International Conference on Hydroinformatics

2014

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REAL-TIME WATER DECISION SUPPORT SERVICES FOR DROUGHTS

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Through application of computational methods and an integrated information system, real-time data and river modeling systems can help decision makers identify more effective actions for management practice. The purpose of this study is to develop real-time water decision support services for decision makers during droughts and floods. To enable ease of use and re-use, the workflows (i.e., analysis and model steps) of the real-time decision support model are published as Web services delivered through an internet browser, including model inputs, a published workflow service, and visualized outputs. The RAPID model, which is a river routing model developed at University of Texas Austin for parallel computation of river discharge, is applied to predict real-time river flow rates. A workflow to predict river flow using the RAPID model has been built and published as a Web application that allows non-technical users to remotely execute the model and visualize results as a service through a simple Web interface. The model service is prototyped in the San Antonio and Guadalupe River Basin in Texas. In the future, optimization model workflows will be developed to link with the RAPID model workflow to provide real-time water allocation decision support services.

INTRODUCTION

Water shortage and flooding have become serious issues in many areas that can cause large loss of property and endanger lives. The importance of effective water management is magnified during these events and rapid and informed responses are needed. One of the main challenges faced by decision makers during droughts and floods is reliable and immediate information collection [*Whilhite et al.*, 1986]. The water decision making process needs to incorporate meteorological information, river network information, and other information. It also requires assistance from multiple models such as weather models, runoff models, hydrologic models, economic models, and so on. The process of information collection, transforming data into appropriate model formats, and model execution is time consuming.

Another challenge is to interoperate different models in a whole system. Existing disciplinary models can be written with different configurations and in different programming languages that may have difficulty communicating. For scientific modeling communities, increasing interoperability and access to models has become a crucial factor for long-term improvement of model performance [*Goodall et al.*, 2013]. Therefore, a structure to organize heterogeneous information and apply it to different models to rapidly solve environment problems is critical for decision makers [*Laniak et al.*, 2013]. Model as a service (MaaS) has recently emerged as an efficient tool to solve the above challenges.

MaaS is an automated modeling system for data access, model execution, and output visulization through the Web. It provides standard data formats for interoperability[*Roman et al.*, 2009]. The model execution does not require specific skills and the visualization of output can be directly achieved on the Web through visualizaton tools. Workflows (i.e., analysis and modeling steps) are developed as a collection of tasks to accomplish some interoperable processes [*Diimitrios et al.*, 1995]. The service sharing of workflows allows users to have easy access to model outputs for researchers, decision-makers and other non-technical users. MaaS also allows model developers to share code and access other models in different communities. Groups can easily manage models and maintain control using the Web services [*Goodall et al.*, 2011]. In addition, MaaS can help to increase data accessibility, reduce the time of data processing, and promote data integration and exchange. With the application of Web services, real-time decision making becomes possible under MaaS. Decision-makers can retrieve immediate model results and make real-time decisions through Web applications.

MaaS can integrate different model components and incorporate model components into a system which can be published through Web services. The services of distributed applications were discovered, integrated, published and reused independent of the specific technology for each single service. One service can be easily interacted with other services without knowing much about them under a service-oriented architecture (SOA) framework. Goodall *et al.* [2011] addressed service-oriented computing for loosely-coupled independent conponents of heterogenous water models and data exchange across the network. Goodall *et al* [2011] use a service-oriented paradigm for the application of water resource models as Web services. But it only demonstrates a simple application for hydrological models. The data transfers between services and the integration of heteogeneous models have not been considered. Feng *et al.* [2011] proposed an approach to publish models through the Open Geospatial Consortium (OGC) and Web Processing Services (WPS) standards. Dubois *et al.* [2013] addressed model integration for the purpose of answering multi-disciplinary questions through Web services. They emphasized the integration and publishing of models beyond simple data sharing. But the modeling system by Dubois et al. has not been developed to integrate with existing systems and data systems. These previous studies focused on separate components of model applications and did not consider the whole process of model application including data processing, model execution and result visualizaton.

The purpose of this study is to illustrate how a more comprehensive integration of data processing, model execution, and output visualization using workflows and MaaS can enable real-time water decision support, as well as other model-based decisions. The workflow system is applied here to build pathways for heterogeneous steps including data processing, model implementation and results visualization. The workflows are published as Web services delivered through an internet browser, including model inputs, a published workflow service, and visualized outputs. The workflow using the Routing Application for Parallel computation of Discharge (RAPID) model has been built and published as a Web application that allows non-technical users to remotely execute the model and visualize results as a service through a simple Web interface. A coupled optimization model workflow system for recommending optimal curtailments during water shortages for decision makers will be built in the future. Visualization of the output using Bing-Maps and WorldWide Telescope is intended to help decision makers predict outcomes from alternative weather scenarios.

CASE STUDY ON MANAGING DROUGHTS IN TEXAS

During summer 2011, Texas experienced the most serious drought since rainfall recording was available in 1895 during the hottest summer of any state in the history of the U.S. The rainfall from October 2010 to September 2011 dropped far below the historical rainfall record set in 1959 and the average temperature during that summer (June to August 2011) was 2 degrees F higher than the historical Texas record [*Nielsen-Gammon*, 2012]. Water loss during this period reached nearly 100 km^3 [*David Maidment*, 2012]. The devastating drought caused large losses of property and degraded human life.

The Texas Commission on Environmental Quality (TCEQ), the environmental agency for Texas, employs water masters in certain rivers basins to provide active water management, particularly during droughts. The Priority Doctrine serves as a foundation for TCEQ’s water management policies. Domestic and livestock users have priority water rights over any permitted surface water rights holders. The permitted surface water rights holders are divided into senior water rights holders, who were granted early water rights, and junior water rights holders, who have obtained water rights more recently. Senior water rights holders have higher priority to withdraw water than junior water rights holders, except when health and safety are involved. During water shortages, if all authorized water users’ needs cannot be satisfied, water rights holders can call TCEQ to carry out water allocation based on the Priority Doctrine [*L’Oreal Stepney*, 2012]. During this process, the amount of water available in the river, both now and in the next few weeks, is one critical factor for TCEQ watermasters to allocate water. River forecasting models such as RAPID can predict river streamflow, but running these models typically requires technical skills that would be difficult for TCEQ watermasters. Therefore, model as a service (MaaS) is proposed to run the model on the Web. End users do not need technical skills and results can be directly retrieved on the Web.

The case study area where MaaS was implemented is the San Antonio and Guadalupe River Basin, which is located in South Central Texas (Figure 1). The limited water supply has become a major source of conflict in the river basin, particularly during droughts. How to allocate water effectively and fairly during droughts has become a critical issue for TCEQ decision-makers.

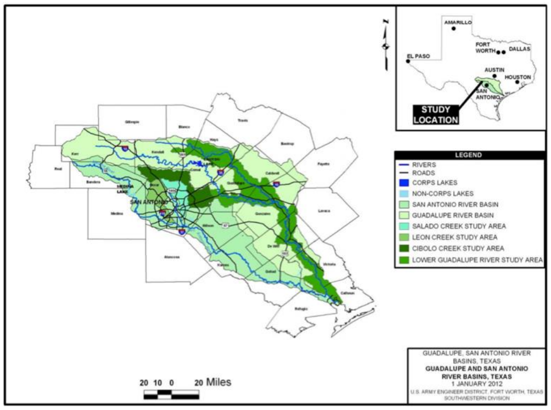


Figure 1. The San Antonio and Guadalupe River Basin

Currently, water rights holders are required to call TCEQ to request the amount of water they wish to use. During a severe drought, daily calls are required. After receiving a water request, TCEQ staff will check the amount of available water in the river by collecting information from USGS streamflow gauges. Then they allocate available water to each water user, respecting water users’ priority, based on their subjective judgment as to the impacts of these allocations. The process is repeated each day as the impacts of the previous days’ allocations become apparent in the river levels, but no forecasting is currently used. This process requires a large amount of time and the response of TCEQ decision makers is not immediate, nor is it based on best available forecasts.

A real-time Web application can improve this water allocation process by automating collection of information and use of state-of-the-art forecasting models. TCEQ decision makers can then utilize the Web application to allocate water in a more scientific approach to assist subjective judgment.

To provide this type of support for this case study, the MaaS approach was implemented with the RAPID model, which is a river routing model developed at the University of Texas Austin for parallel computation of river discharge. Given the river network connectivity and predicted water inflows (i.e., runoff) into the river network, RAPID can be run on any river network to compute river streamflow. River connectivity information is provided by NHDPlus, which describes all river networks and water bodies in the United States [*David et al.,* 2011].

Land surface models (LSMs) with meteorological forcing can be used to compute surface and subsurface inflow as water inflows into NHDPlus river network and to provide the land base for the RAPID model [*David et al.*, 2011]. The land surface model used in this study is the National Weather Service (NWS) Sacramento Soil Moisture Accounting (SAC-SMA) model, which is based on a soil moisture and energy balance model that estimates the runoff production for each grid cell based on radiation, precipitation and surface climate [*Shultz & Corby,* 2006]. The SAC-SMA model is run every hour to generate a time series of runoff values that are fed into the RAPID model to compute river streamflow. The river routing time step is 15 minutes, providing an estimate of the river streamflow rate (cubic meters per second) every 15 minutes. For the purposes of drought decision making, with water allocations made on a daily time scale, these time resolutions are sufficient to enable effective management.

METHODOLOGY

Figure 2 presents the general framework for MaaS to support rapid model-based decision making. There are three main components to the framework: Model as a Service Architecture, Web Application, and Scenario Analysis. Cyberintegrator, a desktop exploratory workflow system, is used to generate and publish workflows (sequences of data and model execution steps) as services. Cyberintegrator is an exploratory scientific workflow system developed by the National Center for Supercomputing Application (NCSA) that can be used to generate and publish workflows as services. Compared to other workflow tools, such as Taverna [*Oinn et al.*, 2004] and Bio-STEER [*Lee et al.,* 2007], Cyberintegrator has significant advantages in its approach to create a workflow. Instead of creating a one-time full workflow and execution, Cyberintegrator allow users to take small exploratory steps to create a workflow as they explore the data. In addition, Cyberintegrator wraps modules (fragments of code) into Web services [*Bajcsy et al.*, 2005]. The structure of software and semantics is hidden behind Web services. Therefore programming expertise is not required to build a workflow.

The design of the workflow disseminates the model application into several disciplinary steps and links these steps into a pathway [*Villa et al.*, 2009]. For instance, hydrologic model applications can be divided into three main steps – data downloading, model execution, and results visualization. For each step, one or more specific tools can be built in the workflow system. Given the input file(s), the output can be generated using the built tool(s). Using data transfer through intermediate storage in a database, each component of the workflow system is connected until a desired result is achieved. Therefore, the workflow system achieves integration and interoperability of heterogeneous components in a loosely coupled environment [*Georgakopoulos et al*., 1995]. This allows each heterogeneous component to be built using independent platforms and developers. Different data formats, programming languages, compilers and development environments for each component will not affect interactivity. Technology-based software barriers among different components are solved. However, saving interim results to a database between components can require some computational time, and users will need to balance how finely to break execution steps into independent components. In this application, a coarse set of steps are used to enable ease of initial implementation and minimal effects on computation time.

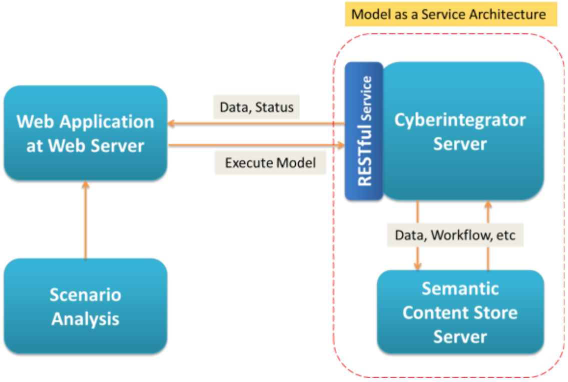


Figure 2. The framework of Model as a Service (MaaS)

Once the workflow is completed, it is published to the Cyberintegrator server, which is a sharing center that allows users to upload and access shared workflows as well as generate RESTful services which can communicate with Web applications through Uniform Resource Locators (URLs). Users can retrieve data and check job status from the Cyberintegrator server via the Web. They can also send model execution commands using URLs to the Cyberintegrator server. A semantic content server is used to keep track of data products, workflows, metadata, etc. [*Myers et al.*, 2009]

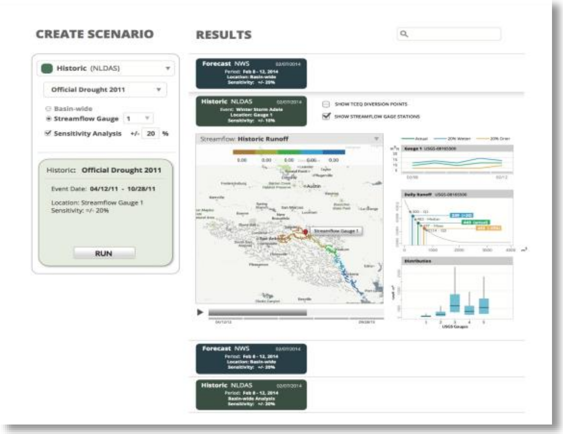
Scenario analysis can be used to generate alternative future options to explore with the Web application. The ultimate aim is to implement the entire process of the real-time water decision support system as a Web application, including Web inputs, a published workflow service, and visualized outputs. The workflow is executed in the background on a remote server in the Cloud (i.e., elsewhere on the internet), which enables easy use of supercomputing or parallel resources. It is not necessary for users to keep a long-term connection to the server. Instead, users receive notification when the job is completed and then can view or download the results. After publication, the completed workflow can be shared with other users or groups through a shared library of Web services.

A Web application can then be designed as a user-friendly interface for assigning workflow parameters, creating alternative scenarios, executing the workflows, retrieving data, checking the execution status, visualizing model results, and sharing the workflow results using service calls to the Cyberintegrator server [*Marini et al.*, 2010]. The created scenarios can also be saved on the Web, which facilitates future scenario analysis by users. Decision makers who are not familiar with a specific model or the workflow management system can still easily execute the workflow and view results using geospatial maps such as Bing Map through the Web interface.

The scenario analysis tool allows decision makers to modify input parameters and compare results side by side. Employing scenario analysis can assist with evaluating possible future events based on different assumptions [*Kepner et al.*, 2004]. For river streamflow prediction and other spatially-distributed models, two approaches to scenario analysis have been implemented in the MaaS framework. The first approach is simply to allow the user to vary an input parameter (in this case runoff levels) by a specified percentage at every location and in every time period during the desired modeling period. The second approach involves using historical data to fit a distribution of the input parameter at each individual location (in this case, runoff computed by the National Weather Service in each watershed). The user is then shown the distribution at each location and invited to vary the input runoff at any one location. Alternatively, the user can assess variability at all locations and then select a single percentage to vary the parameter at all locations as in the first approach.

CASE STUDY IMPLEMENTATION

This section describes the case study implementation of MaaS in San Antonio and Guadalupe river basin. The Web interface and scenario analysis developed for the RAPID model is also presented (Figure 3).



○ Basin-wide
● Streamflow Gauge 1
☑ Sensitivity Analysis +/- 20 %

Historic: Official Drought 2011
Event Date: 04/12/11 - 10/28/11
Location: Streamflow Gauge 1
Sensitivity: +/- 20%

Forecast NWS 02/07/2014
Period: Feb 8 - 12, 2014
Location: Basin-wide
Sensitivity: +/- 20%

Historic NLDAS 02/07/2014
Event: Winter Storm Adele
Location: Gauge 1
Sensitivity: +/- 10%

☐ SHOW TCEQ DIVERSION POINTS
☑ SHOW STREAMFLOW GAGE STATIONS

Forecast NWS 02/07/2014
Period: Feb 8 - 12, 2014
Location: Basin-wide
Sensitivity: +/- 20%

Historic NLDAS 02/07/2014
Period: Feb 8 - 12, 2014
Basin-wide Analysis
Sensitivity: +/- 20%

Figure 3. Web application for real-time MaaS decision support system

The MaaS provides an easy approach for non-technical users to run RAPID through a Web application. Traditionally, users need technical skills to set the running environment for complex numerical models such as RAPID. RAPID runs in the Linux operating system, which requires basic programming skills and an understanding of how to update and link the execution and input files. The MaaS framework provides an automated request system for the model runs and online visualization.

To implement the RAPID model in the MaaS system, the first step was to build the RAPID workflow using Cyberintegrator tools. The RAPID workflow includes three main components: 1) prepare the surface and sub-surface inflow of water to the river network (downloading and transforming NWS data), 2) run RAPID, and 3) animate RAPID results. This workflow was then published to the Cyberintegrator server. The Web application clients can then access the shared workflow in the Cyberintegrator server through Web browsers.

Using the RAPID workflow, users can create scenarios and launch the streamflow model execution through the MaaS Web application. To provide more detailed information to the user on typical runoff estimates at the streamflow gauges that could be used to guide scenario selection, five USGS gauges corresponding to the five catchments in the Upper Guadalupe river basin were selected for statistical analysis.

Exploratory data analysis (EDA) techniques proposed by John W. Tukey are applied for the historical data analysis [*Tukey*, 1977]. The first quartile, median, mean, and third quartile values can then be computed from the historical data and displayed for each gauge as shown in Figure 3. When a new runoff forecast is obtained, the user can view where the new forecast falls within the historical exponential distribution and choose appropriate bounds for sensitivity analysis.

The create scenario section of the Web application (Figure 3) allows users to select parameters for the model execution. For executing RAPID, only prediction with historic NLDAS data (i.e., hindcast) or 5-day forecast NWS data can be specified through the Web application, but other model parameters can easily be added to the interface as desired. The results section in Figure 3 shows the output for each scenario executed, including the streamflow under the wetter (blue) and drier (tan) scenarios.

CONCLUSIONS

This work demonstrates the application of MaaS for a hydrologic model (RAPID) using Cyberintegrator workflow systems. The Web applications and model services can be implemented with any model on the Web and help non-technical users to easily run state-of-the-art models through Web browsers, providing user-friendly interactive support for both real-time and longer-term decision making. The modeling service can also be coupled with other data services. The prototype implementation can be accessed through the Web at http://rapid.ncsa.illinois.edu:8080/rapid2/.

Using the prototype system, TCEQ water managers can easily select an input data period to run RAPID and view the results on the Web. A statistical analysis of the model input data provides guidance in identifying and evaluating plausible scenarios. This will allow water managers to be more informed about how much water is available during a drought and make rapid decisions about potential impacts of water allocation strategies. The final version of the prototype decision support system will also allow water managers to incorporate real-time optimization services for water allocation in the river basin.

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