Coupling the MIKE 11 Channel Flow Model to MODFLOW

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ABSTRACT

Regulatory frameworks are evolving to require water management on a watershed or catchment basis, which implies an integrated groundwater-surface water approach.. However, there is currently no way - short of custom programming - to link surface water models (e.g. MIKE 11) to groundwater models (e.g. MODFLOW). MIKE 11 is a widely-used one-dimensional channel flow model for problems ranging from advanced fully dynamic hydraulics to basin scale hydraulic routing, whereas, MODFLOW is the de facto standard for groundwater modeling. The MIKE 11 engine and MODFLOW have been explicitly coupled together using the new OpenMI standard, which provides a set of interface methods for coupling disparate hydrology-related codes. These methods allow each code to pull required input data from any other OpenMI compliant code. To represent the leakage from MIKE 11 in MODFLOW, MODFLOW was first modified to make it OpenMI compliant and then a modified version of MODFLOW's FHB package was developed. At the beginning of every groundwater time step the modified FHB package requests the current stream leakage from MIKE 11, which MIKE 11 then calculates forward, based on the current groundwater level and the calculated stream flow over the coming groundwater time step.

INTRODUCTION

Increasingly, water resources are being managed on a watershed basis, while addressing problems at the local scale. However, changing to a watershed-based water management system challenges not only our management structures, but it also requires new and more sophisticated tools. Traditional groundwater and surface water models were not designed to answer questions related to conjunctive use of groundwater and surface water, water quality impacts of surface water on groundwater, impact of land-use changes and urban development on water resources, and floodplain and wetland management. Instead, integrated hydrologic models of the watershed behaviour are required.

In 1969, Freeze and Harlan proposed a blueprint for modelling the hydrologic cycle, where the different flow processes were described by their governing partial differential equations - that is using a physics-based approach. There are, however, important limitations to the applicability of such physics-based models. For example,

- it is widely recognized that such models require a significant amount of data and the cost of data acquisition may be high;
- the relative complexity of the physics-based solution requires substantial execution time;
- the relative complexity may lead to over-parameterized descriptions for simple applications; and
- a physics-based model attempts to represent flow processes at the grid scale with mathematical descriptions that, at best, are valid for small-scale experimental conditions.

Experience with MIKE SHE (Graham and Butts, 2005) has shown that in most watershed problems, one or two hydrologic processes dominate the watershed behaviour. For example, flood forecasting is dominated by river flows and surface runoff, while wetland restoration depends mostly on saturated groundwater flow and overland flow. Thus, a complete, physics-based flow description for all processes in one model is rarely necessary. A sensible way forward is to use physics-based flow descriptions for those processes that are important in the particular context, and simpler, faster, less data demanding methods for the less important processes.

Then, the art of integrated hydrologic modelling for engineering decision making is to develop the simplest model possible that allows a decision to be made with an acceptable degree of confidence. This, then, is the motivation for linking MIKE 11 (Havnø et al, 1995) (a popular, sophisticated river hydraulics code) to the widely used MODFLOW code (Harbaugh et al, 2000) for groundwater modelling.

RIVER MODELLING WITH MODFLOW

MODFLOW is the de facto standard in groundwater modelling. However, MODFLOW is strictly a saturated groundwater modelling code, typically with boundary conditions defined by surface water bodies, such as lakes, rivers and streams.

In the case of Rivers (RIV) and Streams (STR1) (Prudic, 1989), MODFLOW requires a time series of river levels for every cell in the model that intersects a river. The river is treated as a head dependent boundary with the bed conductance nominally defined by the width of the river, the thickness of the river bed and the hydraulic conductivity of the bed material. In principle, with perfect knowledge, one could vary the bed conductance and the river level to perfectly mimic the changing river level and river width during changing flow conditions. However, this would require an *a priori* river model that was previously calibrated to changing baseflow conditions in the river. The Stream boundary condition is a river boundary with an internal water balance, such that if the infiltration exceeds the amount of available water, infiltration is stopped.

Additionally, in the STR package, instead of prescribing the water level, the river water level can be calculated based on the amount of water in the river, the river width and the Mannings equation, assuming a rectangular cross-section. However, a rectangular cross-section has the distinct disadvantage that the change in infiltration versus the change flow rate is not correct, since the river width is typically held constant. Recognizing this limitation, the USGS recently released an updated version of the Stream package (SFR1 package) 0 that allows for an eight-point cross-section profile in the river. Unfortunately, none of the commercial MODFLOW user interfaces have yet to support this new package. Furthermore, the mass balance approach used in the STR1 and the SFR1 packages means that they only suitable for modelling long term changes in groundwater-stream flow interactions (Prudic et al, 2004).

Various river hydraulic models have been linked to MODFLOW in the past, such as MODBRANCH (Swain and Wexler, 1996). However, these codes have not been widely adapted in the groundwater modelling community - probably partly because there are no commercial user interfaces supporting them and the river codes themselves are not widely used in the river modelling community.

RIVER MODELLING WITH MIKE 11

MIKE 11 computes unsteady water levels and flow in rivers and estuaries using an implicit, one-dimensional, finite-difference formulation. In the most advanced case, the complete non-linear equations of open channel flow (higher-order, fully dynamic Saint-Venant equations) are solved using the 6-point Abbott-Ionescu method. Alternatively, a diffusive wave, kinematic wave, and quasi-steady state approximations can be used. The program can be applied to branched and looped networks, and to quasi two-dimensional flow on flood plains. It is applicable to vertically homogeneous flow conditions ranging from steep rivers to tidally influenced estuaries. Both subcritical and supercritical flow can be calculated, depending on the local flow conditions. The flow over a wide variety of structures can also be simulated, such as broad-crested weirs, culverts, regulating structures, control structures, bridges and user-defined structures.

MIKE 11 also includes simple hydrologic routing methods, which are suitable when the detailed flow dynamics in the river are not of interest. The routing methods included in MIKE SHE are the Muskingum and the Muskingum-Cunge methods, as well as instantaneous flow routing. The former two methods account for the time it takes for a water pulse to move downstream, whereas the instantaneous method routes the flows through the system in a single time step.

HARMONIT AND OPENMI

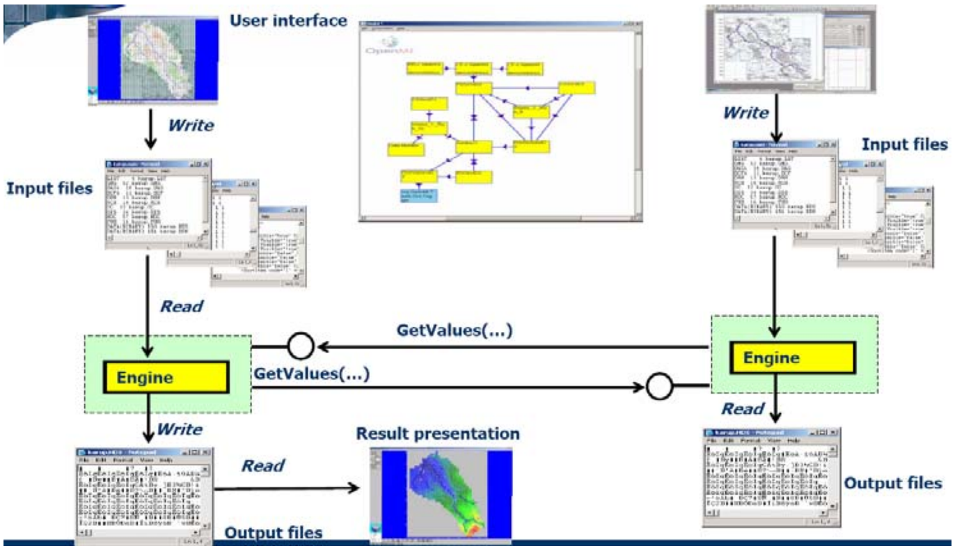

Figure 1 Summary of the interaction between Visual MODFLOW (left) and MIKE 11 (right). The OpenMI coupling is only at the engine level.

HarmonIT is a highly ambitious research project to develop, prove and implement an Open Modelling Interface and Environment (the OpenMI) that will allow the linking of water related models. The OpenMI will make it easier to link hydrologic-related models by means of a standardized set of interfaces for exchanging data on a time basis. As most existing models are not prepared to exchange data on a time step level, internal modifications to the codes are typically required, including (Graham et al, 2003):

- exposing run-time and time step control to an outside entity,
- distinguishing between model initialization and the time step loop, and
- providing access to internal state variables and parameters.

OpenMI is a pull-based pipe and filter architecture, consisting of 'linkable components' that exchange data in a pre-defined way and format. It is a purely single-threaded architecture, where a linkable component handles only one request at a time, before acting on another request. Data exchange is triggered by a 'GetValue' request. The onus is on the receiving component to deliver the requested data, without regard to how. This makes the system inherently flexible, as the requesting component does not care how it gets the data that it needs. It is the developer's responsibility to ensure that relevant data can be delivered when requested. The request is simply sent out to the component, which is obligated to respond - with the actual value, an interpolated value or an extrapolated value.

The real advantage of OpenMI is that any compliant models can be linked together regardless of their underlying architecture. The only requirement is one model must be able to provide information that the other needs.

COUPLING MODFLOW AND MIKE 11

Through a cooperation agreement between Waterloo Hydrogeologic and DHI Water and Environment, the USGS MODFLOW engine used in Visual MODFLOW was modified to make it OpenMI compliant. This was necessary since the USGS has not yet made the public domain MODFLOW code OpenMI compliant. The principle changes to the MODFLOW code included changing the initialization and main solution loop to meet the OpenMI requirements.

As a surface water model, MIKE 11 is commercially available, extremely versatile, widely used and includes a comprehensive graphical user interface. The final point is important to stress because the

OpenMI standard only supports the coupling of model engines. The individual, site specific models must be developed in their respective user interfaces. This is illustrated in Figure 1, were Visual MODFLOW is on the left and MIKE 11 is on the right. At run time the model engines are exchange information and the results reflect the coupling of the models.

The module nature of MODFLOW makes it straightforward to add additional boundary conditions. In this project, a modified version of the FHB boundary condition (Leake and Lilly, 1997) was created and added to the MODFLOW code - that is a surface leakage boundary (SLB) based on FHB package. The two main differences between the FHB and the SLB are

- the SLB package does not require upfront memory allocation for the flow cells (thus being able to take into account dynamic changes in the set of leakage cells during surface flooding) and
- the SLB package can apply the leakage to different MODFLOW layers.

At the beginning of every groundwater time step, MIKE 11 asks MODFLOW for the most recent groundwater level. At the same time MODFLOW asks MIKE 11 for the expected amount of infiltration for the current groundwater time step. MIKE 11 then calculates the river flows forward over the period of the groundwater time step and calculates the infiltration to or from the groundwater based on the groundwater level in the previous groundwater time step. MIKE 11 then passes this accumulated infiltration to MODFLOW, which then calculates a new groundwater level based on the net infiltration. This explicit coupling will dampen the changes in the groundwater since the groundwater-river exchange is constant over the groundwater time step. If more accuracy in the groundwater is required, then the groundwater time step can be shortened.

The MIKE 11 river network has a different spatial scale than the MODFLOW model, which means that the more refined the MODFLOW grid is, the more accurately the spatial distribution of the exchange will be represented. The entire MIKE 11 river system is always included in the hydraulic model, but MODFLOW will only exchange water with the sub-set of the MIKE 11 river model that intersects the MODFLOW groundwater grid. The intersection of the two models is handled automatically (see Figure 2). Similarly, the MIKE 11 river model can be as simple or as sophisticated as required by the user.

SUMMARY AND FUTURE DEVELOPMENTS

The presented OpenMI coupling is one of the first commercial implementations of the OpenMI concept involving commercial codes developed and supported by two independent companies; that is Visual MODFLOW and MIKE 11. The modifications to the MODFLOW code to make it OpenMI compliant were substantial but straight forward, taking about two man-months to complete.

The coupled MIKE 11 - MODFLOW model is controlled via the Visual MODFLOW user interface, but the MIKE 11 river model is completely developed within the MIKE 11 user interface. Similarly the MODFLOW input and results are handled within Visual MODFLOW.

The combined entity can be used to assess many engineering problems were groundwater and surface water flow are impacted by one another, for example, the impact of groundwater extractions on surface water low flows, and the impact of storm events on bank infiltration rates and travel times to drinking water wells.

The newly created OpenMI compliant version of MODFLOW also opens up a host of other potential applications, including linking local-scale and regional-scale MODFLOW models, linking MODFLOW to other hydrologic processes and linking MODFLOW to other hydrologic-related codes, such as optimization and control codes.

ACKNOWLEDGMENTS

For more information on the OpenMI project, please refer to the extensive OpenMI website at www.openmi.org.

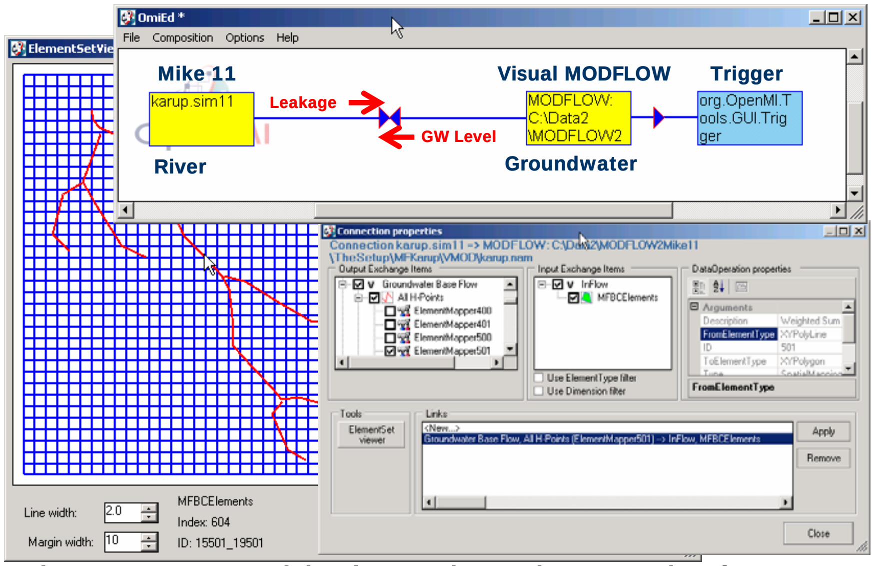

Figure 2 Summary of the data exchange between Visual MODFLOW and MIKE 11. MIKE 11 provides leakages when asked and Visual MODFLOW provides groundwater levels.

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