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Interactive web-based flood modeling at country wide scale and planter size resolution.

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Abstract The flooding of rural and urban areas is an increasing hazard to society. Accurate and timely predictions are essential for the water manager to prepare and respond to these hazards. Predicting flooding requires a numerical model that represents the physical processes (rain, evaporation, infiltration, overland flow, groundwater flow). This model, fed with measurements, and possible measures, calculates the expected flooding. The traditional working method consists of a three step process: schematization setup, running and post-processing, with a total feedback time of hours. This process is suitable for confirmatory modeling. Most of the time, models are applied exploratory, requiring a different workflow. Enabling exploratory modeling requires a shift in utilisation of the instrument. Stakeholders are in control and together evaluate ideas by interacting with the model through a mobile compatible website, supported by the modelers expertise. Enabling this type of interactivity requires a new level of performance. The $3Di$ platform, in which the new approach was applied, consists of a new flooding and hydrological model (1D/2D) with a corresponding cloud based infrastructure. Applications in rural and urban areas of $\mathcal{O}$(1000km2) at a resolution of $\mathcal{O}$(0.1m) have shown its capabilities for both exploratory and confirmatory modeling. The ambition that every component should be at least a 100 times faster than the previous approach, resulted in several advancements, both in the numerical engine and the software that interacts with the user and pushes the data to the web. Here we show advancements in the architecture and model communication.

Keywords: interactive, overland flooding, web-based, modeling, hydrodynamic, social modeling

1 Introduction

The flooding of rural and urban areas is an increasing hazard to society. Accurate and timely predictions are essential for the water manager to be able to carefully plan, design, and control the effects of flooding hazard. For the prediction of these flooding hazards requires a numerical model that represents the physical processes (rain, evaporation, flow, infiltration). This model is fed with measurements from current or historic events. The results of these calculations, the expected flooding, is used for damage estimates, dike design, spatial and emergency planning, and for coordinating response efforts. Several challenges required an innovative redesign of both the numerical model and the information infrastructure where it is nested within.

These challenges arise from the movement towards more modern working methods and the ever increasing data volumes. The working methods are changing on different aspects.

- *Mono-disciplinary versus integrated:* Models used to be created by one or few people working in the same discipline. The challenge now is to model the integrated environment, which can best be approached as a community [Voinov et al., 2010] of different disciplines.

- *Confirmatory versus exploratory:* From assuming that the model is valid and can be used for hypothesis testing to realizing it's a made-up simplification of reality [Oreskes et al., 1994] that can be used to explore possibilities.
- *Passive versus interactive:* Moving from the pre-processing, wait a few hours, post-processing cycle towards a millisecond feedback loop with high resolution and connected physical processes. The challenge here is to move from the scale of a square kilometer [for example Losasso et al., 2008] to the scale of small country.
- *Solitary versus social:* The solitary modeler creating static pictures for a 600 page report describing all the different scenarios to a group of stakeholders in control [1] of a model running simultaneous on their mobile devices and a big screen in the control room.

The amount of data involved in preparing the model is rapidly increasing. There is an increase in supply of data caused by the ever growing measurement resolution and spatial coverage. For example, the topology of waterbodies at a spatial coverage of a small country is used to determine if the water will find its way into one's neighborhood. The topography and infiltration rate at a spatial resolution of a planter determine if the water will flow to one's backyard or the neighbors. How can we design a platform that is suitable for this new modeling approach and meets the corresponding challenges?

The $3Di$ platform, in which these approaches and several new ones are applied, consists of a new overland flooding model (1D/2D) and a corresponding infrastructure. This platform enables interactive web-based modeling of rural and urban areas at coverages of $\mathcal{O}$(1000km2) at a resolution of $\mathcal{O}$(0.1m). Here we describe the advances in the numerical model, architecture, and visualization techniques.

2 NUMERICAL MODEL: FROM PASSIVE TO INTERACTIVE

The $3Di$ computational core originates from components of the SOBEK 1D2D flooding software [Stelling and Verwey, 2006] with three major improvements: 1. streamlining of the software to offer access to the memory of a running model, 2. overland flow at subgrid scale and 3. inclusion subsoil processes at subgrid scale .

To enable interactive use, the flooding software was stripped of it's main timeloop. A core library remains, with all numerical algorithms. On top of this library a light-weight Application Programming Interface (API) exposes direct memory access the variables and to the control functions.

By introspection, the outside world (e.g., a Python-based website, a C#-Graphical User Interface (GUI), a MATLAB-script) can examine model state at run time. More specifically: get current water levels and flow fields, current running state of water pumps, and other structures, active meteorological forcings. Each of these state variables can just as easily be *set* as they are *get*. These functions are implemented in correspondence with the Basic Model Interface (BMI) standard [Peckham et al., 2013]. This is how the model directly 'feels' and uses its new state.

1. **variable = get("name")**: Return a variable from the model
2. **set("name", variable)**: Set a variable into the model

The freedom of interaction is possible due to the core adhering to the Hollywood Principle: "Don't call us, we'll call you". In several workshops, model coupling frameworks [see Jagers, 2010, for an overview], have agreed on the minimal interface that makes a model adhere to the Hollywood principles; by exposing the following methods:

[1] preferably with guidance from domain experts

1. **initialize()**: Load and initialize a model from file.
2. **run(Δt)**: Run a single timestep.
3. **finalize()**: Finalize the model, memory cleanup, file flushing, statistics reporting.

In between these interface calls, the model state may be changed from outside and the core should support that. The library is loaded and can serve as a running process for a long time. A positive side-effect of implementing this interface is that it reveals subtle inconsistencies in existing code, for example initializing different models after one another: incomplete cleanup of previous settings, already allocated memory, and unclosed file pointer all become apparent. To reduce the number of errors a template system was introduced to generate the code used to allocate, deallocate, and expose the variables.

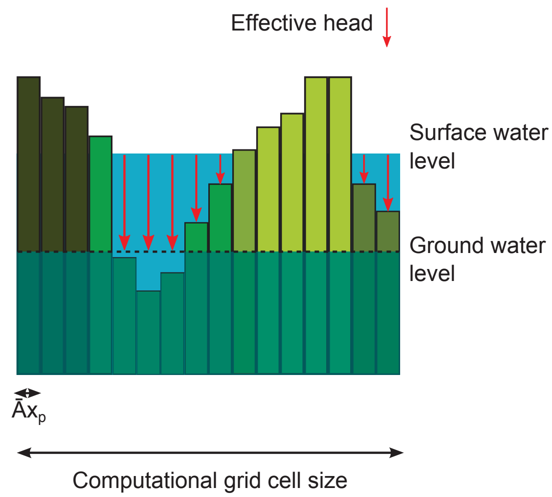


Figure 1. Subgrid infiltration into heterogeneous landscape.

Detailed evaluation of overland flow friction and water storage are simulated at subgrid scale. This enables to compute flooding at the planter size ($0.5\,\mathrm{m}$) pixel resolution of digital terrain maps. It also enables a speedup of a factor 100, as described in Stelling [2012]. To represent water systems in civilized regions the 2D grid was extended with 1D channels and controllable structures (for example pumps, orifices, weirs). This allows for more realistic and interactive overland flooding simulation.

The power of the subgrid concept is also applied to the hydrological processes in the subsoil. An important factor in potential flooding is the storage of water in the subsoil, or the lack thereof. The change in surface water volume is driven by several familiar processes:

$$\Delta V_{\text{surface water}} = (Q_{\text{overland}} + Q_{\text{precipitation}} - Q_{\text{infiltration}} - Q_{\text{evaporation}} + Q_{\text{drainage}}) \cdot \Delta t$$

The heterogeneous landscape and land use are specified in the model as gigapixel bitmaps for soil types, crop types, drainage resistance, and maximum infiltration. Infiltration, evaporation, and drainage are evaluated at pixel resolution, whereas the computational grid cells are larger and ensure high performance.

These advantages allow the model to act as a component in the interactive web-based model environment with a wide variety of possible applications.

3 Platform architecture

Now that a numerical model is available that allows high resolution interactive modeling, how can we hook it up to a tablet, mobile phone and map table, all at the same time, to allow for social and interactive modeling?

To enable such an environment the most logical choice is to use a web-based environment. Over the last years this choice has become more apparent. The large list of browser enhancements (for example inline Scalable Vector Graphics (SVG), canvas, plugin free video [Berjon et al., 2014], and Cascading Style Sheets (CSS) animations [Jackson et al., 2013]) allow for rich visualizations independent of the device type. An overview of the system architecture is given in Figure 2. The architecture follows the general “Model View Controller” pattern [Gamma et al., 1994], with caching of events and data to accommodate for the model continuously running in the background. The implementation of this system required several technical innovations and social considerations.

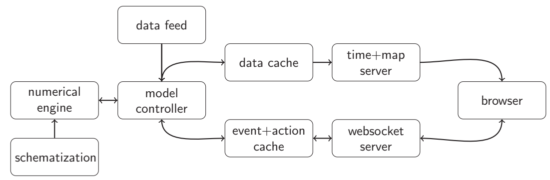


Figure 2. Architecture overview

The end-users, interact with the web-based GUI. The design philosophy is minimalistic, allowing little room for user mistakes. For example discharge locations only have two options (normal and extreme discharge) (see Figure 3a). Sessions with groups of end-users resulted in this design that provides freedom to explore without the insinuation that the model results are “true”. The application of CSS and SVG allows the interface to scale between different screen resolutions so that it can be used on different devices (phones, tablets, browsers, map table).

One of the differences when comparing a desktop user to a web-based user is the short attention span. If no indication of progress is given for longer than two second users will start reloading, clicking erratically or will just close the website, searching for a new “frisson” [Carr, 2011]. To make sure that the model is ready to run when a user arrives a lot of attention is given to the provisioning of the model. Provisioning, in this context, is preparing a model controller so that it starts its computation on request. The platform runs on GNU/Linux based Infrastructure as a Service (IaaS) providers, such as Amazon. For each running engine (one customer can have multiple running engines) a machine is reserved. These machines are prepared with a container that contains the model schematization, tables and grids, and hot restart files. These files are read into memory so that the model is ready to start its computation when needed, resulting in a time between a user logging in and a model start in under 5 seconds.

To communicate the model results the Model Message Interface (MMI) protocol is used [Baart et al., 2014]. This protocol is suitable for sending model variables over the internet. A model message consists of a metadata header in JavaScript Object Notation (JSON) format, optionally followed by the serialized array. Listing 1 shows an example of an MMI message. In this project the Zero Message Queue (ØMQ) protocol is used as a the underlying transport protocol. The advantage of using the MMI, ØMQ combination is that it has flexible metadata, does not copy data, and is very fast.

```
# The first part of the message contains metadata
{
  "name": "waterlevel",
  "shape": [3,3],
  "dtype": "float64",
  "attributes": {
    "standard_name": "sea_surface_altiude",
    "units": "m"
  }
}
# The second part of the message contains a serialized array
\x81\xb3b\xa0\xe8 ... \x01\x90\xe5\x84\xb5\xb0
```

Listing 1. MMI message

Interaction is another challenge where timing is crucial. When a user interacts with the model, for example places a discharge point, turns on a pump or lowers an orifice, the user expects a response within a second. To achieve this, user interactions are directly sent through websockets [Hickson, 2012]. These interactions are cached and pushed into the model on every timestep. Timesteps have to be kept shorter than in a classical model run, 100 ms is common. After a model timestep, the chain is inverted. The model pushes its arrays back in the direction of the browser, which is subscribed to these messages and can directly visualize.

The social aspect is another source of interesting problems. Several group sessions with different settings have been tried. The current setup is that the model is run in a “virtual room”, like a chat room. Multiple people can join the model run. One person is in control and others can view and zoom in on the same model run. Other users can request control of the model. The sessions worked best when a topic expert, not necessary a modeler, was present in the session. A detailed analysis of how the platform is used in a social context showed that the speed and flexibility determine the suitability [Leskens et al., 2014].

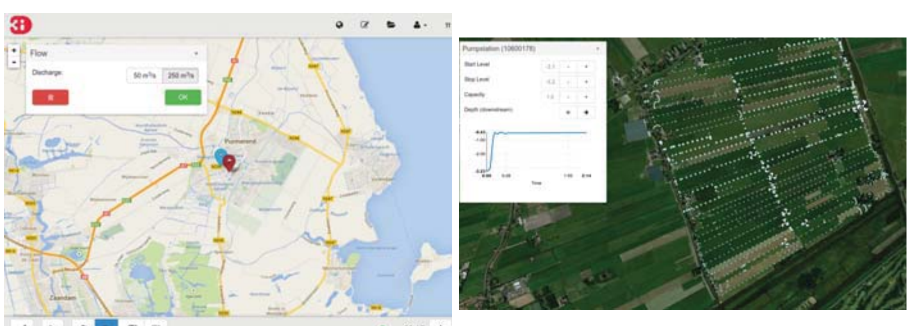
4 VISUALIZATION

The $3Di$ platform serves a wide variety of end-users. It is important to find a good balance between what is computed and how information is perceived. For scientific or engineering users one wants to provide information as close to the model results as possible. For less experienced end users it becomes important that the information is perceived correctly rather than that it is presented correctly.

First a note about the performance. Humans will detect images at a rate of about $12\,\mathrm{s}^{-1}$ as continuous [Landis, 1954]. To enable the model results to be perceived as continuous, taking into account some random network delay, the aim is to generate a map within $50\,\mathrm{ms}$. Generating results at this framerate can be done using two approaches. The first is to reduce the modeling timestep so that it computes in less than $50\,\mathrm{ms}$. This is the only way to get true model results at this framerate. An alternative is to interpolate in time and provide the insinuation of continuous information.

We use both approaches here. We reduce the calculation time so that interaction is fluent and we can pass the flicker fusion threshold. If one wants to use longer time steps we also visualize at a high framerate. An example of this is the visualization of river flow using dots that are animated with CSS animations as a function of the current flow velocity (see Figure 3b).

Another performance technique used to achieve the high framerate is to use the "Mahlen nach Zahlen" method, a reference to a product from the German company Ravensburger ®. A map with cell numbers is prepared in advance. Once a quantity for a new timestep becomes available the map is filled in with the colors corresponding to the cell numbers. This achieves much faster rendering times than drawing the cells using geometry drawing function.



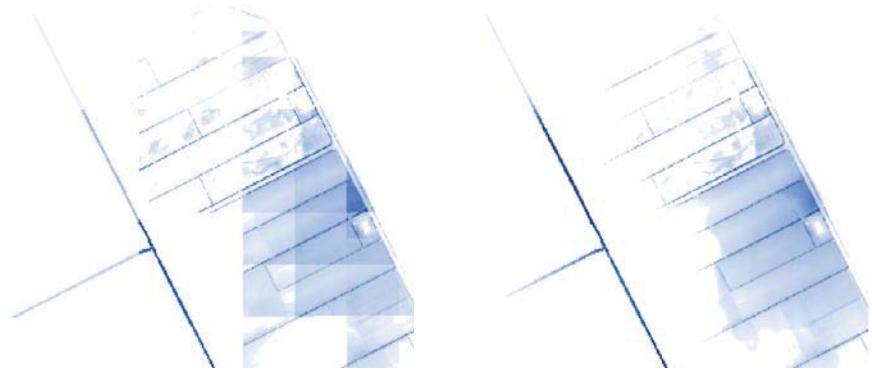
(a) Representation of two dimensional subpixels water level

(b) Representation of one dimensional channel network using an animated stroke pattern.

Figure 3. Browser based interactive model user interface of $3Di$

The variety of end-users exposes the numerical model to non-technical users with little appreciation of implemented numerical schemes. Some artifacts from the numerical schemes result in confusion. The world in the subgrid model is internally represented in voxels (a picture element (pixel) with volume), not unlike the computer game Minecraft. This results in visual artifacts, as represented in Figure 4a. Another type of artifact occurs when a levee crosses a calculation cell both sides of the cell will contain water.

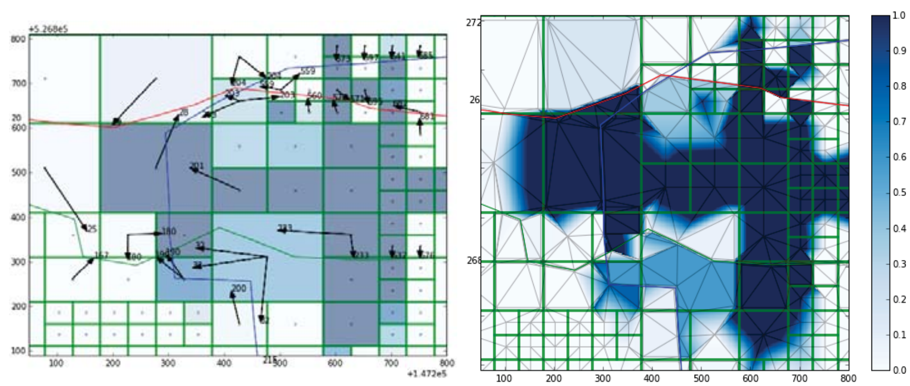
One can argue whether to show these “true” yet confusing results or to process the information so that it is perceived as intended. In the $3Di$ platform the default visualization hides these artifacts by filtering and smoothing the output. Hiding the square world is implemented using different techniques.



(a) Uninterpolated subgrid water level **(b)** Interpolated subgrid water level

Figure 4. Linear barycentric interpolation method

A barycentric linear interpolation technique is used. This is one of the few techniques that allow for the interpolation within the rendering time constraint. It also allows water level results to be interpolated. The quad tree grid is triangulated using Qhull [Barber et al., 1996]. Water level information, from the cell centers is linearly interpolated to the underlying subgrid. The interpolation uses a weighted average to determine water levels. Figure 4b shows the results of this technique .



(a) Redistribution of cell sections based on levee positioning.

(b) Interpolated subgrid water level with levee constraint

Figure 5. Levee-constrained interpolation method

The triangular mesh can be reused to filter levee artefacts. The triangulation can reconstruct levees with use of additional levee geometries. A triangle is the simplest geometrical form and can be used reconstruct any arbitrary shape [Welch and Witkin, 1994]. To incorporate the levee in the trianglulation, the levee and grid geometries are intersected (Figure 5a). For the intersected calculation cells the influential water level points are determined and coupled to the relevant calculation areas. The arrows in Figure 5a indicate which water level is relevant for the dike intersected cell areas. When all waterlevel points are allocated to the dike, the triangulation can be executed with the incorporation of the levee geometries. The newly created triangular mesh now also follows the added levee geometry. Successively the interpolation is executed, resulting in water being retained behind the dike within one calculation cell. The interpolated result is shown in Figure 5b.

5 Discussion and conclusion

The major advancement is that we have enabled interactive web-based modeling at a high resolution and wide coverage. The interactive, exploratory, overland flooding simulations can be used in sessions with policy makers to help them make sensible decisions. Several developments have enabled this advancement.

The redesign of the numerical engine follows the trends set in inter-model coupling. Applying the hollywood principle transformed the engine from a static executable into an interactive component.

Viewing model results through the web was already a reality (see [Blower et al., 2013] for example). We have made progress to run and interact with models through the browser. The use of modern web technologies allows the same interface to be used on a browser, a phone and on a map table. What is not available, for complex models, is the ability to set up a new model through the web. At the moment it is still cumbersome to implement this functionality. However within the next few years it is likely that also this part of the modeling workflow will become browser-based.

The speedup of the model by applying the subgrid method allows for a faster interaction time and a more detailed resolution. Several other models use a similar numerical approach, albeit with limitations. The subgrid scheme by Stelling [2012] is partly based on the subgrid method for flooding and drying by Casulli [2009], who implements his methods in the unstructured UnTRIM research package Casulli and Walters [2000]. The coupled 1D-2D hydrodynamic model MIKE-FLOOD [Group, 2014] also offers subgrid overland flow.

The high resolution results in great “face validity”. For now, the $3Di$ platform is suitable for exploratory purposes, as only a few marks of the confidence checklist [Baart, 2013, pp. 136] have been ticked. Work has started on a skillbed for the $3Di$ platform. A skillbed is an automated test suite that compares results to a wide range of analytical cases, measurements, and results from other numerical models.

A lot of technical and numerical problems have been solved, but the methodological challenges of the new working methods are proving more difficult. An open issue is that end-users tend to confuse high resolution and higher frequency results with a high accuracy, a topic for further research.

Possible future directions include combining the subgrid approach with an unstructured flow solver, such as Delft3D-FLOW Flexible Mesh [Kernkamp et al., 2011]. The pixel based approach has the advantage that it is simple to implement and to scale. Unfortunately the world is not so square, especially not on larger scales, when one goes beyond the scale of a small country.

Another planned step is to incorporate or preferably to couple the system with other numerical engines. The monolithic approach of putting all processes into one model has proven cumbersome in previous implementations. The current model controller can easily incorporate other models because the communication and control are already out of the model engine. Water quality, coastal, and socio-economic models are possible candidates for inclusion in the platform.

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