Integrated Environmental Modeling applied at the basin scale: Linking different types of models using the OpenMI standard to improve simulation of groundwater processes in the Thames Basin, UK.

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ABSTRACT

The Thames Basin in the south-east of England consists of multiple and separate aquifer systems, which are used for public and private water supply and also provide baseflow to the River Thames and its tributaries. The most important aquifer is the Chalk, a pure white fractured limestone, which has been extensively studied over the past decades to understand its hydraulic characteristics. A distributed numerical model can be built, therefore, to simulate the groundwater flows within this aquifer. Groundwater processes in other aquifer systems such as the Jurassic limestone (Great and Inferior Oolite Groups) in the north-west of the basin are complex and less well understood. These aquifers also support river baseflow under drought conditions.

This paper presents the results of using the Open Modeling Interface (OpenMI) standard to allow appropriate models to be linked. The composition consists of a fully distributed groundwater flow model of the Chalk, a simplified groundwater model of the Jurassic limestones and a river model. OpenMI allows the different types of models to communicate during run-time. This approach allows an appropriate representation of the flow processes within the Thames basin and consequently improves the simulation of groundwater flows, enabling better management of groundwater and surface water resources under future climate scenarios.

INTRODUCTION

Over the past decade, there has been a significant increase in computing power which has permitted the inclusion of more detailed processes within environmental numerical models. However, the structure of a numerical model is mainly dictated by the nature of the environmental processes it addresses. This has led to the development of separate models that simulate separate environmental processes. Delivering the objectives of water management legislation such as the Water Framework Directive (European Commission, 2000) has required the simulation of integrated environmental processes at the catchment scale. Representing different environmental processes within one numerical model for this purpose is difficult and may yield a code that is hard to manage. An alternative more pragmatic approach that integrates models and capitalizes on previous investment in existing models is useful to add value to resource management tools.

The Open Modeling Interface (OpenMI) standard has been developed to connect models built to simulate different environmental processes (OpenMI Association, 2010). The OpenMI standard includes a set of software interfaces that can be implemented in an existing environmental model to make it OpenMI compliant. *OpenMI* compliant models can exchange data at run-time allowing the dynamic integration of different models and consequently the simulation of interacting environmental processes

Implementation of the OpenMI standard was used in this work to link four different models developed to simulate and manage groundwater resources in the Thames Basin, UK. These models encapsulate conceptual understanding at different level of complexity from a relatively simple description of groundwater flow in fractured limestone aquifers to a fully distributed groundwater flow model of the chalk aquifer. A Muskingum river-flow routing model is included in the composition which also provides the linkage between the groundwater models. The composition also includes a management model that constrains groundwater pumping rates based on river flows to minimize impacts on river flows. The aim of this paper is to demonstrate how the OpenMI technology can be used to link these models to improve the integrated management of water resources in the Thames Basin study area.

THE STUDY AREA

The Thames Basin, defined by the catchment of the River Thames and its tributaries, is located in the south-east of the United Kingdom (Figure 1). The highly urbanized area of Greater London occupies the central and eastern parts of the basin while the western parts are predominantly rural. Groundwater pumping accounts for approximately 40% of the 6 million m^3/d of water provided for public supply. The basin is composed of a series of aquifers separated by low permeability materials. The most important aquifers are the Cretaceous Chalk and the Jurassic limestone. The different aquifers are not contiguous and are only connected by rivers.

The Chalk, which is the most important aquifer within the UK (Allen et al., 1996), is a highly permeable aquifer with fractures and solution enhancement leading to karstic features. In the central part of the basin, the Chalk is overlain by deposits of Palaeogene age, consisting of inter-bedded sands and clays underlying thick confining clays. Because of the permeable nature of the Chalk, rivers are sustained by groundwater input (baseflow) which typically provide between 85 to 95% of the total flow.

The limestone aquifer occupies the north-west part of the study area. It can be divided into two hydraulically independent units: the Great Oolite Group (GO) and the Inferior Oolite Group (IO). The Fuller's Earth Clay, which separates these two units, is absent in some areas and the GO and IO can then be considered as one unit. The limestone is well-drained by rivers which form tributaries to the River Thames. Both the GO and IO are covered by clays which confine the groundwater system to the south-east of the limestone aquifers. The aquifer system, characterized by its complex fractured structure, is very responsive to recharge. The groundwater discharge from the limestone aquifers is routed via rivers across non-aquifers and onto the Chalk where it can again interact with the subsurface flows.

An important component of the water management within the basin is the dependence of groundwater abstraction on river flows, particularly under drought conditions when some pumping has to be reduced. As a result, groundwater abstraction in the Chalk during the drought periods may depend on groundwater discharge from the limestone aquifer at the top of the catchment many kilometers upstream. The simulation of abstraction management requires the development of multi-linked aquifer models.

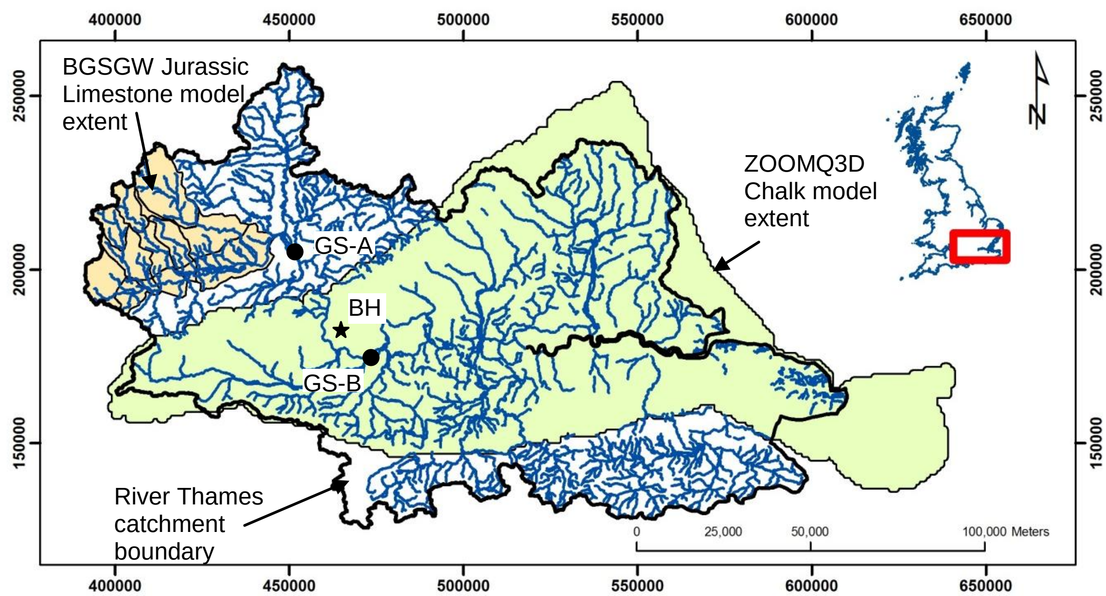

Figure 1. Location of the study area

METHODS

Two groundwater models are used to simulate groundwater flow in the Chalk and limestone aquifers. A river model is included to route river flows and to pass the groundwater discharge from the limestone aquifer to the Chalk aquifer. These models are driven by recharge calculated by the distributed recharge model ZOODRM (Mansour and Hughes, 2004). ZOODRM takes weather data together with soil and vegetation parameters to calculate evapo-transpiration and soil moisture. It uses a digital terrain model to route the surface runoff to river channels.

Groundwater flow in the Chalk aquifer is simulated using the fully distributed groundwater flow model ZOOMQ3D (Jackson and Spink, 2004). The area is discretized using 1 km square grid cells. Monthly stress periods are used to vary both recharge and pumping. The boundary conditions are mainly no flow everywhere except at the northern model boundary where leakage nodes are included to simulate groundwater discharges from springs. The River Thames and its tributaries are the main drain for the aquifer system.

Groundwater flow in the fractured limestone aquifer is simulated using a semi-distributed groundwater code, BGSGW. This model represents sub-catchments of the aquifer as stores or cells. These cells are parameterized by bulk storage coefficient and hydraulic conductivity parameters. They can be connected both horizontally and vertically to neighboring cells. This allows a simplified three-dimensional representation of the limestone aquifer system.

The river model, MCRouter, used to route the water within the river channels, is based on the Muskingum method. A full description of this method is given by Chadwick and Morfett (1986). The model assumes a simple rectangular cross-section for the river channels. It takes surface runoff calculated by ZOODRM and combines it to the baseflows calculated by either ZOOMQ3D or BGSGW before applying the routing algorithm. River water can also leak into the aquifers if simulated groundwater heads drop below the elevation of the river bed. Finally a simple code, called Abstraction Manager, is used to regulate the pumping rate at a Chalk pumping borehole based on the river flows at an adjacent river section.

Pipistrelle (http://fluidearth.net), a Graphical User Interface (GUI) that allows model users to build and run compositions of OpenMI compliant components is used to create the composition of models. Figure 2 shows an illustration of how the four models are connected. Each black arrow represents a link between two models. This link may be made of one or multiple data transfer items. For example the link from MCRouter to the abstraction management model represents one transfer item related to the river flow rate calculated in MCRouter. The link from the abstraction management model to ZOOMQ3D represents one exchange item related to setting the pumping rate in ZOOMQ3D, and the link from the abstraction management model to MCRouter represents one transfer item related to the pumped water returned to MCRouter. The link between BGSGW and MCRouter represents 14 transfer items each related to one cell in BGSGW passing baseflow to MCRouter. The link between ZOOMQ3D and MCRouter is made of a large number of transfer items corresponding to the number of river nodes interacting between the two models.

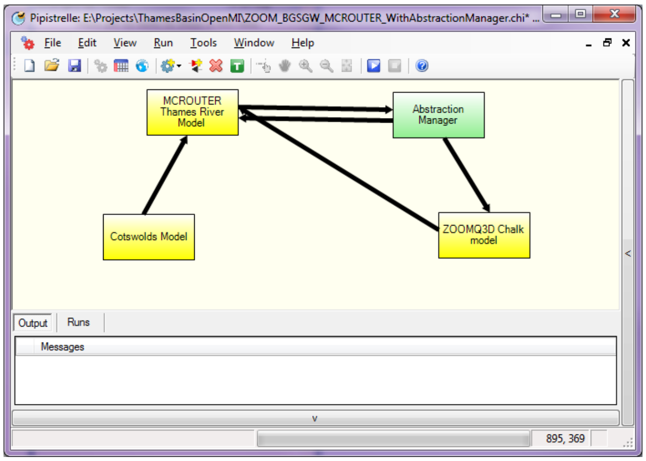

Figure 2. Linking models in Pipistrelle

RESULTS

Two compositions have been created to study the effects of abstraction management on the behavior of the groundwater system and river flows. The composition passes the river baseflow from the limestone model to the MCRouter river model which adds it to the surface runoff channel flows already calculated by the recharge model ZOODRM. The river model is connected to the Chalk model allowing both influent and effluent river conditions depending on the Chalk groundwater levels. In the first composition a constant abstraction rate of 150 Ml/day is assumed to take place at the pumped borehole (BH in Figure 1) at all times irrespective of the river flow rate. In the second composition the abstraction management module regulates the abstraction rate at BH based on the river flows simulated at gauging station GS-B, which is adjacent to BH (Figure 1). The pumping rate is set at 50 Ml/day when the river flows at GS-B drop below 400 Ml/day and at 150 Ml/day when the river flows exceed 800 Ml/day. The pumping rate varies linearly from 50 to 150 Ml/day when the river flow is between 400 and 800 Ml/day. The abstraction management module augments the river flows at GS-A by the amount pumped at BH (Figure 1). This represents the return of abstracted water to the Thames as treated sewage discharge.

Figures 3 and 4 show river flow hydrographs simulated at GS-A and GS-B respectively. The hydrographs produced from compositions 1 and 2 are shown as solid and dotted lines respectively. The simulated river flows are the same in the two compositions except during the drought periods. The differences between the hydrographs simulated at GS-A (dashed line) and the pumping rate as calculated by the abstraction management module at BH (center line) in composition 2 are also shown in Figure 3. The hydrograph difference has the same shape as the hydrograph of the pumping rate because the limestone model produces the same flows in both compositions upstream of GS-A. The differences in the river flow hydrographs simulated at GS-B (not shown) are complicated by the interaction of the river with the Chalk aquifer upstream of GS-B. The minimum river flows calculated at GS-A are 295.7 Ml/day and 145.7 Ml/day in compositions 1 and 2 respectively during the drought period of summer 1976. Minimum river flows calculated at GS-B are 357 Ml/day and 201.3 Ml/day during the same period.

The river flow hydrographs indicate that the inclusion of abstraction management decrease the river flows even more during drought periods. This is caused by the reduction of water returned from the abstraction manager module to GS-A and is opposite to what would be desired. This may happen if pumping is not supplied from alternative boreholes to satisfy the 150 Ml/day water demand. However, the inclusion of abstraction management reduces the fall in groundwater heads during drought periods as shown by the groundwater level time series recorded at BH plotted in Figure 4. The reduction in groundwater level fall may be as important as river flows if they support environmental features such as wetlands. The best management scenario has to be selected, therefore, as a tradeoff between maintaining the river flows and preventing significant drawdown in groundwater levels.

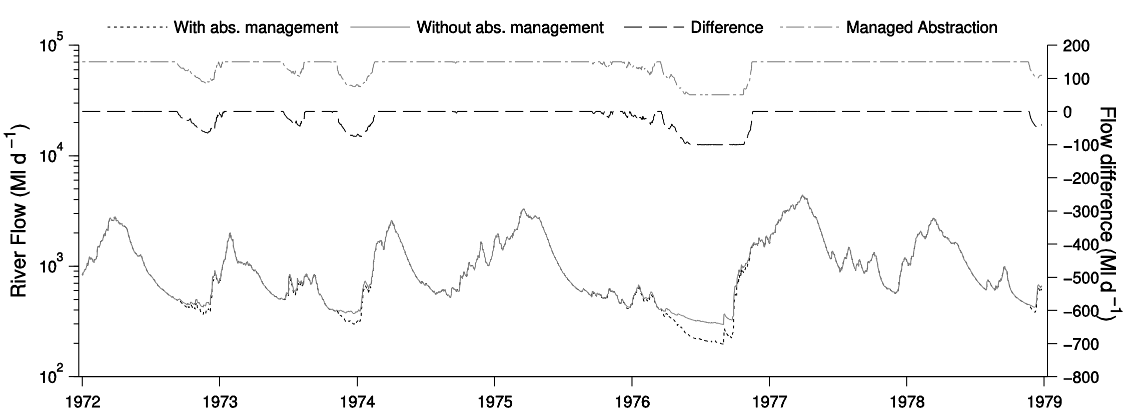

Figure 3. River flow hydrographs (log scale) at gauging station GS_A

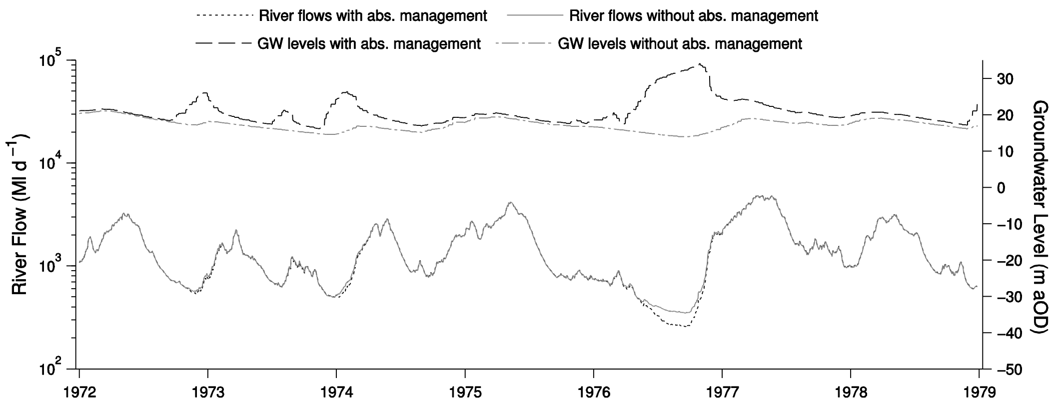

Figure 4. River flow hydrographs (log scale) at gauging station GS_B

SUMMARY

This paper presents a methodology to simulate multi-aquifer systems by linking independent groundwater models, a river model and an abstraction management module using the OpenMI standard. The groundwater models have been developed in different model codes and at different levels of complexity to reflect the specific knowledge of the different aquifers and their functioning. This demonstrates the capability of OpenMI to link models of different structures to improve the simulation of flow processes on a catchment scale. Operational water resources management was also introduced into the environmental modeling composition. Pumping rates at a borehole next to the River Thames are regulated based on the flows in the adjacent river section while the pumped water is returned to the river 35 kilometers upstream of the pumping location. The inclusion of abstraction management decreased the river flows during drought periods because of the reduced pumping rates returned to the river. However, it had a positive impact on the simulated groundwater levels. This work demonstrates the flexibility that OpenMI offers for linking models and for the assessment of different water management scenarios. It is concluded that the integrated model, as presented in this study, gives a more realistic representation of the main aquifer processes and interactions in the Thames Basin and hence will provide a valuable tool for the integrated management of groundwater resources.

ACKNOWLEDGMENTS

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