Challenges of modelling a complex multi-aquifer groundwater system at a national scale: case study from the UK

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ABSTRACT

Modelling of the UK groundwater system, composed of multiple discrete aquifers, is undertaken to help assess water resources at the national scale. This groundwater system is made of the major aquifers that overlie each other in some places but which are nonetheless not in a hydraulic contact, and the minor aquifers formed in the superficial deposits. While the major aquifers are not in the direct contact, they are linked by the river network and may exchange water thanks to the aquifer-river interaction processes. In this paper we present a numerical model of this complex system, which is not as demanding to build and run as a fully distributed multi-layered model. The model represents the three most important UK aquifers: Chalk, Jurassic Limestone, and Permo-Triassic Sandstone as separate layers discretized using square buckets that are connected horizontally. These layers are connected to the river network and receive recharge through the buckets that represent their outcrops. An extra layer is also added to represent the minor and non-aquifers. The model was tested at 37 gauging stations distributed across the country. Good fit to the observations was obtained in the steady state run. Further work will include incorporation of abstractions and additional model refinement to represent spatial heterogeneity.

INTRODUCTION

Droughts and water scarcity pose a significant risk to the environment and the economy in some parts of the United Kingdom (UK). Referring to south and eastern regions of the UK, a recent report by the UK's Environment Agency on water resources in England and Wales stated: *"Compared to the rest of Europe, water resources are under greater stress only in drier countries such as Cyprus, Malta, Spain and Italy"* (EA, 2008). The ever increasing demands on water resources and climate change may lead to further worsening of the current water problems. Groundwater maintains the flow in rivers and provides a third of drinking water in England and Wales. In the South East of England, up to 80% of the drinking water is derived from aquifers (EA). In other areas of the UK groundwater also provides a substantial proportion of water supply, even in the wettest parts of the country. It is crucial, therefore, to assess the availability of groundwater resources under current and future climates and this is usually achieved through modeling. Ideally, a model that integrates surface and groundwater processes and provides assessments of the water availability at the national scale is needed. The Global Water Availability Assessment model (GWAVA) (Meigh et al., 1999), a surface water-groundwater model with integrated water demand component, has been applied to provide an assessment of water security across the UK (CEH & BGS, 2012). However, as for many other large scale models, GWAVA limits the movement of groundwater to surface water catchment boundaries and fails to give an adequate representation of regional groundwater flow processes. For example, an analytical solution based on a non-linear storage reservoir, described by Moore (2007), has been applied to simulate changes in groundwater storage and baseflow. Whilst the GWAVA initiative pioneered the joint assessment of surface and groundwater resources in the UK, the model improvements still failed to include the multi-layered aquifer system and important sub-surface processes, for example groundwater flows across the surface water catchment boundaries (CEH & BGS, 2012). The aim of this paper is to present a groundwater model that can be used alongside GWAVA and improve the simulation of groundwater processes. This module solves the finite-difference formulation of the governing groundwater flow equation and yet it allows for a simplified representation of aquifers compared to a conventional fully distributed groundwater model. Grid nodes are created over defined areas only and they are linked to some or all of their neighboring nodes as defined by the user. This overcomes the deficiencies of the current GWAVA groundwater approach that are described above.

STUDY AREA

The groundwater system of the UK comprises a complex, intertwined composition of major, minor, and non- aquifers. The major aquifers overlie each other in some places but are not in a hydraulic contact. They are, however, linked by the river network and may exchange water thanks to the aquifer-river interaction processes. Groundwater abstraction in the UK is predominantly supplied by three main aquifers: Chalk, Permo-Triassic Sandstone and Jurassic Limestone. The Chalk is the principal UK aquifer, supplying 55% of the total licensed groundwater abstraction (Allen et al., 1997). The aquifer importance is pronounced by the fact that its outcrop extends throughout southern England, where the

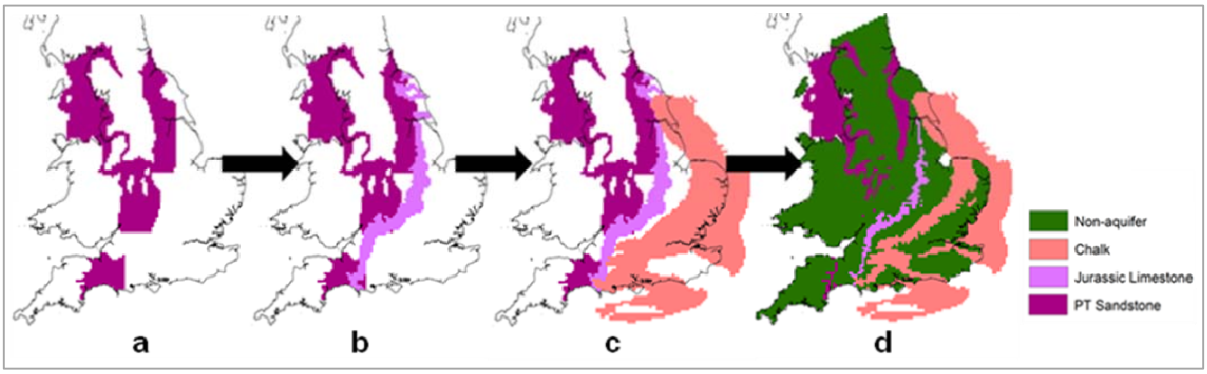

Figure 1 The spatial arrangement of the three major UK aquifers and the "non-aquifer" layer.

population density is high, rainfall low, and surface water reservoirs scarce (Allen et al., 1997). The Chalk was formed during the Late Cretaceous time (100 – 66 Ma), when sea levels flooded southern England depositing a soft white ooze composed of skeletal plates of algae and shell fragments. Despite the high porosity of the material, the matrix permeability is insignificant due to very small pore sizes. As such, the transmissivity and storage coefficient are controlled by fractures, the distribution of which within the formation is not uniform and limited to its upper sections. Although, chalk may be several hundred meters thick in some places, the productive aquifer may only concern the top few tens of meters. A typical borehole yield is on order of several thousands of cubic meters per day (Allen et al., 1997). The second most important aquifer is the Permo-Triassic sandstone (291 – 199 Ma), covering 25% of the total licensed groundwater abstraction. The aquifer is formed in a series of sedimentary basins, originating in a desert environment (BGS), which provide the main source of groundwater in the northern and central England. The thickness of deposits is variable and may reach up to 1000 meters in some places. The hydrogeological properties of the Permo-Triassic sandstone depend on the local characteristics of the deposits, e.g.: grain size, sorting, degree of cementation, and as such they are highly variable and difficult to predict. The groundwater flow occurs through both, matrix and fractures, with the dominant mode of flow depending on the degree of cementation and fracturing (BGS). The borehole yields are highly variable but may reach up to ten thousand cubic meters per day (Allen et al., 1997). The third most important aquifer is the Jurassic Limestone (200 – 161 Ma). The Jurassic age rocks crop out in a band extending from south-west to north-east coast. The sediments, that may be up to 1500m thick, were deposited under tropical climate conditions in shelf or marginal marine environment (Allen et al., 1997). They are relatively hard, characterized by low specific yield values, however, the karstic dissolution of fractures and formation of conduits resulted in high permabilities (BGS). The largest yields are provided by the Lincolnshire Limestone, with some reported values exceeding thirty thousand of cubic meters per day (BGS). The model presented here represents the three most important UK aquifers: Chalk, Jurassic Limestone, and Permo-Triassic Sandstone. The aquifer layers were included in the model in the order that corresponds to the actual sequence of the geological formations (Figure 1a to 1c). Both, the onshore and offshore aquifer sections that are known to maintain groundwater flow, were included. The total modeled area is approximately 195,000 km^2.

METHODOLOGY

The BGSGW code used for this study solves the finite-difference formulation of the groundwater flow equations implicitly. The aquifer-river interaction processes are included through a river leakage term. BGSGW offers some advantages over conventional distributed models. For example, a layer can be discontinuous, the cells within it do not have to be aligned in a horizontal direction, and the number of cells in the layers can differ. Such design lowers the amount of nodes required by the model and improves its efficiency. The current model is composed of four stacked layers, which are discontinuous in some places, with each layer corresponding to a distinct geology class. Three of the layers represent the major UK aquifers, as described above, and the fourth, called "non-aquifer", represents the minor and non-aquifers (Figure 1d). The extents of the layers were generated using the outputs from the UK bedrock fence diagram model (Mathers, 2014). Figure 2 shows the Thames Basin area, in southern England, with the red line delineating the extent of the surface catchment of the River Thames and its tributaries. As illustrated, this catchment includes the three major aquifers within its boundaries. Chalk and Jurassic Limestone exist at outcrop while the Permo-Triassic Sandstone exists at depth only and has no connection to rivers within the basin. These aquifers are not hydraulically connected and they extend beyond the defined surface catchment area so groundwater flows may cross the boundaries of this area. BGSGW also offers flexibility in terms of discretization. A layer has to be discretized with rectangular-shaped cells, however, the number and dimensions of the cells are adaptable; thus lumped to fully-distributed designs can be accommodated. In this study, the modeling domain was discretized with 5 km by 5 km square blocks. A cell is conceptually represented by a tank, with averaged hydrogeological properties. Each cell might be connected to up to six closest cells: four in the horizontal direction and two in the vertical (up or down) direction. Some of these connections can be eliminated based on the conceptual model. Here, the cells are connected in the horizontal direction only, allowing for no water exchanges between the different layers. The layers are connected to the river network and receive recharge through cells that represent their outcrops. The outcrop, in the numerical sense, is formed by cells that are "uppermost" in the composition of stacked layers. A cell will thus form outcrop either if it belongs to the top layer or if there are no cells above it in the overlaying layers. All "uppermost" cells in the model are shown on Figure 1d. Any uppermost cell that has a river within its boundaries has an assigned river node. Figure 3 illustrates how the outcrop cells are connected to the river network. Since the layers are arranged in the vertical order, the cells appear to be aligned horizontally. In fact, the horizontal arrangement and elevations of the cells are not specified. However, the river nodes have specified elevations, which represent the average river bed elevations in the given cells. The model needs recharge values as input. These values were provided by a distributed recharge model (Mansour & Hughes, 2004). The groundwater flow model parameterization was informed by the review of the physical properties of the major and minor aquifers in the UK (Allen et al., 1997; Jones et al., 2000). All grid nodes in a single aquifer layer were parameterized with only one transmissivity and storage coefficient value that reflects the average properties of the aquifer. Using the hydrologeological map of the UK, the “non-aquifer” layer was split into zones to delineate rocks with different groundwater productivity. Based on the analysis of the properties of the minor aquifers in the UK (Jones et al., 2000), transmissivity and storage coefficient values were selected that are representative of

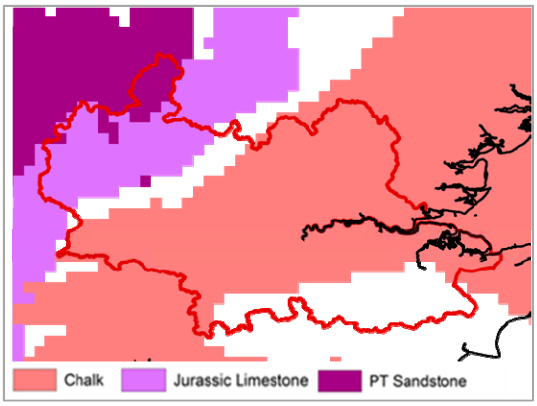

Figure 2 Groundwater flow is not restricted to the catchment boundaries.

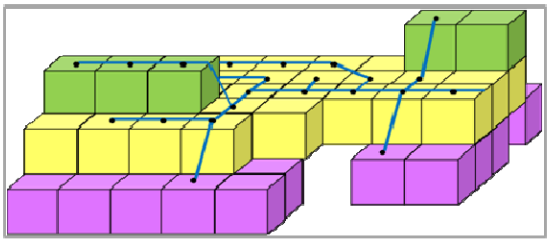

Figure 3 The layers are linked to the river network through the "uppermost" cells.

the rock types in each of the zones. The model produces total baseflow values at every river node and the groundwater heads at every cell node in every layer. Both, steady state and time-variant runs were conducted and the model performance was assessed against the observed baseflows at 37 gauging stations distributed across the UK. The time-variant model was run on a daily time step for 36 years. The Nash-Sutcliffe coefficient (NSF) was selected as a measure of performance. The observed daily flow time-series were obtained from the National River Flow Archive, and baseflow separation was performed using the Institute of Hydrology Low Flow Method (Gustard et al., 1992). The observed long term average baseflow values were obtained from the hydrometric register (CEH & BGS, 2008). Neither surface water nor groundwater abstractions have been included in the current version of the model.

RESULTS

The model was run under steady state conditions using the long term average recharge values obtained from the distributed recharge model. The Nash-Sutcliffe coefficient for all 37 gauging stations was 0.86 although this needs to be used with care since all model flows are naturalized as there are no abstractions included in the model. The stations which showed major mismatch between the simulated and observed long term baseflow values lie within the “non-aquifer” layer. A-time-variant run was undertaken by using daily recharge values provided by the distributed recharge model. This run produced variable results, with the average Nash-Sutcliffe coefficient of 0.17 for all 37 gauging stations. This is a significant improvement over results obtained with GWAVA, which overall NSF score for groundwater component was -0.55 (CEH & BGS, 2012). Four out of six of the poorest performing catchments derived all or large portion of its baseflow from the "non-aquifer"; the other two were chalk catchments. To show a range of model outputs, the simulated versus observed baseflow time-series at two gauging stations are presented (Figure 4). The first station is Thames at Windsor Park, which is the second best "performer" and a major downstream gauging station on the river Thames (Figure 4 bottom). The second one is Ely Ouse at Denver Complex (Figure 4 top).

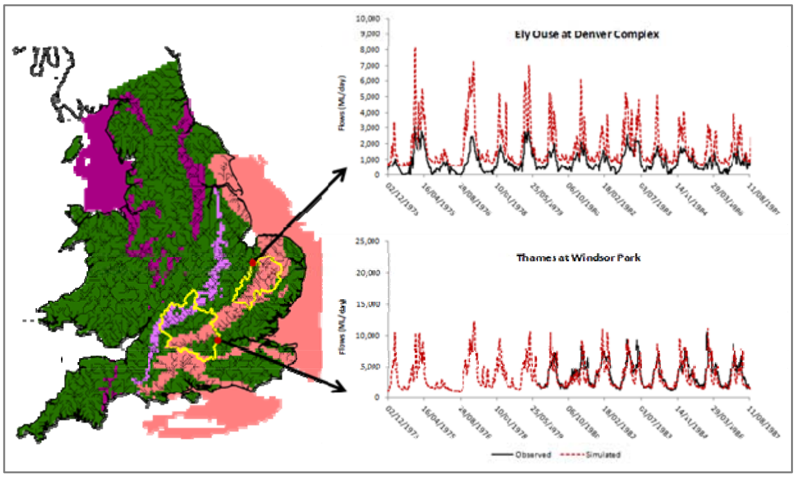

Figure 4 Baseflow time-series with high (bottom) and low (top) NSF score.

SUMMARY

The model described here considers all the principal components of the UK groundwater system. Representing one geology type with one layer offers a novel approach for simulating multi-catchment groundwater flow, which is less conceptually and computationally demanding than the methods used by the traditional fully distributed models. The 36 years long time-variant model run on a daily time step takes approximately 12 minutes on an Intel Core i7 CPU @ 2.93 GHz PC. Despite its simplicity, the model provides a realistic representation of the UK hydrogeology, which, as far as we are concerned, has not yet been achieved by any other model at this scale. Given that no abstractions were included, the results presented here need to be treated with care. The inclusion of pumping boreholes will necessitate refining the values of the hydraulic parameters even in the areas that are performing acceptably in this current version of the model. Future work will include refinement of the layers to represent spatial heterogeneity, and addition of a new layer corresponding to the superficial deposits, which sustain some important minor aquifers. It is envisioned that this model, integrated with GWAVA surface and water demand modules will allow for the combined effects of the climate change and water management practices to be assessed at the national scale. As such, the model will become an important tool in the strategic water planning to ensure security of the water resources in the UK.

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