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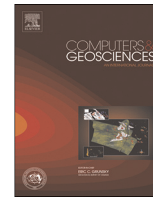

A cloud-based MODFLOW service for aquifer management decision support

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ABSTRACT

A framework to publish simplified MODFLOW groundwater modeling capabilities to a web interface for use by water managers and stakeholders is presented. Numerical modeling simulations can assist aquifer management decisions, but the amount of time and professional expertise required to wield modern groundwater models often exceeds the resources of regulating agencies – even for simple modeling tasks that are repetitive in nature. The framework is capable of automating such modeling tasks, accepting user input, executing MODFLOW, and generating specialized results including maps and modeling reports. This framework was used to build a pilot system for an aquifer in central Utah, allowing a user to simulate the effects of proposed well diversions. This prototype system allows a user to input properties for any number of candidate wells, execute an associated MODFLOW model, and view drawdown contours and regions of decreased spring flow on a web map interface. The modeling analysis is cast into a geoprocessing workflow using ArcGIS and Arc Hydro Groundwater tools, and then made accessible from a server. Such automated and accessible modeling systems have promising potential to facilitate efficient groundwater resources management and reduce modeling errors.

1. Introduction

Water resource managers are faced with the difficult task of satisfying a growing demand for fresh water with a static, and sometimes declining, supply. Groundwater has often been tapped as a convenient and accessible resource for satisfying demand, especially during drought cycles. Unfortunately, many aquifers have been over-allocated, leading to aquifer subsidence, decreased water quality, and increased costs associated with pumping from greater depths and deepening existing wells (Changming et al., 2001; Galloway et al., 1999; Konikow and Kendy, 2005). These issues have generated increasing pressure on water managers to develop more sophisticated techniques for managing aquifers in a sustainable fashion. Judicious management of groundwater resources demands that high quality information be placed in the hands of decision makers. Modern groundwater modeling techniques are often used for water system forecasting, yet these modeling analyses are usually accessible only at the high cost of dedicated modeling professionals.

To obtain projections of future aquifer conditions in response to a set of proposed changes, water agencies both in the United States and abroad often use MODFLOW models. Once a regional model is developed and calibrated, modelers may analyze the effects of a proposed policy or water diversion change by altering and executing the model. Recognizing the repetitive nature of many of these modeling tasks, Jones et al. developed a strategy to automate the process (Jones et al., 2010a, 2010b). We build on that effort, showing how an automated MODFLOW process can be published to a web interface for direct use by water management professionals.

In recent years, the development of cyberinfrastructure for sharing of water resources data and simulation tools via web services and shared online databases has been the focus of considerable research (Ames et al., 2012; Castronova et al., 2013; Castronova and Goodall, 2010; Diaz et al., 2007; Glenis et al., 2013; Horsburgh et al., 2008, 2009). Recent efforts have demonstrated the utility of cloud-based decision support systems that integrate historic and current water data into a single, easily accessible web interface enhanced with interactive mapping capabilities (Dymond et al., 2004; Glenis et al., 2013; Oulidi et al., 2012; Refsgaard et al., 2010; Tillman et al., 2007). In the case of

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groundwater, most of these systems are for data mapping and analysis, but are not designed to run MODFLOW models. Liu et al. (2010) recently developed a system for running MODFLOW models on a commercial cloud. However, it is primarily designed for enabling easily scalable distributed computing for cases involving large batch runs, such as stochastic analyses. In this paper, we demonstrate a new scripting framework that enables agencies to develop automated systems for modifying and executing MODFLOW models on the cloud via a web interface in support of groundwater management.

The Utah Division of Water Rights (UT-DWR) is responsible for authorizing all groundwater diversion in Utah. To analyze groundwater impacts due to a proposed water right change, UT-DWR has collected several MODFLOW models covering most of the major aquifers in the state. Unfortunately, modifying and running these models for every application that must be evaluated is unfeasible; it simply takes too much time from the few engineers capable of building models and interpreting results. To address this problem, we have developed a pilot cloud-based system to assist the UT-DWR in evaluating the impacts of proposed groundwater extraction changes in Northern Utah Valley (Jones, 2012). The automation provided by this system significantly reduces the time and effort required to perform a groundwater simulation as part of a water rights review, thereby allowing experts to use models as an aid in the decision-making process in a greater number of cases.

2. System overview

The cloud-based analysis system may be divided into three successively encapsulating components: a MODFLOW model, an ArcGIS geoprocessing workflow, and a web interface (Fig. 1). Arc Hydro Groundwater (AHGW) tools allow the geoprocessing workflow to encapsulate the MODFLOW model, and a web service allows users of the web interface to execute the geoprocessing workflow.

The Northern Utah Valley MODFLOW model which was created and recently updated by the USGS (Cederberg et al., 2009) was chosen as the pilot application. It is a steady state model with multiple confining units represented by four layers. While the following description of these components will specifically discuss the pilot application, the system can be adapted to enable similar geoprocessing workflows to be developed to automate any MODFLOW simulation. Furthermore the overall organization could potentially be used for other simulation programs.

2.1. Arc Hydro Groundwater

AHGW is an ArcGIS extension that offers geoprocessing tools and a standardized database schema to maintain hydrogeological data with GIS (Strassberg, 2005; Strassberg and Jones, 2010; Strassberg et al., 2007, 2011). MODFLOW Analyst is a subset of the AHGW tools that allows MODFLOW models to be stored, modified, and executed from an ArcGIS platform such as ArcMap or ArcGIS Server. It can be used to transfer model data from native MODFLOW input files to a geodatabase that has been formulated using an extension of the AHGW data model called the MODFLOW Data Model (Jones and Strassberg, 2008). After the geodatabase is populated, AHGW tools in tandem with standard ArcGIS operations may be used to modify and run models, and visualize the model inputs and outputs (Jones et al., 2011). This approach to groundwater modeling enables modelers to (1) automate common modeling tasks with scripted workflows and (2) leverage the sophisticated mapping capabilities of ArcGIS. The cloud-based system capitalizes on both of these features.

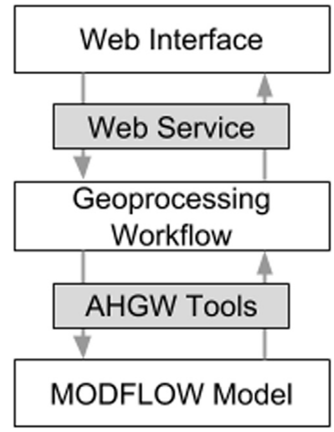

Fig. 1. Data flow schematic showing components used for the Northern Utah Valley system.

2.2. Geoprocessing workflow

The geoprocessing workflow refers to a program that calls the sequence of geoprocessing tools to perform the MODFLOW analysis. The workflow may be expressed using Python or any programming language that complies with requirements of the web service and is capable of executing ArcGIS geoprocessing tools. Regardless of the implementation, the workflow automates the operations required to (1) properly modify MODFLOW input files, (2) run the model, (3) interpret the resulting output files into meaningful ArcGIS features, (4) save maps of the result features in formats suitable for archival and web mapping, such as PDF and KML files. As the script is executed, status messages communicate the progress of the workflow to the web interface.

For the pilot system performing a well-permitting analysis, the MODFLOW input files are modified to include elements representing well applications. Two indicators, aquifer drawdown and the change in discharge of springs feeding Utah Lake, are the results the analysis derives to evaluate impacts. A simplified representation of this pilot workflow is shown in Fig. 2 with a detailed discussion following.

1. *Modify model:* The geoprocessing workflow requires input arguments defining the coordinates, screen elevations, and pumping rate for each candidate well associated with a permit application. The *Create MODFLOW Well Records* tool appends this candidate well input information to a table of all MODFLOW well features, and the *Export Package WEL* tool formulates the WEL file using this amalgamated table. With the newly generated WEL file, the MODFLOW simulation is ready to be executed.
2. *Execute model:* The execution of the MODFLOW simulation is performed with a single AHGW tool, *Run MODFLOW*. This tool requires two input parameters: the path to the MODFLOW name file, and the path to the executable. A MODFLOW executable file is downloaded with the AHGW tools and may be copied into an accessible directory.
3. *Interpret model results:* After MODFLOW executes, the workflow begins reading the model output files and creating features to represent drawdown and the change in spring discharge. The *Import MODFLOW Output* tool populates one table with the calculated drawdown for each cell, and populates another table with the calculated flows through each drain element. The *Create MODFLOW Features* tool then joins the drawdown table with point geometries representing the two-dimensional cell center of the MODFLOW grid. Standard geographic tools may then be used to generate lines of equal drawdown from these results.