallow water flow, no waves or other additional processes included) for several different possibilities of these three shallow water solvers on the same modern hardware.

2 Area of interest

Lake IJssel and Lake Marken originated from the construction of dams and land reclamation of an inland sea in the Netherlands (see the left picture in Fig. 1). For Lake Marken the dynamic behavior is mainly governed by wind-driven waves and water flow. 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 (see for instance [12]), and water quality and ecological studies (see for instance [11]).

Marker Wadden, a collection of artificial archipelago-type of islands, is located in the east of Lake Marken (see also left in Fig. 1). The first construction phase started in 2016 (for a remote sensing image during this construction, see the upper-right picture in Fig. 1). Currently, there are plans for an extension of Marker Wadden for which the local and global impacts need to be assessed.

3 Local grid refinement via domain decomposition in Delft3D 4

For impact assessments of the possible extension of Marker Wadden and studying transport in between the islands (grid) resolutions higher than currently used are needed in the silt model of Lake Marken. On the left of Figure 2, the original curvilinear computational grid of the applied Delft3D 4 model with a resolution of about 150 m is shown in light blue. The contours of the Marker Wadden islands (dark blue) clearly show that this resolution is insufficient for the modeling of the flow and transport processes around the Marker Wadden. The pink area in the right picture of Figure 2 shows the local area of interest.

For refining the grid in the local areas of interest we exploit the possibilities of the current Delft3D 4 domain decomposition implementation. Because of the choices made in that implementation, one should take care of specific properties. The solver for the shallow-water equations uses an Alternating Direction Implicit (ADI) time integration method on orthogonal curvilinear grids. It contains domain decomposition in the geographical domain, also to enable grid refinement, with forward and backward elimination sweeps through all subdomains in the two implicit ADI directions. At the interfaces between the subdomains it uses lower-order stencils. In case of grid refinement constant interpolation is applied. When subdomains with

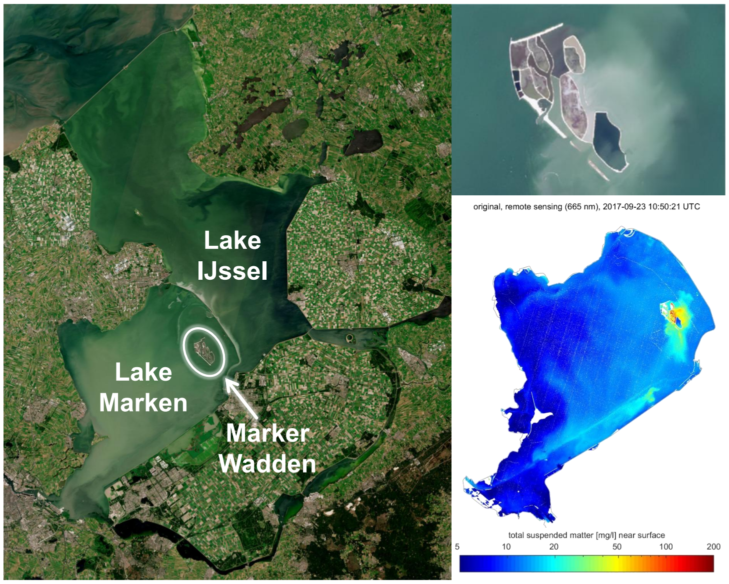

Fig. 1 On the left the area of interest: Lake IJssel and Lake Marken with the location of Marker Wadden marked by a white ellipse, satellite image on June 30th 2018 from Copernicus Sentinel-2, ESA [5]. On the right top a satellite image on September 23rd 2017 of Marker Wadden during a construction phase from Copernicus Sentinel-2, ESA [5]. The right bottom picture shows the total amount of suspended matter near the water surface of Lake Marken at that moment and is based on the same source data from Copernicus Sentinel-2.

different grid resolution are coupled, numerical errors may occur that propagate globally at the corners of interfaces. This is due to the current implementation of domain decomposition in Delft3D 4: unknowns near the interface of the coarse grid at the internal corner are not uniquely defined and, therefore, not coupled properly to the adjacent unknowns near the interface of the fine grid. Based on these specific properties, we made the practical choice of using an additional transition zone around the area of interest and of using domain decomposition only in one direction to prevent internal corners. The transition zone is indicated in blue in the right picture of Figure 2: the numerical effects introduced by the domain decomposition grid refinement are assumed to damp out sufficiently in that zone before they enter the local area of interest. We decompose the original domain into two subdomains, a west subdomain and an east subdomain. The east subdomain contains the transition zone and the area of interest. The west subdomain uses the original computational grid. On the east subdomain the computational grid is refined with a factor of 5. On the left picture of Figure 3 the computational grid on the west subdomain is shown, in the middle picture the one on the east subdomain.

The model is run for a simulation period of one day that includes the storm Poly of July 5th 2023 that had a peak in Lake Marken at around 12h. Figure 4 shows the computed magnitude of the depth-averaged velocity at that peak around Marker

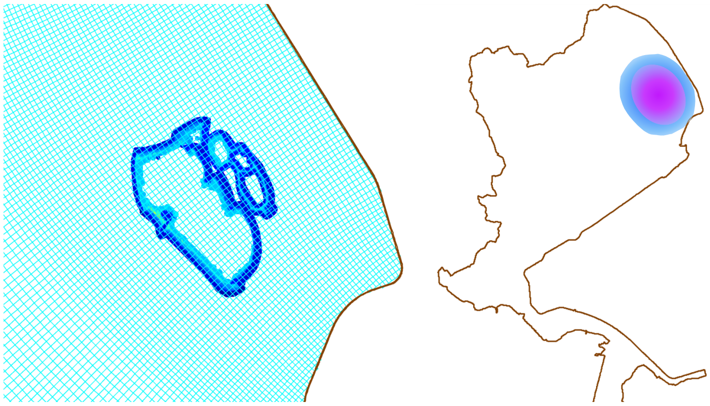

Fig. 2 On the left: original curvi-linear computational grid (light blue) and high resolution samples of the shoreline of Marker Wadden. On the right: area of interest (pink) and transition zone (blue).

Wadden. In the left picture the result obtained when using the original computational grid with a resolution of about 150 m; in the right picture the result obtained when using the grid with locally a resolution of 30 m. By comparing the two different results in Figure 4 it can be seen that this improves due to locally a higher resolution that captures essential details of the Marker Wadden.

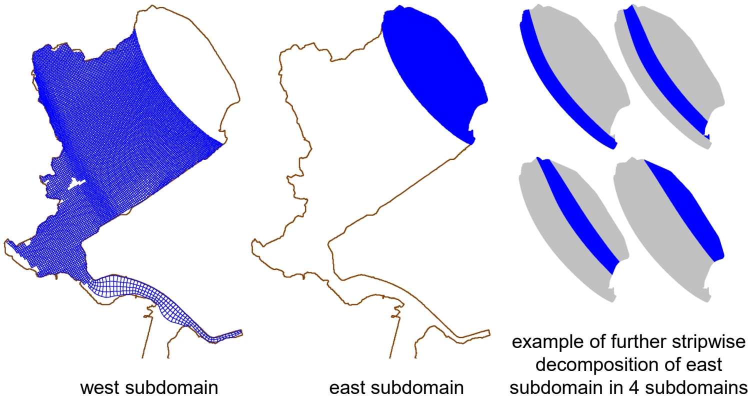

Fig. 3 On the left: the computational grid applied in the west subdomain. In the middle: the 5 times refined computational grid applied in the east subdomain. On the right: the east subdomain decomposed in 4 strips.

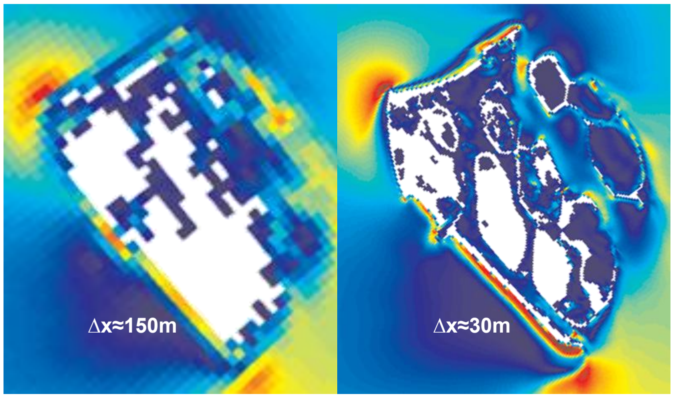

Fig. 4 Computed magnitude of depth-averaged velocity at the peak (about 12h, July 5th 2023) of storm Poly around Marker Wadden in Lake Marken. Left: original computational grid with a local resolution of about 150 m. Right: refined computational grid with a local resolution of about 30 m.

3.1 Faster computations on modern hardware with Delft3D 4

Modern hardware tends to have multicore nodes with shared memory for an increasing number of cores. In the domain decomposition implementation applied in Delft3D 4 that possibility to lower computational times can only be exploited in one direction. The implementation is such that only in one direction the forward and backward elimination sweeps through all subdomains in the implicit ADI direction run efficiently in parallel for shared memory. This is due to the way the parallel method for tridiagonal systems by Wang [20] and the use of threads for the communication between the subdomains in shared memory has been implemented.

To enable this possibility for the silt model of Lake Marken, the east subdomain is further decomposed stripwise in new subdomains without further refinement. Here, for load balancing, each new subdomain contains about the same number of computational grid points. See the right picture of Figure 3 for the case of a further decomposition in 4 subdomains. To study the parallel performance of this approach, we have considered a further decomposition of the east subdomain in 2 subdomains (in total 3 subdomains), 4 subdomains (in total 5 subdomains), and 20 subdomains (in total 21 subdomains). For 21 subdomains the computational load is balanced: each of the 20 subdomains on the east has the same amount of computational grid points as the entire west subdomain.

The model is run on a multicore node with 2 Intel Xeon Platinum 8462Y processors, 64 cores, 512 GB shared memory, and AlmaLinux 8 operating system. The green squares in Figure 5 show the wall-clock time for the local grid refinement and decompositions considered with Delft3D 4. With this approach the wall-clock time for the flow part of the silt model can be reduced with a factor 8 on 21 subdomains on 21 cores. This turned out to be of practical value for current real-life applications of the silt model with Delft3D 4 on modern hardware.

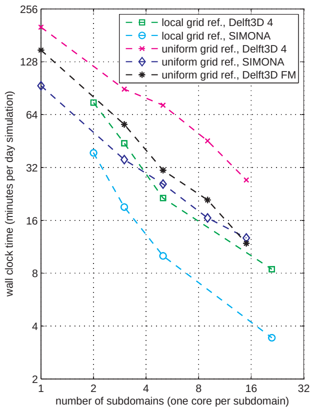

Fig. 5 Wall-clock time (purely solver times without I/O) for the flow part (only shallow water flow, no waves or other additional processes included) of the silt model of Lake Marken for three different shallow water solvers and possible approaches.

4 Local grid refinement via domain decomposition in SIMONA

Besides Delft3D 4, also the shallow water solver from SIMONA was used to model the flow in Lake IJssel and Lake Marken. The computational kernels of the shallow water solvers of Delft3D 4 and SIMONA are similar: both use the same ADI (Alternating Direction Implicit) time integration method on a staggered orthogonal curvilinear computational grid. Parallel implementation of SIMONA was developed [16, 19] 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 4 [6, 18, 17], but not implemented later on. Ideas of the latter were adapted for incorporation in SIMONA to enable more modelling flexibility and further improvement of the parallel performance, see [4]. (For application of this approach to operational forecasting of flooding on Lake IJssel and Lake Marken, see [13].) SIMONA has more advanced features than Delft3D 4 for domain decomposition and parallel computing and uses MPI for communication between subdomain. However, SIMONA has less functionality for modelling additional processes like coupling to waves and sediments like Delft3D 4. Note again that, here, we compare the computational time (purely solver times without I/O) for the flow part (only shallow water flow, no waves or other additional processes included). The light blue circles in Figure 5 show the wall-clock time for the local grid refinement and decompositions considered with SIMONA. It can be observed that SIMONA shows the same type of behavior as Delft3D 4 when the number of subdomains increases but is on average more than two times faster than Delft3D 4.

5 Alternative approaches with uniform grid refinement

If the computational grid is uniformly refined by a factor of 5 then there are more possibilities for a parallel speed-up with the current implementations of the shallow water solvers in Delft3D 4, SIMONA, and Delft3D FM. Note that, here we use the same computational grid, model settings, and model input for these three shallow water solvers. For Delft3D 4 we show another possibility with a stripwise domain decomposition (with no further refinement) where each subdomain has about the same amount of computational grid points. The magenta crosses in Figure 5 show the corresponding wall-clock times. For SIMONA we considered the parallel version in which the computational load is distributed automatically and equally in stripwise (non-overlapping) subdomains. Although, due to the more efficient implementation, the corresponding wall-clock times (the dark blue diamonds in Figure 5) are quite reasonable, still the approach with local grid refinement for SIMONA is faster. Delft3D FM differs more from Delft3D 4 and SIMONA, for details we refer to [14] and the specific application to Lake Marken in [10]. Results of Delft3D FM for the same refined curvilinear grid do not exploit the possibilities of being able to use an unstructured grid and are considered here just for illustration purposes. The black stars in Figure 5 show the corresponding wall-clock times. It can be observed that Delft3D FM and SIMONA show on average similar behavior of the wall-clock times in case of uniform grid refinement. Though, overall, one may conclude that for computational time it pays off to refine only locally.

6 Conclusions and outlook

For investigating different societal aspects of the Dutch lakes by integral impact assessments, there is a need for accurate hydrodynamic and water quality models. A major requirement is enough local resolution around the measure with enough global system behavior while computations are fast enough. For a typical practical example we considered different domain decomposition approaches in three shallow solvers. An approach with domain decomposition in the current implementation of Delft3D 4 was applied for local grid refinement and significant reduction of the wall-clock time on modern hardware. This turned out to be of practical value for current real-life applications. Other possibilities were explored to obtain an overview of what is currently possible and feasible. Outcomes of this will be input about what can be further improved in the near future in the modelling strategy and/or the simulation software being used.

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