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# INTEGRATED URBAN WATER RESOURCES MODELING IN A SEMI-ARID MOUNTAINOUS REGION USING A CYBER-INFRASTRUCTURE FRAMEWORK

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Water resources management in cities is facing growing challenges related to increases in water demand, uncertain future climate variability, and conflicts related to water rights and access. Integrated water resource management (IWRM) is an inter-disciplinary process, which considers the connections and feedbacks among different built, natural, and human elements of a water resources system. An IWRM process often involves the use of a modeling and simulation framework that can incorporate infrastructure, environment, and human dimensions to explore the system and seek solutions. In this paper, an integrated urban water modeling framework is introduced for studying a range of urban water research questions and facilitating IWRM. The framework was created with the GoldSim Monte-Carlo simulation software to take advantage of built-in functionality combined with flexibility and extensibility. The GoldSim software is used as the integrator and supports fast access and application of data resources, exchange of data among sub-models, and capacity to produce long-term simulations with sufficiently high spatial resolution to support urban water management and research. Also, decision support elements have been included in the framework, such as a web-based interface, results analysis module, and visualization tools. Working with local water managers the framework has been designed to provide information for stakeholders, water managers and researchers to answer questions related to climate impacts on water supply and the interconnected urban water system, as well as sustainability tradeoffs of urban water system configurations.  With the web interface and user interface capacity of GoldSim, the framework has been used for stakeholder engagement and K-12 outreach and education activities. This paper describes the integrated urban water modeling framework and presents an analysis of climate impacts and a comparison of decentralized versus centralized urban water management solutions for the Salt Lake City, Utah metropolitan area in the western United States.

## INTRODUCTION

Water resources managers in cities are facing growing challenges related to increases in water demand, uncertain future climate variability, and conflicts related to water rights and access. Water managers need to decide how to allocate resources and design systems with uncertain future climate conditions and changing population demographics to reduce system vulnerability. One approach that water managers can employ to address water management in complex urban systems is Integrated Water Resources Management (IWRM). IWRM is a process that helps stakeholders coordinates their decisions to achieve more sustainable water resource systems [1]. A cyber-infrastructure (CI) framework can help water managers address their challenges by supporting an IWRM process providing access to data, modeling, and simulation tools in a way that the broad system interconnections and feedbacks can be explored and implications of decisions analyzed. A general CI framework would contain hardware (e.g., data repositories, map and data servers, high-performance computing) and software (e.g., data models, scripts, model codes, analysis and visualization software) components with logical interfaces for user and web-based interaction.

In this paper, an integrated urban water resources modeling (IUWRM) framework is introduced. The framework is built using the GoldSim simulation software and includes a range of CI components to help it be applied for IWRM and to answer complex urban water research questions. Elements considered in the framework development have been model elements, input and output data formats, the need for a common data schema, and the data flow to answer research questions and support IWRM. The framework supports data-intensive models that require up-to-date, consistent, accessible, well-organized, and documented data and associated metadata [2]. A case study demonstration is presented for the Salt Lake City, Utah metropolitan area.

## CASE STUDY

The case study selected to demonstrate the integrated urban water resources modeling framework is the Salt Lake City, Utah, metropolitan area located in the western United States. Salt Lake City is a medium sized city with a metropolitan area population exceeding one million residents. According to the Köppen climate classification, the city experiences a Continental Mediterranean climate with an annual mean precipitation and annual mean temperature of 40.89 cm (16.10 in) and 11.2 °C (52 °F), respectively. The City Department of Public Utilities provides stormwater management, wastewater collection, and drinking water services to more than three hundred and forty thousand people. Between 2006 and 2007, Utah experienced the third-fastest annual population growth rate in the United States, ranking behind the states of Nevada and Arizona. This rapid growth is expected to continue with a projected increase to more than seven million people within 50 years. Salt Lake City currently is the most populous city in Utah and is expected to remain so into the future. Approximately sixty percent of the Salt Lake City’s water supply is extracted from four creeks draining four of the seven canyons to the east of the city. The canyons/creeks that provide the majority of the surface water supply are City Creek, Parley’s Creek, Big Cottonwood Creek, and Little Cottonwood Creek. Parley’s Creek (Figure 1) is an important part of the water supply system because it contains two reservoirs (Little Dell and Mountain Dell) comprising the majority of storage available. The primary inflows to the two-reservoir system are from Lamb’s and Dell Creek. A diversion also exists from Lambs creek to Little Dell reservoir due to the greater storage capacity in Little Dell. The Parley's water treatment facility is located at the outlet from Mountain Dell reservoir. The treated water is delivered to the Salt Lake City distribution system through a pipeline. Bypass from the reservoir system enters Parley's creek and flows through Salt Lake City to the Jordan River and eventually into the Great Salt Lake.

## INTEGRATED MODELING

A broad integrated urban water resources modeling framework would include atmospheric, hydrological, geological, environmental, economic, and sociological components. These components have complex interactions with human-natural water systems. In this study, selected components that affect the Salt Lake City's water system were selected to be incorporated into the modeling framework. The GoldSim Monte-Carlo simulation software [3] was used to provide dynamic simulation of the inter-related parts of the Salt Lake City urban water system. Integrated water system components in this study are divided to two different categories. The first category includes the components which affect the water balance directly such as the natural system hydrology, water supply, stormwater, and climate. The second category has indirect impact on the water system such as demand and management actions.

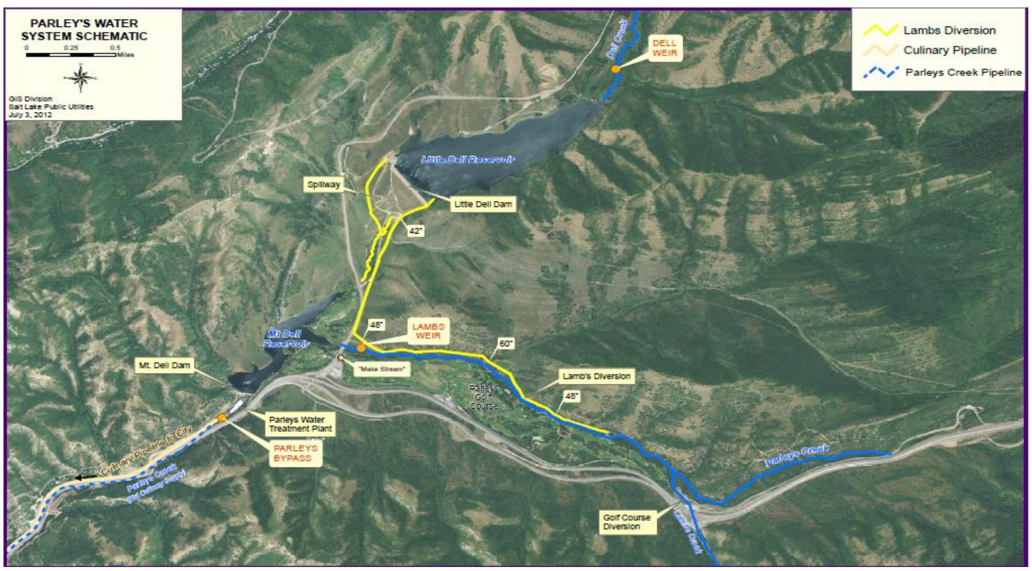


Figure 1. Schematic of Parley's Creek two reservoirs, part of Salt Lake City's water system

The IUWRM framework integrates various models included in the two categories to support the broadest set of possible planning and decision analyses. Following the IWRM strategy, the framework was designed to help to plan and manage the water infrastructure system and related sources to maximize the economic benefits and social welfare, leading towards sustainable solutions. The GoldSim software was used to create the IUWRM framework. GoldSim served as the integrator with interfaces to the external codes of various software for specific calculations. External software was connected to GoldSim by embedding equations or by calling code through dynamic-link library (DLL) interfaces. DLL interfaces were needed to connect GoldSim with external models which were too sophisticated to be implemented with equations within GoldSim. For example, the Snowmelt Runoff Model (SRM) was included within GoldSim, but the U.S. Environmental Protection Agency's Storm

Water Management Model (SWMM) was connected using a DLL created in C++ to model the stromwater runoff. GoldSim also has the capacity to execute dynamic probabilistic simulations that can be used for this application. The flow module of GoldSim was used to solve the allocation of different sources in Salt Lake City water system, and system dynamics (SD) modeling in GoldSim was used to model reservoir operation. Ultimately, in the future, there is the possibility of connecting a wide range of models to GoldSim. Figure 2 shows examples of additional models that are currently being integrated into the IUWRM framework. For example, to represent future climate projections, data from the Coupled Model Intercomparison Project (CMIP) and dynamically downscaled data from the Weather Research and Forecasting Model (WRF) are being used. To model ecosystem processes, the Regional Hydro-Ecologic Simulation System (RHESys) is being incorporated. And to model urban runoff quality, The Hydrological Simulation Program in Fortran (HSPF) is being added.

## MANAGEMENT TOOL

To provide user interaction to the IUWRM, the GoldSim model was packaged as a Player file, which permits it to be executed with a dashboard or accessed without a license to GoldSim. In this way, a player file can be passed and others can view and execute simulations using the model under different selected circumstances to test alternative scenarios. Related instructions and metadata to explain the model and input parameters, how each module in IUWRM was designed and modeled in order to run it can be attached; therefore, a useful player file should be self-explanatory and well-designed. Figure 3 shows a simple example of the Parley's Creek Management Tool that was created to allow users to test the reliability of the Parley's Creek component of the water system under different climate, hydrological, and structural scenarios. The figure illustrates different input controllers to permit analysis of scenarios and then see, plot, and save results to compare different management actions.

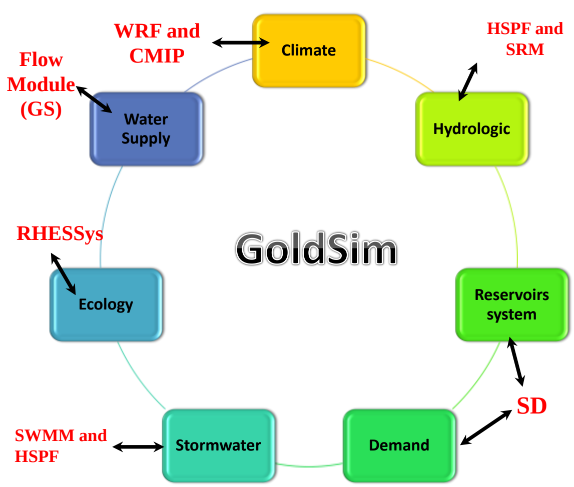


Figure 2. Different components of IWRM and related models

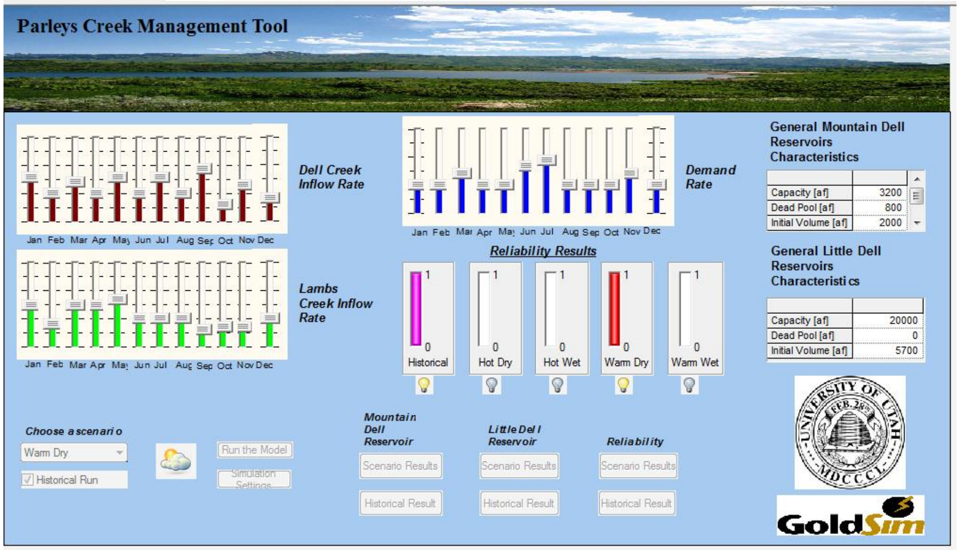


Figure 3. Parley's Creek Management Tool dashboard

## DATA MODEL

A flexible method was needed to organize the data and metadata for the IUWRM framework. Community standards and data models can establish a method to use, share, and publish data to overcome the wide range of water resources data terms and structures. The data model used for this project was created to provide a generic and relational data management system. The data model sets data values in proper formats like time series, parameter, etc. Moreover, this data model can be used to make the metadata structures to define how data are gathered for different components, as well as the gathering process characteristics like who collects data and where. For this purpose, a set of controlled vocabularies are defined for the object and attributes names to facilitate data interoperability and preserve consistency and homogeneity of metadata. The Water Management Data Model (WaM-DaM) selected for the IUWRM framework was designed by Abdallah and Rosenberg [4] to provide an open-source data management system to support water management and hydrologic modeling. They have tested WaM-DaM for a three node network in the Little Bear River, Utah. The application of Wam-Dam for the present project is being accomplished with the help of the Wam-Dam designers.

## WEB APPLICATION

After building a GoldSim model, Goharian *et al.* [5] deployed the Parley's Creek Management tool as a web application or "app". The only software requirement that is needed to run the app was a web browser (no plugin needed). Therefore, the app can be executed on most major desktop computer operating systems (Linux, Mac OS, and Windows) and many mobile devices that have full web browser support. The app is able to work independently of the user's operating system, because a service-oriented architecture was implemented that enables the model execution on a server that resides remotely in the cloud. In this project, the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard was utilized as the protocol for running models. The advantage to using the OGC standards was that many tools have been developed to comply with these standards. Communication between tools was seamless due to the standardization of data transfers [6].

The model was made accessible as a custom web service using 52 North. 52 North is an implementation of the OGC WPS specification written in Java and run through Apache Tomcat. It provides a WPS interface to geoprocessing libraries including Sextante and Grass, but also enables custom R and Python scripts to be incorporated and exposed as WPS services. To enable the model execution to be exposed through 52 North it was scripted using Python.

The Parley's Creek reservoir system model was packaged as a GoldSim Player file, which allowed its execution to be scripted. In this format, the inputs to the model are contained in Excel files that were pointed to by the GoldSim Player model file. The Excel files must be edited or overwritten to change the input parameters to the model. A Python script was developed to modify the Excel input files using the xlwt and xlwd libraries. The Python script then executes the Little Dell model which writes its output in an Excel file. Requests are sent to the 52 North server through another Python script using OWSLib, a Python package designed for client programming with the OGC web service standards [7]. While the web service is accessible from anywhere and fairly easy to use, it would not be easy for a non-technical user to use directly. Consequently, a simple Graphical User Interface (GUI) was designed for the web service to make it more accessible and easy to use. The GUI was built using The Engineering Toolbox for Hydrologic Simulation (TETHyS): a web application development suite that is optimized for hydrologic modeling web applications. In this case the client is the app on the Tethys server. The app takes user input and submits a request to the web service using OWSLib. The 52 North server executes the Python script that modifies and runs the Parley's Creek GoldSim model. 52 North then returns the Excel file produced by the model to the client. Schematic of the process is presented in Figure 4.

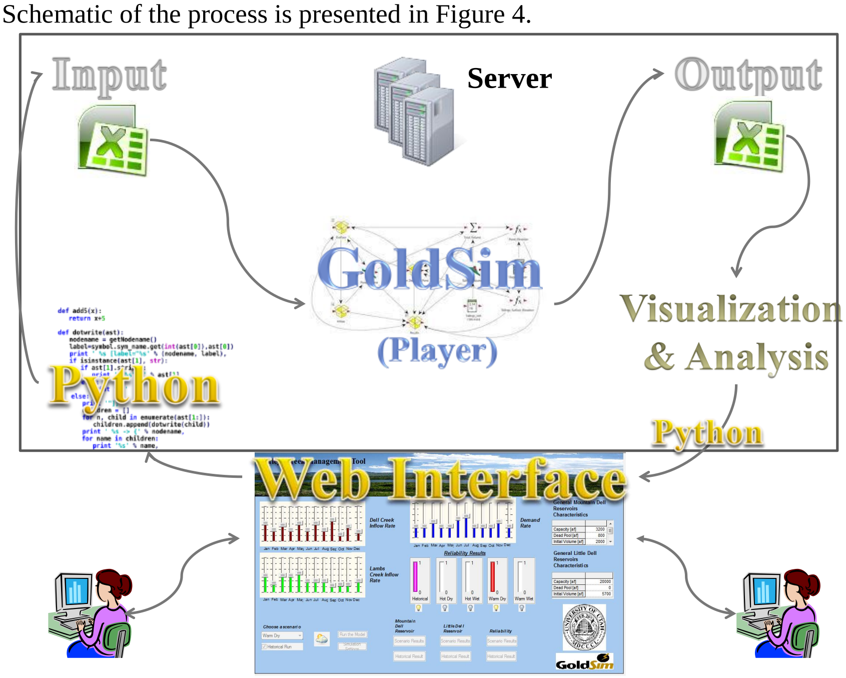


Figure 4. Web application development framework

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