Coupling of GIS and Hydraulics – Application at Dornbirnerach, Austria

Michaela Jud[1], Florian Schwertfirm[2], Christoph Rapp[3] & Matthäus Schilcher[1]

[1]Department of Geoinformatics, Technical University of Munich, Germany, Arcisstraße 21, 80333 Munich
[2]Kreuzinger & Manhart Turbulenz GmbH, Kirchenstraße 34, 81675 Munich
[3]Department of Hydrodynamics, Technical University of Munich, Germany, Arcisstraße 21, 80333 Munich
E-mail: Michaela.jud@bv.tu-muenchen.de; f.schwertfirm@km-turbulenz.de; rapp@tum.de; matthaeus.schilcher@bv.tu-muenchen.de

Abstract

Recent flood events like the massive catastrophes in Pakistan and Thailand have shown the devastating impact that such events can have on people and property. Flood warning and forecasting systems can help to reduce damages through early evacuation from areas at risk and to move possessions to safe places. With sufficient warning, temporary defense can also be installed to mitigate the effects of flooding. Especially in mountainous regions such as in the Alps an efficient prediction is important if sudden heavy rainfall events occur. Well founded decisions can only be made with real time simulations of such events. Within this paper an innovative method of coupling a geographical information system and a hydrodynamic model is being presented. The generation of the simulation grid is done in ArcGIS using standard tools and developed Python-scripts. The ArcGIS-tool is very user-friendly and flexible which ensures secure handling. The massive parallelization of the hydrodynamic model makes real time computations even possible. With this tool real time predictions are feasible to support the flood warning and forecasting systems.

Motivation

Climate change is one of today's major challenges: Each year disasters like floods, tsunamis or hurricanes cause fatalities and damage all around the world. In the Alps extreme rainfall events pose such an environmental hazard. The prediction and analysis of these events is an important step in reducing or avoiding damage to people or infrastructure.

Numerical hydrodynamic models like shallow water equation solvers are state of the art for investigating the impact of such events (Schäffler et al. 2011) and are also the basis for the allocation of hazardous flooding zones and elementary for the fulfillment of the European Flood Risk Management Directive. On the other hand geographic information systems (GIS) like the software ArcGIS 10 provide detailed environmental information, data management, data storage and visualization tools (e.g. mapping) and is therefore a powerful data infrastructure system. Through the coupling of both methods the advantages, namely accurate and fast flood simulation and a user friendly data infrastructure, can be combined resulting in an efficient tool for the forecast and analysis of the flow in natural rivers. With "faster than real time simulation" and analysis during such events disaster management and protection of people can be highly improved.

Investigated task

This paper shows the prototypical process when coupling the two programs ArcGIS 10 and the shallow water equation (SWE) solver ShallowFOAM. This paper focuses on the software ArcGIS 10 used as pre- and postprocessing tool for the solver, the data management, the data storage and the visualization. The coupling is realized by a Python-script which provides the model data and the grid for the simulation with shallowFOAM as well as the reverse conversion to ArcGIS. In the following, the simulation results of an extreme rainfall event for the city of Dornbirn, Vorarlberg are being presented.

Theoretical background

Hydrodynamical model ShallowFOAM

ShallowFOAM is a parallelized shallow water equation solver (SWE) developed by the Department for Hydromechanics of the University of Technology of Munich on the basis of OpenFOAM. The SWE are a special case of the Navier-Stokes-equations where the momentum transport in the vertical direction is neglected (Beffa, 1994). With OpenFOAM such differential equations can be discretized and solved on unstructured grids in a finite volume formulation (FV). The equations for the flow depth and momentum transport in the horizontal direction are discretized on a 3D FV net with only one cell in the vertical direction. The necessary parameters for the representation of the terrain and surface roughness, namely the elevation of the terrain and the Manning factor are stored in 3D scalar fields on the grid (Kreuzinger & Schwertfirm, 2010) and are provided by the ArcGIS processes developed within this project.

Geographical information system – software ArcGIS 10

The geographical information system collects the heterogeneous data (exemplarily shown in Table 1) and imports it into a database. The software ArcGIS 10 is used as a preprocessing tool and for the (re-)transformation of the preprocessed data into the data-format for shallowFOAM via Python-scripting.

Coupling concept

Data basis

All necessary data for the creation of the simulation grid e.g. roughness-values are listed in the following Table and was generously provided by the Department for Water Resources of Vorarlberg and the Department for Survey of Vorarlberg.

Table 1: Data basis

Data set	Format	Scale / resolution
Digital elevation model	Raster	1x1 m horiz. 0.1 m vert.
Orthophoto	Raster	0.1 x 0.1 m²
Catchment area	Vector	1:1000
Soil data	Vector	1:1000
Land use	Raster	1x1 m²
Measurement station (rainfall, discharge)	Vector	1:1000
Cadastre map	Vector + building	1:1000
Constructions	AutoCAD	1:1000
Cross profiles	AutoCAD	1:1000
Event data discharge	Excel-format	

Concept

The coupling between the two methods is realized in seven steps as shown in the Figure 1.

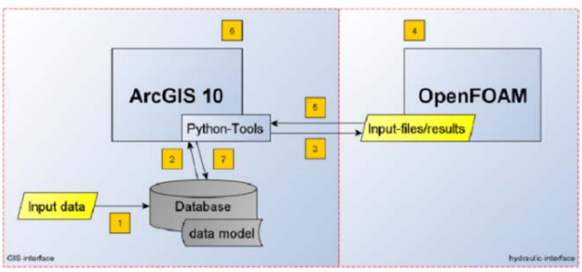

Figure 1: Coupling concept (Jud, 2011)

First, the input data which is described in Table 1 is stored in a database as a data model (step 1). The data model is used to bring the single input data sets into relation. Afterwards the data is loaded in ArcMap for the preprocessing (step 2):

The preprocessing steps in ArcGIS are realized with standard tools provided by ArcGIS under usage of the ArcGIS model builder.

The user can interactively select the area of interest which will be the computational domain: Additional data (structures, cross profiles, DEM, etc.) can be added to this selection.

The selected area is represented in ArcGIS as terrain data set (TIN – triangulated irregular network) constructed from the DEM including breaking edges such as the stream net or cross profiles and structures.

Then the user can define the resolution of the simulation grid: The domain can be subdivided into coarser and finer regions: Embankments and areas with steep slopes are discretized more detailed than very flat or far away zones. This causes a reduction of the data amount without losing the data quality, thus reducing the computation time of the data transformation from ArcGIS to OpenFOAM as well as computation time for the hydrodynamic simulation.

The user can interactively define the boundary conditions and the patches. Further the cadastre data is used to identify buildings in the simulation area. The borders of the buildings are collected in one logical boundary patch.

Next the terrain data set is transformed in a polygon feature data set (triangles). Each single element of this data set represents a cell of grid. For each single cell a Manning factor is derived from the land use data or from an orthophoto. A season dependent definition of the Manning factors for different agricultural crop land is possible within the provided ArcGIS-interface. This flexibility is a big advantage offered by the software for the simulation.

In the third step the preprocessed data is exported to the standard OpenFOAM mesh and file format, including scalar fields of elevation and Manning factors. The transformation has been realized through a Python-script.

Fourth, the simulations are run in shallowFOAM and the results such as flow direction, flow depth and velocity are passed back to ArcGIS (step 5) using a Python-interface. ArcGIS can be used again to do several postprocessing steps (step 6) and to analyze the results in detail. At the end all results are stored in the data base (step 7).

Implementation

The coupling concept has been realized mainly using standard tools provided by ArcGIS 10. The single tools were combined to a script using the ArcGIS model builder. The model builder allows the creation of complex tools which can be handled via an interface. Some tools for the transformation of the data into OpenFOAM file format were programmed in Python.

The following example shows exemplarily the generation of terrain data set with different grid resolutions which is an important task for the reduction of the computational time. Figure 2 shows the tool mask provided for the user, who can define individually the buffer distance around the stream net. This distance delimits the area with the finest resolution, because a fine resolution is desired within the river bed. For a smooth transition from fine to coarse the user can define even some further resolution steps in dependence of the buffer distance. Next, the user can define the resolutions of the flat area and for those with steep slopes where a very fine grid is mandatory.

After entering these five buffer magnitudes the tool generates the resolution-differentiated simulation grid automatically.

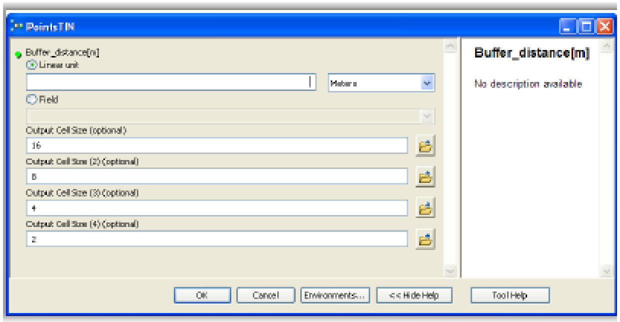

Figure 2: Tool mask for grid refinement (Jud, 2011)

Results

Real time simulation of the runoff during an extreme rainfall event

The complete work flow was applied to simulate an extreme rainfall event in the city of Dornbirn.

Dornbirn lies in Vorarlberg, Austria and is part of the catchment area of the Dornbirnerach.

The Dornbirnerach is one of the major rivers in Vorarlberg, Austria (3rd ranked after Ill and Bregenzerach). It rises at the Hohe Freschen in 2001 m and flows into the Lake Constance. The catchment area extends over 218 km² at a river length of 60 km. The average discharge is approximately 6.9 m³/s. The following Figure 3 shows the location of the test area within the catchment area of the Dornbirnerach.

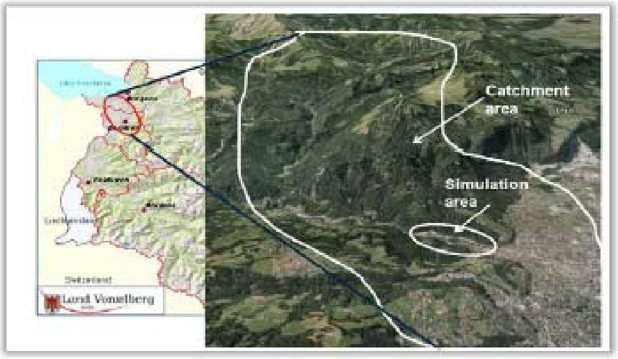

Figure 3: Location of the test area (www.google.de)

For the real time simulation an event of the year 2010 has been chosen. In the night from 20th to 21st August 2010 the Dornbirnerach rose from 1.7 m³/s to over 200 m³/s in less than one hour (see Figure 4).

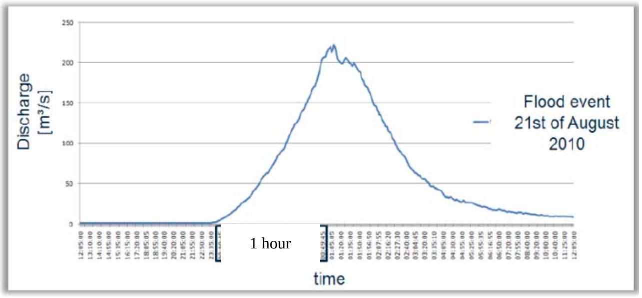

Figure 4: Discharge curve at Dornbirn, 21st August 2010

Figure 5 shows a comparison of the situation in the Dornbirnerach before and during such a heavy rainfall event.

Figure 5: Dornbirnerach at the gauge Enz under normal conditions and during a heavy rainfall event

The 0.5 km long test area is represented by 25.000 cells and lies in Dornbirn's periphery.

The simulation of this event is conducted in two steps:

First, a stationary base flow with a constant discharge rate of 1.7 m³/s is computed. This base flow is then used as a starting field for the simulation of the event with the measured discharge rate at the gauge Enz (Figure 5) as a time varying inflow boundary condition.

At the outflow boundary a flow depth - flow rate relation is set. The simulation spans a physical time of at least 10 h to cover the complete event. With the chosen stability criterion for the time integration the simulation takes approximately 5 h on eight cores of a Dual-Core AMD Opteron(tm) 8216 Workstation at 2.4 GHz.

Figure 6 shows the flow depth in the domain 2 h hours after the start of the rainfall where the discharge rate is 217 m³/s at the domain's inflow. The river stays more or less in its bed. Marked in the Figure 6 are three probe positions, P1, P2 und P3 at which the flow depth is sampled over time.

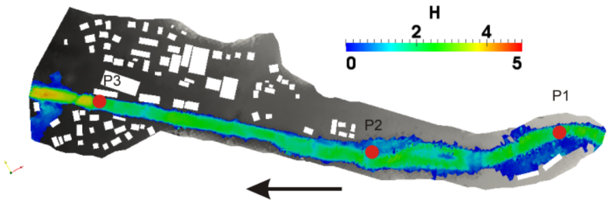

Figure 6: Computational domain, flow depth color coded

The flow depth at each probe position is shown in Figure 7.

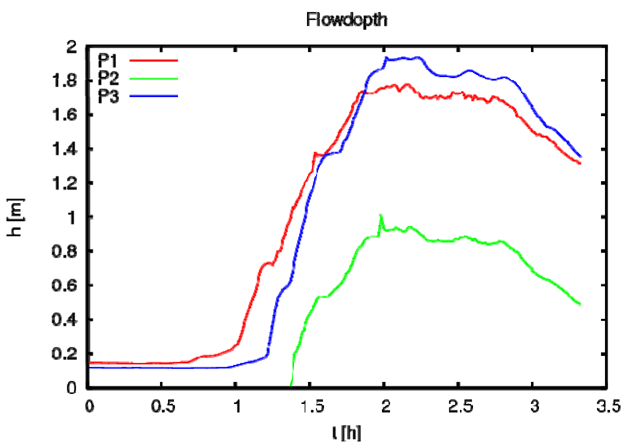

Figure 7: Flow depth at three positions marked in Figure 6

The dynamics of the heavy rainfall event, the time lag between the different positions as well as the different characteristics of the flow depth depending on the terrain elevation at the probe position is clearly visible and demonstrates the dynamics which are captured by the numerical model.

Performance

The OpenFOAM library provides a full MPI parallelization which is employed by the solver ShallowFOAM (FoamCFD, 2008). The grid provided by the ArcGIS interface can be decomposed with a preprocessing step for an arbitrary number of processors, where the efficient processor number is limited by the ratio of work load and communication per processor. Figure 8 shows the scaling of the computation time over the number of processors for the current test case. The test case was computed with one, two, four and eight cores. The computation time t_C is normalized with the computation time t_{C1} required on one processor. The scaling is almost ideal for the parallelization on one workstation and can be expected to be very good on large high performance computing clusters.

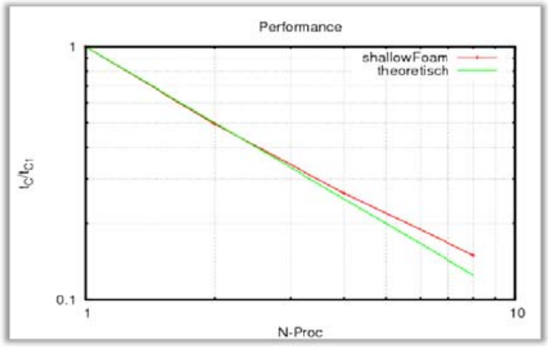

Figure 8: Parallelization performance

Visualization in ArcGIS 10

After the transformation of the simulation results back into ArcGIS water depth or flow velocities can be visualized. The graphical representation of the simulation results corresponds to the guidelines given in the European Flood Risk Management Directive.

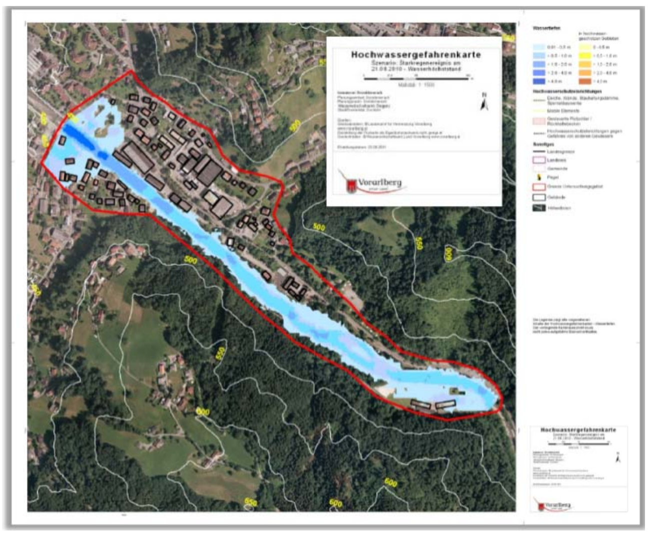

Figure 9: Visualization in ArcGIS, (according to Tanasescu, 2011)

Figure 9 shows the highest water level during the rain storm event of the 20th of August according to the guidelines of the Flood Risk Management Directive. Combined with an orthophoto and the cadastre data this map helps to predict the potential risk caused by this event.

Conclusions and perspective

The application of the ArcGIS-ShallowFOAM interface on the test area Dornbirnerach and the simulation of the heavy rainfall event from August 2010 show the advantages of this approach: the GIS infrastructure provides a high quality data basis and an interface for pre- and postprocessing whereas the solver ShallowFOAM produces the simulation results faster than real time. With this combination of tools real time predictions of heavy rainfall events can deliver early warnings for flooding areas and support the catastrophe management.

In future work further validation of the simulation results and performance will be made with an expanded test case (approx. 15 km^2), more detailed modeling of hydraulic structures and a variation in turbulence models.

Acknowledgements

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