NEXT GENERATION HYDRO SOFTWARE

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A few years ago Deltares started a large multidisciplinary project named Next Generation Hydro Software. The main focus of the project is to improve, harmonize and integrate existing hydro software that has been developed throughout the years. Important technological innovations include development of the new computational core D-Flow Flexible Mesh, as well as the user-friendly, open modelling environment Delta Shell. The project involves more than 40 scientists and software engineers.

The new integrated system will allow both water managers and modelers to do their work better and faster. The unique characteristic of the project is that it focuses on the possibility of setting up integrated models of the whole aquatic chain from the source to the sea, resulting in complex model configurations. The challenges further increase because of the involvement of experts from many different fields within the aforementioned aquatic chain.

Furthermore, the project addresses the complete workflow of a modeler, including model setup, calibration and validation. For this purpose the system includes new scientific visualization, analysis and interactive modeling tools that enable users to improve their understanding of the modelled processes.

Applications of the system show the successful integration of 0D (lumped hydrological models and real-time control rules), 1D (river flow and water quality models) and 2D/3D model components (river, estuary and coastal areas). In this paper some of the preliminary results of the project are demonstrated, as well as its current status and a preview of possible future developments.

INTRODUCTION

Deltares hydro software has been leading the way for decades and is used throughout the world by water managers, modelers, consultants, and researchers. Since 2011, a total number of five packages are being integrated and have undergone a fundamental technological overhaul as part of the Next Generation Hydro Software (NGHS) project. The packages, used within the international water modeling community, include: Delft3D (Lesser *et al.*, [1]), Simona (Vollebregt *et al.*, [2]), SOBEK (Verwey, [3]), and the packages used mainly in the

Netherlands: DUFLOW (Clemmens, [4]) and SOBEK-RE (WL | Delft Hydraulics, [5]). These packages are used for the simulation of flood forecasting, optimization of drainage systems, control of irrigation systems, river morphology, salt intrusion and surface water quality and many other applications. Delft3D and Simona are modelling suites used for two-dimensional and three-dimensional flow, as well as sediment transport and morphology, waves, water quality and ecology processes. One of the main goal of the NGHS project is to integrate functionality captured in these packages within a single software framework named Delta Shell (Donchyts *et al.*, [6]).

The idea to start the NGHS project originates from 2005. An international knowledge position audit stated that the Deltares software needed a profound renewal to remain state-of-the-art. Besides this statement, an in house inventory of the software showed that: parts of the software were outdated and some of them were built using compilers that are not supported anymore; the software consisted of over 6 million lines of code, resulting in increasing maintenance costs; throughout the years many different programmers had worked on the software resulting in a too high complexity of the code. Finally, Deltares redefined its software strategy in which it stated again that the Deltares software should be state-of-the-art at all times.
Another important aspect is that the final results should be released as open-source components. This relates to both the new multi-purpose numerical model D-Flow Flexible Mesh as well as the integrated modeling environment Delta Shell.

Due to the large size of the project it was supported by the Dutch government and water boards (Rijkswaterstaat and STOWA), but also by research institutes (Delft University of Technology and UNESCO-IHE), which have been using existing Deltares software for decades or more. It was agreed that the main deliverable within the project would be a new computational core working on unstructured grids that would be able to replace the existing five computational cores that were used at the time (Figure 1). The new computational core is called D-Flow Flexible Mesh 1D2D3D (or D-Flow FM).
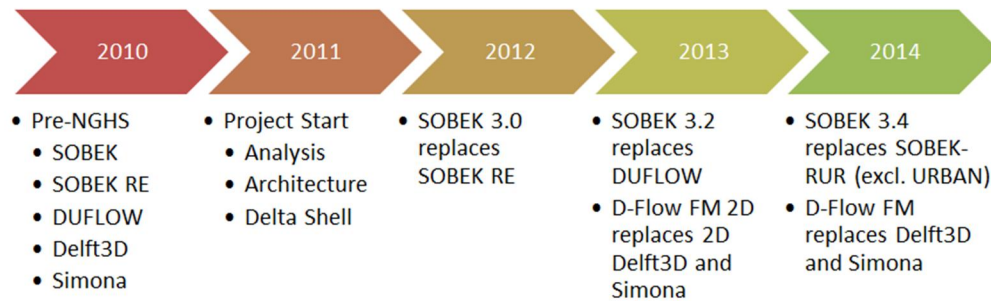

Figure 1. Time path and releases of the NGHS project

Further analysis showed that the existing 1D software packages (SOBEK-RE, SOBEK, DUFLOW) had functionality that could not be replaced in time within the D-Flow Flexible Mesh 1D core. It was therefore decided to integrate the existing SOBEK computational core within the new 1D Flow model plug-in in the Delta Shell framework. Thanks to the modular design of the framework and its plug-ins, the D-Flow Flexible Mesh 1D core can easily be integrated in the future when all the needed functionalities are present.

The strength and the main innovations of the new hydro software lie within **the new computational core D-Flow Flexible Mesh** and **the integrated modeling environment Delta Shell**.

The main benefits of the new hydro software for users are: it has a new, powerful computational core that works faster than the current versions; this powerful computational core can provide an integrated model of the water system, from source to sea (Figure 2); the new computational core uses unstructured grids, resulting in a more precise and effective representation of the flow; the improved computational core allows for very large and complex models and scales well. Furthermore, the most important features of the new modeling environment assume that: a map of the area is continuously present, so all the measures affecting the catchment are visible at a glance; it is possible to couple and run several models; the same tools are used for different models; numerical models are decoupled from the high-level data structures like hydrographic schematizations, grids, or measurements; a wide user group should be able to use the new software (developers, modelers, advisors, managers).
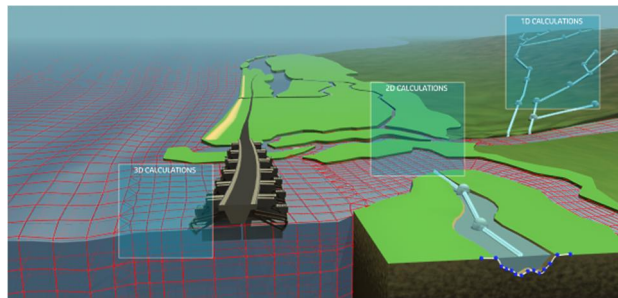

Figure 2. Types of numerical models implemented within the NGHS project

The final result of the project will be an integrated 1D-2D-3D simulation suite that can operate in both command-line and graphical user interface modes. The suite will be called **Delft3D Flexible Mesh**, with the following modules integrated within Delta Shell:

- D-Flow
- D-Waves
- D-Morphology
- D-Real Time Control
- D-Water Quality
- D-Rainfall Runoff

The NGHS project is a typical example of an integrated environmental modeling (IEM) project. IEM is an emerging discipline aiming to solve complex environmental problems as discussed in literature (Laniak *et al.*, [7]) . The NGHS project covers practically all of the areas discussed in the roadmap, including *IEM applications*, *IEM science*, *IEM technology* and *IEM community*. Furthermore the graphical user interface developed within the project has extensive integration with GIS technologies and standards, which plays an important role for the data preparation and presentation. This also helps to bridge the gaps between scientific research modeling and management (Argent, [8]).

From the software design perspective, the new system follows industry software development principles in both project management (Agile, Scrum, eXtreme Programming, see Schwaber, [9], Beck, [10]) and software engineering practices (OOA/OOP - object-oriented analysis and design, DDD - domain driven design, AOP - aspect-oriented programming, see Booch, [11], Evans, [12], Kiczales, [13]).

One of the most used design principles followed by the NGHS software is Inversion of Control (IoC), which is sometimes called the Hollywood Principle. In particular, it was applied to integrate the model components, which never implement the main run loop itself but instead are integrated as replaceable software components (shared/dynamic libraries) using a workflow API (application programming interface). After careful consideration, none of the existing model coupling frameworks have been used to integrate model components at the system level, mainly due to the fact that none of the model coupling frameworks allowed the level of abstraction required to couple input/output at the *Entity[1]* level.

Most of the Delta Shell components are developed using the C# programming language, including a number of library components developed using C/C++. Most of the model components were developed using the FORTRAN programming language.

D-FLOW FLEXIBLE MESH - THE NEW COMPUTATIONAL CORE

D-Flow Flexible Mesh is the new software engine for hydrodynamic simulations on unstructured grids in 1D-2D-3D. It combines the familiar curvilinear meshes from Delft3D with unstructured meshes that consist of triangles, pentagons, hexagons and 1D channel networks, all in one single mesh. This enables the modeler to construct high quality model meshes with less effort, in particular for complicated geometries such as delta regions, river junctions, harbors, intertidal flats and more. Besides, schematizations that require multiple spatial scales can now benefit from much easier coupling between 1D, 2D and 3D mesh regions.

The numerical solver combines proven technology from the hydrodynamic engines of SOBEK 2 and Delft3D and generalizes this for unstructured grids (Kernkamp *et al.* [14]). In recent years, several major new innovations have been undertaken: 3D (hydrostatic) hydrodynamics on adaptive sigma layers and fixed z-layers, including several heat flux models and turbulence models (mainly k-epsilon). High-resolution vegetation effects are evaluated using a subgrid specification of vegetation coverage and the resulting vegetation roughness. Sediment transport and morphology is based on a generalized version of the Delft3D-MOR(phology) module.

The new model kernel implements several high performance features. Multicore processor architectures are automatically utilized, using OpenMP. Schematizations with very large meshes will benefit from domain partitioning and running on distributed memory clusters with the MPI-based parallel solver in D-Flow FM (van der Pijl *et al.* [15]). Next, higher accuracy is achieved by the use of subgrid features, for example: a subgrid weir energy loss formulation, and 2D conveyance computation on linearly sloped bed levels.

In addition to the above core hydrodynamic components, D-Flow FM also can be coupled to other modules for specific physical processes. For example, there is a WAVE-coupling with the SWAN wave modeling program (Booij *et al.* [16]). Also, there is a water quality/ecology coupling with the DELWAQ program (Postma, [17]). The former is a time-step-based online coupling, which uses the ESMF interpolation utilities for mapping the flow and wave grids onto one another (Hill, [18]). The D-Flow FM core implements the Basic Model Interface (BMI)

[1] Entity: In DDD - an object that is not defined by its attributes, but rather by a thread of continuity and its identity.

standard to facilitate these couplings (Peckham, [19]), and this has proven to open up surprising new interaction possibilities, for example: to interact directly with a running model and the model state from a graphical user interface.
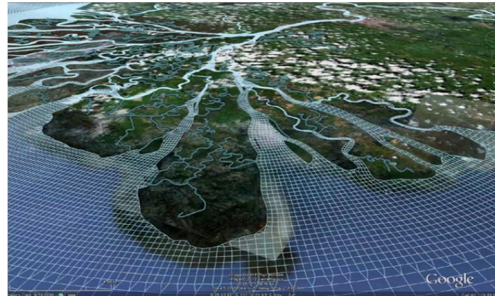

Figure 3. Example of an unstructured grid used within a D-FLOW FM model

DELTA SHELL – OPEN INTEGRATED MODELING SYSTEM

Integrated modeling has become a very popular topic within environmental modeling, since it helps solving problems that are difficult to simulate using a single model. However, managing the complexity of integrated models and minimizing the time required for their setup remains a challenging task. Delta Shell intends to simplify this task by providing a set of components used to define, save and visualize various scientific data structures, as well as coupled model configurations. Delta Shell can operate in either command-line or graphical user interface mode. The architecture of the system is presented in Figure 4.
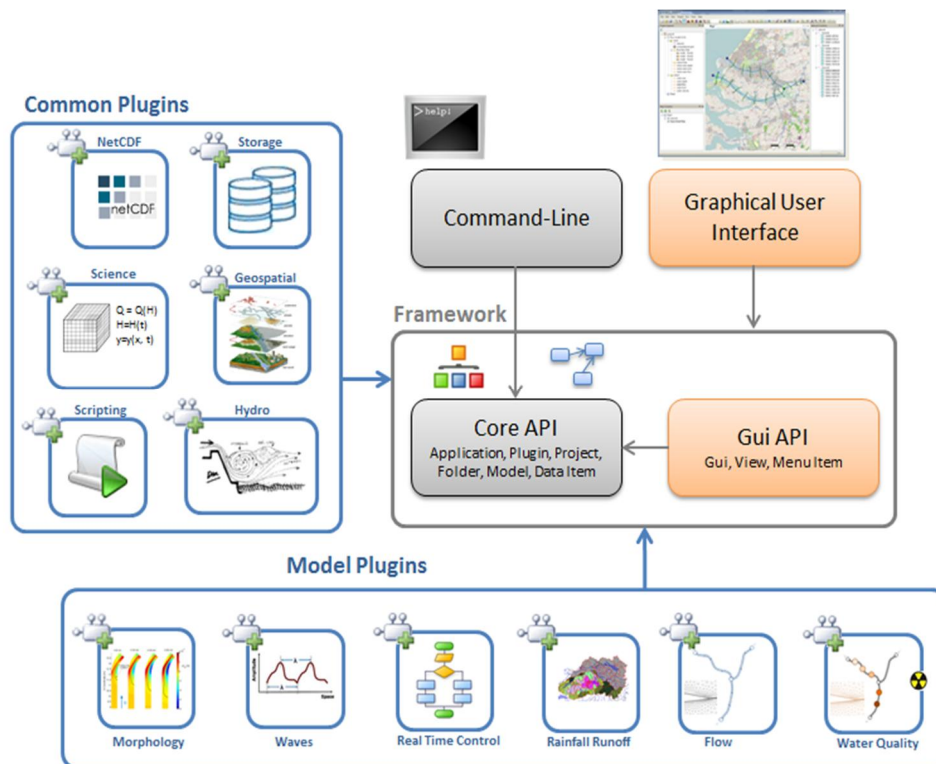

Figure 4: Overview of Delta Shell architecture configured for Delft3D Flexible Mesh 2015

The development is largely based on high-end open-source libraries and is available as open-source software. The architecture facilitates development of new **plug-ins**, for example to import/export model configurations, integrate models or provide specific visualization components or manage geospatial and time dependent data. Furthermore, it provides a clean and intuitive application programming interface (API) fully accessible from the Python-based scripting environment. Some of the applications developed using Delta Shell software framework include, but are not limited to:

SOBEK 3 - a new version of graphical user interface used to simulate flow of water and transport of pollutants in catchments, rivers and channels is shown in Figure 5.

D-Flow FM graphical user interface - the new software package for hydrodynamic simulations on unstructured grids in 1D-2D-3D developed at Deltares, is shown in Figure 6.
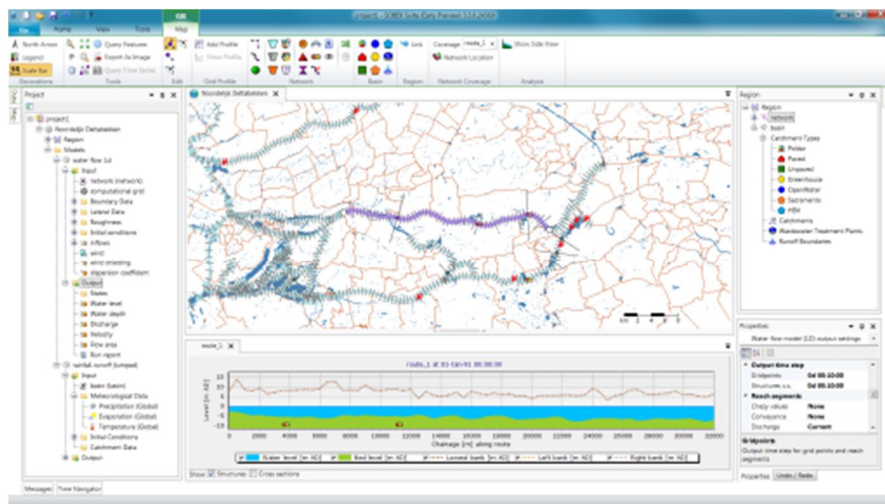

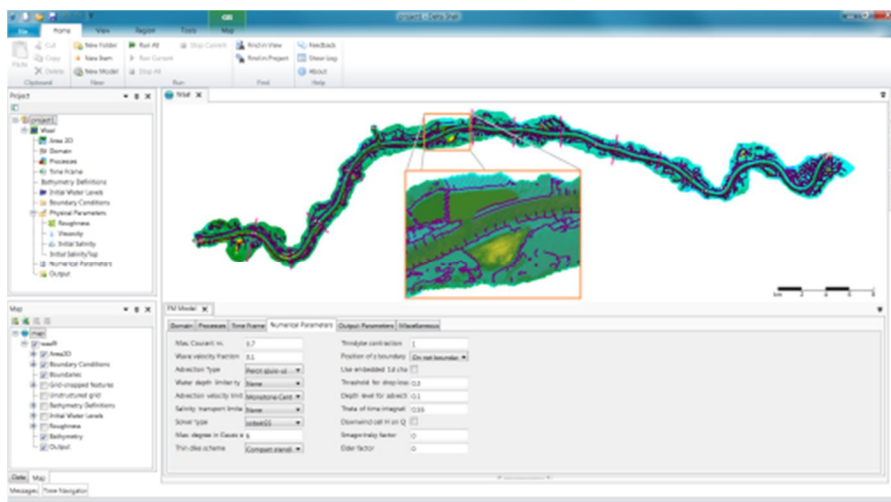Figure 5. Example application of Delta Shell: SOBEK 3

Figure 6. Example application of Delta Shell: D-Flow FM

To ensure state of the art functionality a number of user workshops were organized to make an inventory of the end user needs and to allow users to provide feedback on what has already

been developed. The results of these workshops had a large influence on the Delta Shell architecture.

One of the challenges of the Delta Shell development was to allow flexible coupling of the environmental models in a single system with minimal changes to the model engines. Delta Shell uses a very flexible, non-intrusive approach to coupling models by assimilating integrated modelling experiences gained during development of the model coupling standards such as OpenMI, ESMF, OMS (Gregersen, [20], Hill, [18], David, [21], Jagers, [22]) and operational forecasting systems such as Delft-FEWS (Werner, [23]).

Another important goal of the Delta Shell development was to target different user types, like researchers which prefer working in environments such as Matlab, decision makers requiring an aggregated view of the models, and advisors asking for a rapid setup and calibration of the models. By allowing variation in the ways Delta Shell can be operated (command-line, scripting, user interface and on a longer term web-based) it was possible to satisfy most of the needs of these user groups.

Delta Shell is heavily based on a number of high quality open-source components and open standards. Its file formats include the popular embedded database SQLite and the multi-dimensional storage format NetCDF, for geospatial data and manipulation it uses libraries like SharpMap and GDAL/OGR, and for naming of quantities etc. the CF (Climate Forecasting) conventions. A scripting component, based on the open source IronPython library, provides flexibility not available in previous versions of the SOBEK suite.

CONCLUSIONS AND OUTLOOK

The NGHS project that has been described in this paper focused on phasing out and integration of existing software and reducing maintenance costs. Delta Shell as a modeling framework has been used to achieve these goals. Model plug-ins that represent or can replace existing software have successfully been developed within the project. A new computational core named D-Flow FM, which is capable of modeling 1D, 2D, and 3D applications in a flexible and integrated fashion, has been developed and integrated within the Delta Shell framework.

Deltares plans to continue this development in international collaboration (through open source), by further improvement of existing instruments and through the implementation of new innovative model codes and promising new developments in the field of software engineering.

Most of the results of the NGHS project will be available as open source products on the Deltares open-source web site[2] after the project is finished.

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