

Developing an integrated framework to build a decision support tool for urban water management

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ABSTRACT

This paper presents an integrated, computer-based generic framework to couple urban water related models into a decision support tool (DST) for urban-water management. The DST, built on a participatory modelling approach, enables stakeholders to analyze impacts of climate variation, population growth, and alternative management solutions ranging from centralized to distributed options. The coupling of external models, building of the DST, and execution of simulation processes is achieved by employing GoldSim, which is linked to a database management tool and a shared library. A post-processing package generates outcomes for decision makers in the form of a new criterion, the Water System Performance Index (WSPI). The application of DST is demonstrated for the water service area of the Salt Lake City Department of Public Utilities (SLCDPU). Results show that a decentralized alternative increases the reliability of the system without changing the system's vulnerability. Centralized alternative improves the overall performance of the system based on WSPI results, but decrease in performance is still noticeable under the hot and dry climate condition. Overall, the system is very sensitive to changes in climatic conditions. Results show that during droughts, supply management is not the sole solution and compulsory demand-management practices should be instigated.

Key words | decision support tool, hydroinformatics, model coupling, system dynamics, urban water management

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INTRODUCTION

In response to variation in water availability and water demand in cities, water managers are faced with difficult decisions to sustainably manage urban water systems. The decision-making process is further complicated by changing and often unforeseen constraints. The process needs involvement of multiple decision makers, including environment specialists, designers, economists, government officials, and the community; and a framework for analyzing potential solutions and identifying the most preferred option. Assessing water management alternatives, including new infrastructure development, generally requires considering both quantitative and qualitative factors to account for broad system goals such as sustainability (Makropoulos *et al.* 1999). However,

uncertainty associated with physical representation of water components and dynamic interactions between components makes the study of water resources systems a complex task (Winz *et al.* 2009). Adding to this, changes in climate and natural system responses exacerbate the complication of analyzing and finding sustainable solutions.

While the two terms decision support system (DSS) and decision support tool (DST) are used interchangeably in the literature, they are slightly different. Hewett *et al.* (2010) suggested that DSSs are the frameworks upon which DSTs are developed. DST is only one tool of many that help managers in the process of decision making within the scope of a DSS framework (Jakeman *et al.* 2006; Hewett *et al.* 2010).

DSTs help to reduce the complexity of a water system's interrelationships and develop a well structured assessment process. Based on Power (1997), any kind of expert information or support systems, geographic information systems, or online analytical processing or software agents can be a DST as long as it enhances the communication and coordination among managers, stakeholders, and researchers. Establishment of communication through a DST requires comprehension of the real world problem, modelling framework, and appropriate hydroinformatics tools to analyze and evaluate solutions. To provide the broadest applicability of a DST, one should take a global perspective and employ a coupled system modeling framework (Lam *et al.* 2004; Malleron *et al.* 2011). Different types of DSTs have been developed in the broad context of water resources planning and management (Mysiak *et al.* 2004; Fassio *et al.* 2005; Holmes *et al.* 2005; Jolk *et al.* 2010; Kumar *et al.* 2015). However, most of these tools are developed based on specialized water resources software. *WEAP 21* (Yates *et al.* 2005), *MODSIM* (Labadie 2006), and *AQUATOOL* (Andreu *et al.* 1996) are examples, which can be used to model water systems and inform decision makers of the performance of their systems under different management scenarios.

Individual parts of a water system can be modeled by detailed physical-, process-, and system-based simulation models; however, including dynamic interactions between these components is a difficult task. Water resources systems have complexity, including feedback loops, robustness of the order, numerosity, and emergent organization. There are mainly two ways to capture the interactions between different parts of a water system. One way is using integrated numerical-, physical- or processed-based models (e.g. integrated water flow model, IWFM). IWFM mainly simulates the groundwater and surface water and their interactions (Dogrul 2014). However, IWFM and similar complex models are difficult to use for the management of water systems, unless they are equipped with DSTs. Also, these models are often limited to a few water components and are not flexible enough to easily modify or add new water system and analysis modules to them. The other way of integrating models in order to capture the dynamics between the water components is using system dynamics (SD) approaches. There are many SD

models developed for water resources, such as Canada's Water Resources SD model (Simonovic & Rajasekaram 2004). However, these models are designed solely based on mathematical/statistical relationships between different water-system elements which are not presented by physical and conceptual models. The present paper presents an integrated framework that substitutes SD model elements with relevant physical-, process-, and system-based water models and analysis modules. To develop the DST presented herein and others, numerous challenges exist. The main challenges to develop a DST for the integrated management of urban water resources systems are: (1) bottom-up implementation based on stakeholder input; (2) comprehensive representation of complex, interconnected water resources systems; and (3) post-processing of analysis results to facilitate communication.

The first major challenge in terms of modeling management policies and practices is involving stakeholders in the model and DST development process. To improve the process and communication, it is essential to engage decision makers and stakeholders throughout the participatory modelling (PM) process (Voinov & Bousquet 2010), development and application of a DST (Abbott 2007). Recently, several studies have demonstrated public participation and stakeholders' engagement in decision making during data gathering, policy establishment, and modeling and simulation stages to develop more appropriate DSTs, enhance decision making, and better represent different views and needs (Thorkilsen & Dynesen 2001; Rekolainen *et al.* 2003; Hewett & Quinn 2004; Quinn *et al.* 2009; Hewett *et al.* 2010). Voinov & Bousquet (2010) studied various frameworks that include stakeholder participation and compared them with participatory modeling approach results. The scientists have a difficult job in providing timely and insightful information for the use of policy makers. Lack of an established framework and standard dialog indicates that there is a serious need for further collaboration between researchers and decision makers. This paper presents an example of a successful collaboration between academia, government, and the private sector through a PM and bottom-up approach to address local water-management related questions and concerns with a DST. The section 'Collaborative actions between researchers and decision makers' addresses the method that is

used in this study to involve stakeholders in the model and DST development process.

A second challenge is to comprehensively represent complex, interconnected water resources systems. Urban water systems are a specific area for application of DSTs that need representation of the water supply, stormwater drainage, and wastewater management (Makropoulos *et al.* 2008). In order to fully explore the interactions within the urban water system, it is necessary to develop an integrated modeling framework, which includes climate projections, hydrologic and hydraulic processes, infrastructure systems, management alternatives, and more. Different researchers have developed DSTs for urban water systems (e.g. Sakellari *et al.* 2005; Makropoulos *et al.* 2008; Willuweit & O'Sullivan 2013); however, by necessity to keep the development tractable they have been designed with a specific framework and structure such that the tools are not easily adapted to other geographic areas, time periods, and scenarios. In water resources systems, defining the spatial social, political, and ecological boundaries requires substantial and careful effort to represent the complex behavior within and between local, federal, private and public organizations (Brandmeyer & Karimi 2000; Voinov & Bousquet 2010). This often involves more than development of a specific environmental media model. For example, a precise watershed decision-making model needs a hydrologic model coupled with other models to transport water through different media and infrastructure systems. Argent (2004) classified the modeling development and application of a scientific phenomenon into four levels. This process can be initiated by developing a base-level model, which is designed to answer a particular problem for a specific location and time. The modeling process can be further extended and generalized to the top level (Level IV). In the top level or level IV, the interactions between the components of model are often of more interest. A top-level model should be designed for use of various end users, who have no information about the how the model works or theory behind it. Thus, the model can be used for planning and operating purposes and to represent different user-defined scenarios. Although the top-level model is more useful for planning and management purposes, a flexible model should offer a multi-level application to users, i.e. the model should be developed with the intention of

operating at different levels (Argent 2004). While the original model development framework of this study is a multi-level process, its application as a top-level model is shown and discussed in this paper. This model represents the complexity and connection of sub-models in an integrated fashion, and also it is packaged for planning and policy analysis by separating the main model from the DST. The discussion of developing the model is presented in the 'Representation of a complex and interconnected water system' section, while developing the DST for this study is discussed in the 'Application of SLC-IWRM DST' section of the paper.

A third challenging issue with the DST development process is that model outputs are raw and in need of post-processing for analysis and communication. Decision-making methods may be used to select the most appropriate strategy from the feasible decision space. However, making the most appropriate decisions is a challenging task when the priorities and objectives of decision makers are in conflict with each other. Therefore, there is a need for policy-focused assessment and simulation models to be integrated with an automated evaluation framework to clearly compare alternatives (Rousta & Araghinejad 2015). A detailed review of multi-criteria decision-making (MCDM) frameworks can be found in Hajkowicz & Collins (2007). Xi & Poh (2013) introduce a new DST by integrating SD simulation with a multi-criteria decision-making method, analytic hierarchy process (AHP). The SD part is used to simulate the long term changes in water supply sources in response to population growth (PG) in Singapore. Then, AHP ranks possible solutions based on results produced by the SD model to support the decision-making process, a fundamental requirement for any DST as demonstrated in this example. Ultimately, it is the role of managers and stakeholders to use their judgment and make the most appropriate decisions (Jakeman *et al.* 2006). These challenges are addressed in the 'Informed decision making' section of this paper.

An effort to overcome these three challenges is presented in the next section along with approaches to address other hydroinformatic challenges in DST development including: (1) models developed for a particular geographic region; (2) models being machine-/library-/operation-system dependent; (3) software or codes are not open access; and (4)

models have spatial and temporal scales, and extent mismatches. In general, developed models are useful if they can be portable. The portability of models depends on various factors including the availability, accessibility, and compatibility of source codes and sub-models (Rizzoli *et al.* 2008). In this paper, section 'Addressing model integration and hydroinformatics challenges', the above-mentioned hydroinformatic challenges are addressed by coupling open-access environmental/water-related models for a comprehensive coverage of the urban water systems using *GoldSim* software as an integrator of various physical-, process-, and system-based water models (GoldSim 2013). In the next section, the motivation for selecting Salt Lake City (SLC), Utah, as a case study is described. Then, the proposed method and its application to address the challenges of developing an integrated water resource model and overcoming the hydroinformatics barriers are described. Finally, a comparison of implemented decentralized and centralized alternatives for SLC's urban water system is presented by demonstrating the effectiveness of the developed DST product to support the decision-making process.

METHODOLOGY

To design an effective DST, the first step is to fully understand the system, its problems, identify decision makers and stakeholders, fully comprehend desires and goals, and consider limitations and constraints. Therefore, here, the statement of the problem and stakeholders perspective is first presented. Then to address the issues noted, the proposed methodology will be presented. The framework employs widespread hydroinformatics skills and tools to support the decision-making process and overcome DST development barriers. The DST is applied to a case study of urban water management in SLC, UT. Stakeholders input during the development of the DST was essential to gain understanding of how the system is operated and also engage key water managers and decision makers in the process. The goal for the DST was to produce information and effectively communicate the information back to the stakeholders; thus, the final product and results of the framework are based on stakeholders' needs identified through consultation. Key accomplishments include the

creation of a multi-factor vulnerability assessment and a new metric, called the Water System Performance Index (WSPI), which combines measures of reliability and vulnerability of a water system via joint probability distributions of reliability and vulnerability along with copula functions.

Problem statement

PG (both from immigration and births), social welfare, political climate, industrialization and manufacturing advances, infrastructure, resource availability, and other factors influence urbanization (Skeldon 2006). In Utah, these factors are aligning to fuel one of the highest urbanization rates in the USA (United States Census Bureau 2010). During 2013–2014, for example, Utah's population increased at a rate of 1.4%, which placed Utah as the fourth ranked state in terms of the 5-year growth rate. Most of the urbanization is occurring and is projected to occur in the Wasatch Front area encompassing SLC, the capital of Utah anchoring a metropolitan area with more than one million residents (United States Census Bureau 2013). The projected growth in population, combined with uncertainty of climate change and the potential for drought, provide a complicated picture for water management decision making in the western United States (Karl *et al.* 2009; Woodbury *et al.* 2012).

The SLC Department of Public Utilities (SLCDPU) is responsible for providing water to customers in the service district. Bardsley *et al.* (2013) assessed the impact of uncertain climate and changing population on SLCDPU water service. The results show that the future climate and water demand change can lead to disruption to supply water for the service area of SLCDPU. Therefore, SLCDPU is interested to evaluate the performance of the water supply system in SLC and investigate the vulnerability of the existing water system to varying factors such as PG, climate change, natural hazards, and failure of key system components. Solutions are sought to secure water availability and assess future alternative management strategies to reduce system vulnerability.

Collaborative actions between researchers and decision makers

Efficiency of the collaborative process relies heavily on the appropriate dialog, consistent communication, effective

knowledge and information exchange, and cooperative transfer of skills and methods among participants (Voinov & Bousquet 2010). Building collaboration between researchers at the University of Utah and urban water managers with SLCDPU required more than a decade of relationship building, visioning, planning, and then a sequence of collaborative research activities. The relationship building was essential to provide the necessary foundation for individuals to create and nurture understanding and trust to effectively engage in collaborative activities. In this particular example, the relationships were being built without an awareness or interest in defining collaborative research projects. Rather the approach was to explore problems of mutual interest and brainstorm solutions that could be tested from a research perspective and from an implementation perspective. As there was no modelling activity involved in the process, the collaboration was formed based on a participatory action research (PAR) approach. Moreover, instead of a top-to-bottom approach, where decisions and objectives are dictated from government agencies or private groups, PAR enabled us to use a bottom-up approach to involve stakeholders throughout the decision-making process. This naturally led to visioning of solutions and pathways toward solutions for a diverse 'problemshed' rather than a watershed, in other words, we changed the unit of analysis from basin to issue network (Mollinga *et al.* 2007). As individual problems prioritized, more detailed planning of investigations evolved. This was the period when co-creation of research activities was initiated. In the collaborative co-creation of studies and solutions, researchers and water managers would meet regularly to define specific questions, models, tools, approaches to conduct research of mutual interest. Therefore, the need to have a participatory model, which can be used to test scenarios, called for development of an integrated model and a move towards group model building (GMB) to develop the conceptual model, and participatory simulation (PS) to evaluate various stakeholders' decisions and scenarios. GMB offers, using SD tools, to involve managers and stakeholders in the process of developing the causal loop diagrams during the group meetings. After the learning history sessions, a mutual understanding between the modeler, first author, and stakeholder group was achieved and the group started sharing visions and planning perspective. In this step, the PS

approach, initiated at Massachusetts Institute of Technology (MIT) in early 1960s, was implemented to develop a DST (e.g. Wilensky & Stroup 1999; Guyot & Shinichi 2006). The DST allows people to interact with the model, change the rules and decisions, modify the scenarios, and use them for further analysis and comparison. This sharing of research methods led to the desire to create common platforms and tools for addressing the same, similar, and even different research questions. It was at this stage that the need for collaborative research activities evolved. The research collaboration initially focused on model development and scenario planning, eventually leading to results analysis and translation to policy analysis. As has been done in many other research-public water-management collaborations, this effort progressed to articulating specific research objectives, methods, and process for investigation from the original independent collection of activities that were shared for interest purposes only. Practically speaking, over the decade of interaction, the collaborative process transitioned from quarterly informal and random meetings to more formal quarterly exchanges of research interests and activities, and eventually to a structured quarterly meeting with defined deliverables and collaborative tasks.

Representation of a complex and interconnected water system

The SD framework chosen makes it possible to study the complex relationship between various components of a water system (Winz *et al.* 2009; Mirchi *et al.* 2012). The main assumption in connection, and therefore integration of water system components, is that the integrated system comprises various water stocks and water flows that connect them. To help meet the challenges of analyzing the complex water system of SLCDPU, a SD-based model along with integrated system-modeling framework were devised. The *GoldSim* software, as an extended SD tool, is used to integrate all sub-models, solve the water allocation problem with linear programming (LP), and run Monte-Carlo simulations. *GoldSim* is able to embed sub-modules, solve mathematical equations, transfer information from databases, and more importantly couple software with available open source codes through dynamic-link libraries (DLLs). *GoldSim* users are able to develop user-defined modules,

external functions, by building DLLs of separate models written in C++, FORTRAN or other compatible programming languages. These external functions represent the capability and calculations of an external model at run time and are bound to *GoldSim* through building external model DLLs. The request process consists of initialization, returning the function version number, performing a normal calculation, and cleaning up after a simulation. More information about implementing external DLL Elements can be found in *GoldSim* (2013). Also, DLL files of models, used in this study, are available online in the same folder as the main *GoldSim* model (<http://watermanagement.ucdavis.edu/people/erfan-goharian>). Therefore, the main advantage of the selected integrated system-modeling framework in this study is that almost any type of modeling process can be embedded and coupled in different temporal and spatial resolution. The integrated system-modeling framework aimed to connect models and make codes re-usable, i.e. these models are not designed for this specific study and are

robust and flexible to work with other models and codes in other studies. Figure 1 presents the major parts of the integrated model and how the workflow proceeds. First, hydroclimatic conditions are analyzed and used to drive the integrated water resource management (IWRM) model. One advance to the IWRM modeling approach presented in this paper is the coupling of detailed process models to capture dynamics, interconnections and responses of different water system components in each time step. To build the framework and enable this approach, advances in cyber-infrastructure and coupling methodologies were also needed which are discussed later in this paper. The IWRM model can be run based on historical information, pre-defined management scenarios, climate scenarios, population and demand growth scenarios, and other user-defined or a combination of all scenarios. To analyze the results for decision making, a new vulnerability metric is calculated and combined with reliability to calculate the WSPI to present the outcomes in different formats

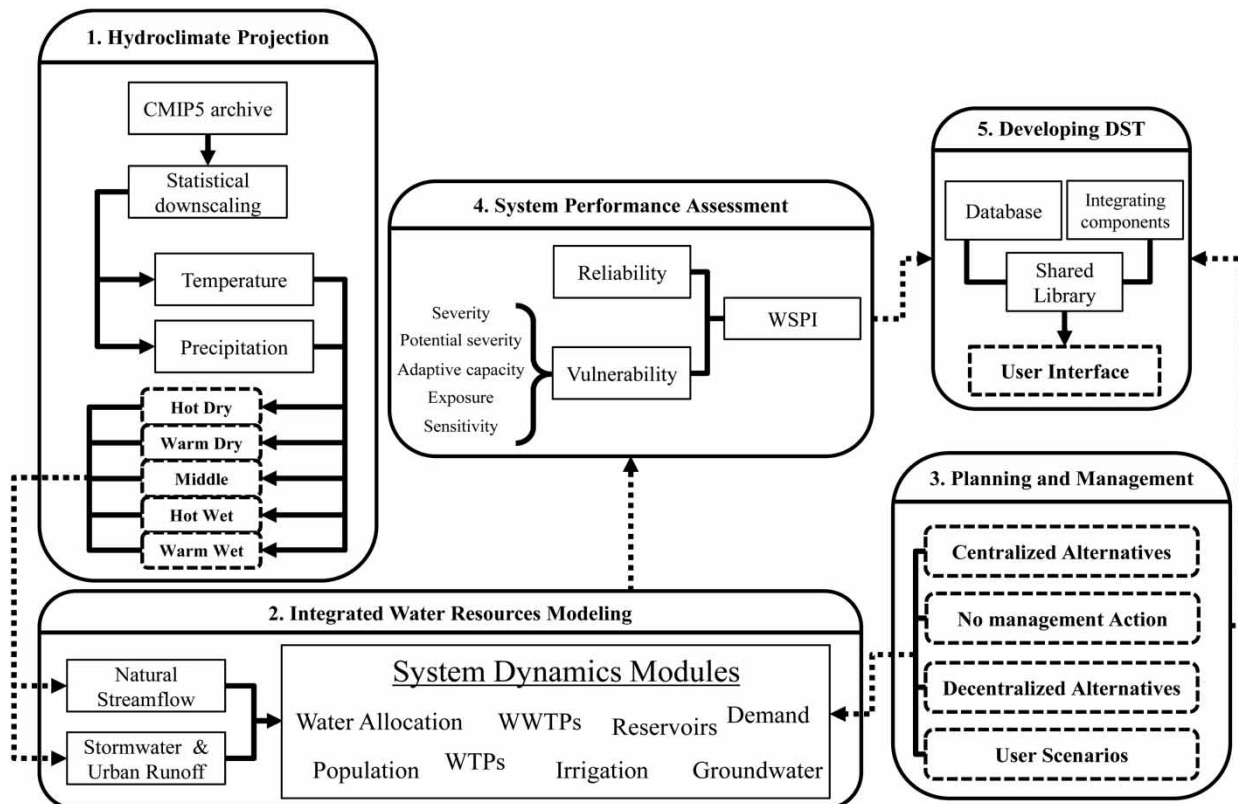


Figure 1 | Schematic framework for developing IWRM decision support tool.

and for different scenarios for stakeholders and users (Goharian *et al.* 2017). Finally, the DST of SLC-IWRM is designed to inform water managers in SLC of changes in water system performance to internal and external factors, and aid better decision making. The role of the tool is not to provide a definitive guideline, but rather to support the process of IWRM and help managers and stakeholders gain understanding of the water system and responses to influencing conditions (e.g., climate change) and management actions (e.g., additional water source).

The integrated model in *GoldSim*, as well as all individual models like the SWMM model, was built for this study (there is no other existing and available integrated model for SLC system). Details of the simulation model, sub-models, and mathematical equations (e.g. underlying mass balance equations) can be found in Goharian *et al.* (2016) and Goharian (2016). While parts 1 to 4 of the framework (Figure 1) are fully described by Goharian (2016), this paper focuses more on the key aspects of the coupling methodology, development of the SLC-IWRM DST, and presenting results for different selected management alternatives under different climate change scenarios.

Informed decision making

Managing water systems requires qualitative and quantitative thinking skills. Although decision makers and stakeholders look for the most appropriate decisions for the success of systems, the way they think and decide can vary considerably. The performance of a water system can be defined based on the selected objective decisions and subjective choices. So, tradeoff among conflicting objectives needs to be quantified in order to provide information about the performance of a water system. This quantification can be achieved by using probability based criteria including reliability, resilience, and vulnerability (RRV). However, RRVs may still present controversial information. Decision makers therefore will target multiple objectives, such as reducing the total number of failures in the system (reliability) and simultaneously reducing the harmful consequences of corresponding failures (vulnerability). In this study, failure is assumed as the inability of the water supply system to provide enough water for demands, i.e. facing a shortage event (failure condition) in the SLCDPU service area.

For this project, the reliability of the water system is defined as the number of times the system is not able to supply water demand from available surface water and the vulnerability is estimated based on a top-down vulnerability combined with a bottom-up vulnerability approach (Goharian *et al.* 2016). The vulnerability of the system is a function of several factors including exposure (*Exp*), normalized population index (*PI*), severity (*S*), potential severity (*PS*), and adaptive capacity (*AC*). Adaptive capacity consists of water system adaptive capacity (*WSACI_i*) and Social Adaptive Capacity Index (*SACI_i*), the latter can be estimated based on the social vulnerability index (*SoVI*) of Salt Lake County, acquired from Goharian *et al.* (2016). Generally, reliability and vulnerability objectives have the same behavior for a water system. However, there are occasions that just one failure in the system, such as flooding, can lead to significant damage to the system. WSPI, developed by Goharian *et al.* (2017) provides simultaneous information about the reliability and vulnerability of water systems using Sklar's theorem (Sklar 1959) and copula functions,

$$H(\text{reliability}, \text{vulnerability}) = C(\text{Rel}, \text{Vul}; \theta) \quad (1)$$

where *H* is the joint cumulative distribution function of variables *Reliability* and *Vulnerability*, *C(Rel, Vul)* is the copula function of the bivariate distribution (probability distribution of reliability (*Rel*) and vulnerability (*Vul*)), and θ is the vector of the copula parameter. This index represents mutual information of the frequency and the severity of failure events. WSPI is developed based on the marginal probability of reliability and vulnerability, their joint probability, copula functions, and exceedance and non-exceedance values from the cumulative density function of the joint probability. Thus, the WSPI increases with an increase in reliability and decrease in vulnerability of the system, and vice versa.

$$\text{WSPI} = P(\text{Vulnerability} > \text{Vul}, \text{Reliability} \leq \text{Rel}) \quad (2)$$

The formulation and calculation of WSPI for SLC and under different management scenarios and climate conditions are presented later in this paper. Moreover, the *MATLAB* package of WSPI calculation can be accessed from <http://watermanagement.ucdavis.edu/people/erfan-goharian>.

Addressing model integration and hydroinformatics challenges

Data access and sharing

Often for the purpose of simulating environmental and water resources systems, an excessive amount of input information is required. The initial step to develop a DST is to have a well organized, adequately populated, and accessible data management system. To effectively execute the management of data and the access by the models, the simulation model needs direct access to the various databases and data sources. Data transfer across the databases and model should be performed in a way to guarantee the quality of the data transfer. It should be noted that in our framework, data availability is the prerequisite to initiate the job. Therefore, it may be not applicable to cases, such as those in developing countries, with insufficient information systems and limited available observation data. In our framework, transferring data from/into databases with various data structures and storage is facilitated through the direct connection of *GoldSim*, linked to open database connectivity (ODBC) compliant databases. *GoldSim* can import from and export to a generic database or a specific simple or extended *GoldSim* database. A generic database can be defined as any database which is ODBC compliant to link the database to the *GoldSim* data entry elements. ODBC provide access to data sources, regardless of the type of the database management system which is used to store information. Selected data in database tables with unique IDs should be matched with *GoldSim* data entry elements to map data transfer to *GoldSim* and the simulation model. So, the only task for the user is to define the linkage based on element IDs, then *GoldSim* is able to transfer the data between the database and simulation model at any time. For this purpose, all the input and output data for the SLC-IWRM DST are organized in a shared database which can be accessed by *GoldSim* through Excel spreadsheets or directly using ODBC protocols. Moreover, all the information is stored in databases with its accompanying metadata and can be continuously updated to aid real-time simulation and inform decision makers simultaneously. The simulation results are stored in a database, visualized and analyzed using the *GoldSim* visualization tool, and

post-processed and visualized using *MATLAB* codes. More information in this regard can be found in the *GoldSim* user manual (2013).

Generic simulation with specialized models

To address the issue of needing specialized individual models to answer specific questions, this study had to identify a flexible simulation tool to enable the integration. For this purpose, *GoldSim* was selected to be the integrator and core simulator. The dynamic simulation capability of SD models provides a desirable balance between specialized software (e.g., Water Evaluation and Planning (WEAP)) tools and modeling via programming languages (Figure 2). The framework in this study provides the opportunity of linking specialized software and programming languages to the dynamic simulation software, resembling subroutines concept, through the external dynamic libraries. For example, the urban rainfall-runoff simulation and storm-water management practices had to be defined by complex sets of functions, which can be found in SWMM, but not readily accessible by *GoldSim*. In this situation, *GoldSim* suggests two solutions to link sub-models to the main model: (1) developing separate program modules and the DLL element (written in C, C++, FORTRAN or other compatible programming languages); and (2) embedding governing sub-model's equations directly within the *GoldSim* by use of the *Script* element. Using these two methods prevents modelers using global variables, which is not

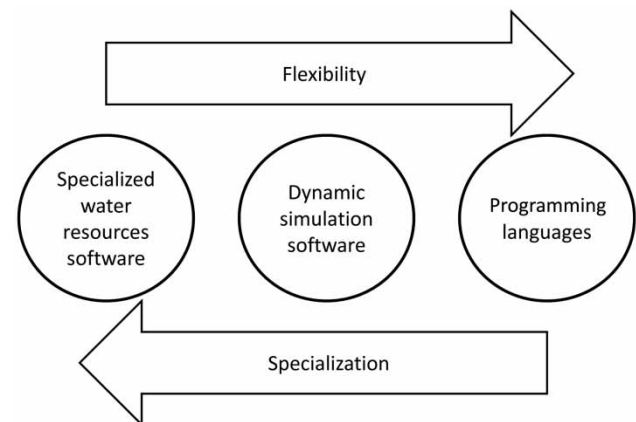


Figure 2 | Various degrees of flexibility and specialization of water system modeling methods.

recommended in programming (Rizzoli *et al.* 2008), and instead loosely couples the sub-models to the main integrator model. The first method requires primary coding of the governing functions of the sub-models and compiling it into a DLL. Then, *GoldSim's External* element and specified DLL transfer input and output related to the assigned external function name (similar to the subroutine concept). Therefore, any compatible specialized model can be connected to the *GoldSim* core model with either of these two methods.

The advantage of using dynamic simulation software is its ability to ease changes and improvement in modeling without decreasing the specialization (concentration level of a simulation model on a particular subject) and precision (degree of the realism of a simulation model) of modeling, i.e. SD has the ability to increase the upgradeability (the ability of improvement and expansion of a simulation model) and modularity (degree of separating and recombining system components of a simulation model). The developed model in *GoldSim* is capable of evolving and changing with time and solves differential equations through numerical integration (GoldSim User Manual 2013). However, it still needs clear representation of equations for components to link with the main model and also well structured information to show the data types in the model (Rizzoli *et al.* 2008). Zeigler (1991) suggested the use of object-oriented programming to demonstrate organized knowledge and a clear match between the system concept and its representation in software, and support the idea of abstract data types.

GoldSim provides an object-oriented dynamic simulator with the ability to simulate complex systems (Liu *et al.* 2005). A system component can be defined by its data type, state transitions, and output transformations. Modeling of this system component, in an object-oriented programming framework, benefits from inheritance, encapsulation and polymorphism concepts (Rizzoli *et al.* 2008). Inheritance concept structures modeling knowledge in order to make them re-usable, encapsulation defines the interface of abstract data type, and the polymorphism concept offers use of different defined behaviors for a common interface. Therefore, using the update function, *GoldSim* can simulate what-if scenarios, test management actions, and represent the uncertainty associated with the modeling process through the Monte-Carlo simulation.

Model integration

One of the common problems in developing DSTs is integration of models. Details of modules and sub-models are reduced and interconnections and interdependencies are often disregarded or poorly embodied in the DST. Approaches for model integration include master-slave, integrated coupling, and data coupling (Figure 3) (Brandmeyer & Karimi 2000). In this project, all three approaches were used. The *GoldSim* controller was used to moderate the integration of sub-models created and embedded into *GoldSim* following the master-slave approach (Figure 3(a), e.g., reservoir simulation or snow-runoff model (SRM)). *GoldSim* was

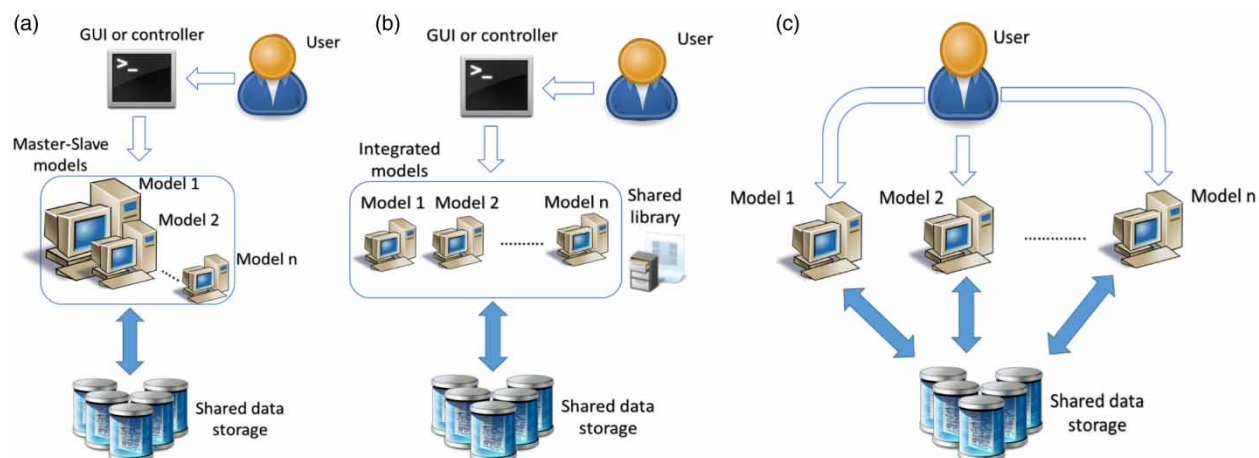


Figure 3 | Schematic of coupling methodology frameworks used for this project: (a) master-slave joined coupling; (b) integrated joined coupling; (c) data coupling.

also connected to other models using their dynamically link library (DLL) (e.g., as was done for connecting to the US Environmental Protection Agency Storm Water Management Model (SWMM) for this project) (Figure 3(b)). For the peer-to-peer connection, there was a need for a shared library with code and tools in *GoldSim* to make the connection between models, which is offered in *GoldSim* through the *Script* element. Data coupling (Figure 3(c)) was also used for this project to provide transfer through middleware using spreadsheets and databases as noted above. For example, streamflow from the natural hydrologic model were stored in a shared database for input to the *GoldSim* integrator from an external hydrologic model provided by Colorado Basin River Forecast Center (CBRFC). *GoldSim*'s ability to facilitate coupling in multiple ways increased the flexibility of the framework by providing 'the capacity with which two or more programs could share and process information irrespective of their implementation languages and platform' (Howie *et al.* 1996).

Resolution and dimension coherence

One of the main challenges in integrating urban water system models is identifying and enforcing appropriate spatial and temporal resolutions for the simulation. In addition, the fidelity of alternatives and scenarios may warrant different resolutions. While the spatial dynamics have been addressed in previous studies by Ahmad & Simonovic (2004) by coupling geographic information system (GIS) with SD, here *GoldSim* offers using an internal clock to match the simulation timesteps between different models. In the study presented here, the SLC-IWRM must represent different scales of water management alternatives (e.g., centralized reservoir versus decentralized rainwater harvesting (RWH)) and reconcile temporal resolution differences among the stormwater (minute), hydrologic (6-hour), water demand (daily), and water supply allocation optimization (daily). *GoldSim* was set up to aggregate and disaggregate data when needed and facilitate transfer of information across fidelity scales based on the hierarchy structure of the models. For this purpose, the model implemented internal clocks for each container (term and element which is used in *GoldSim* to represent sub-models) such that any unscheduled timesteps generated inside the

container only interrupt the clock pertaining to that container. Therefore, the elements within a container will be updated based on the internal timesteps. For instance, if one sub-model embodies dynamics that altered very fast (calling for a 1-day timestep) and the other parts of model characterized based on slower dynamic changes (calling for a 10-day timestep), a 10-day timestep will be picked for the global (integrator) model simulation, while the sub-model, which changes faster, is still running in 1-day timestep. In this way, the other elements and sub-model status outside of the container do not need to be updated in smaller timesteps. Furthermore, *GoldSim* present the results and analysis based on user-defined reporting periods. Reporting periods can be presented by accumulated, average, change of, or the rate of change of values over selected time periods, and scheduled dynamic (increasing or decreasing) or constant timesteps. These capabilities of *GoldSim* helped us to prevent further coding to match the data scale in different sub-models in SLC-IWRM for varying simulation timesteps and post-processing of the results. A daily time step was used as the integrated time increment in the simulation, and results were reported in daily, monthly and annual time scales. Additionally, information within a module or between different modules was transferred with a time delay in *GoldSim*. Delays have a key effect on the dynamics feature of the system. Furthermore, *GoldSim* used its internal database of units to standardize dimensions and units for the simulation.

Providing access

Another challenge in building a DST is providing access (Holmes *et al.* 2005; Makropoulos *et al.* 2008) since most are developed in proprietary software or programming languages and (or) interfaces are not provided or not able to grant easy access to simulations. For this project, *GoldSim* software offers creation of a dashboard for users and is available for public use. Users need to download and install the *GoldSim* player version of the model to have access to the DST and explore the simulation model. The *GoldSim* player is free and can be executed on user systems. The provided SLC-IWRM model contains the main model and provides a dashboard (DST graphical user interface (GUI)) for users to build, execute, and analyze their own scenarios,

pre-defined scenarios, or the ones presented in this paper. The web application of reservoir simulation sub-model of SLC-IWRM is accessible online (Swain *et al.* 2016). Figure 4 illustrates the main elements of SLC-IWRM and their connections to the DST and post-processing WSPI package. Although part of post-processing is executed in *MATLAB*, which is not open access, the open-access and compiled package is available online (<http://watermanagement.ucdavis.edu/people/erfan-goharian>).

Application of SLC-IWRM DST

Urban water systems face many challenges, including demand-supply imbalance, expansion of urban and suburban areas, energy use, flood risk, drought, changing climate, and more. Water management alternatives must be considered to address these challenges. Solutions often employ centralized infrastructure systems, which in the context of water supply is typically large storage reservoirs, water diversions, and water treatment plants (WTPs). Alternative approaches employing distributed infrastructure

practices (e.g., RWH, local reuse) are also of interest among water managers (Brown *et al.* 2009; Sharma *et al.* 2010; Domènech 2011; Lloyd *et al.* 2012; Nelson 2012; Sapkota *et al.* 2013). The choice of whether to implement centralized, distributed, or hybrid infrastructure solutions remains undetermined for most cities. Unanswered questions related to performance, cost, energy needs, environmental sustainability, and more face decision makers (McCully 1996). Analyzing the wide range of conditions associated with centralized and distributed infrastructure requires a DST that can simulate multiple scenarios, analyze the performance of the water system, and compare the implementation of various options (Hardy *et al.* 2005). The DST presented in this paper was designed to enable stakeholders to analyze impacts of climate, PG and other factors as well as explore alternative solutions ranging from centralized to distributed options. The scenarios and solutions analyzed here evolved from multiple meetings between the authors, supporting research team, and the SLCDPU director and water management personnel, which produced three guidelines: centralized alternatives should be prioritized based on

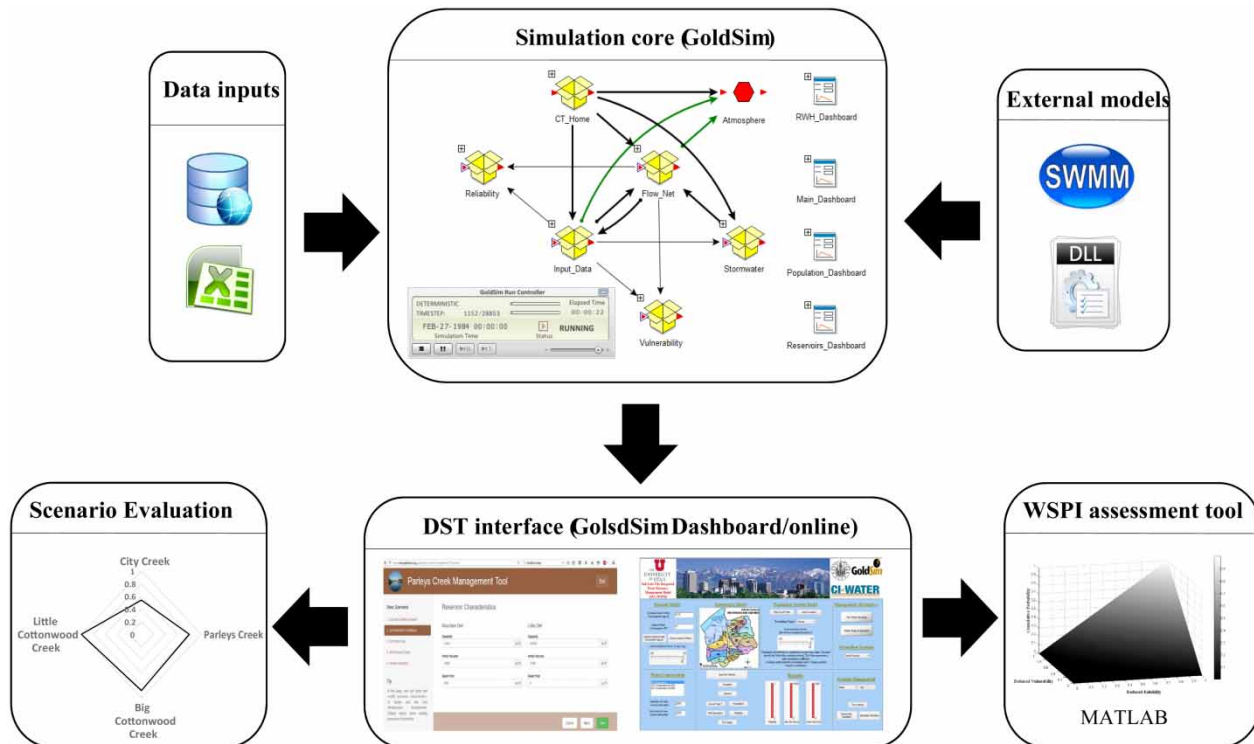


Figure 4 | Schematic overview of SLC-IWRM tool structure.

available water resources; decentralized solutions should be based on spatial needs relative to available water; and implementation of alternatives must consider water rights and regulations.

Based on these guides, RWH was chosen as the decentralized solution and improvement of large water storage infrastructure (i.e., reservoirs) was chosen as the centralized alternative (CA). Scenarios were based on selections from three categories. (1) Source changes – based on CMIP5 downscaled projections, the extreme and central tendency patterns of temperature and precipitation changes were used: Hot-Dry (HD), Warm-Wet (WW), and Middle Tendency (M) (Goharian *et al.* 2016; Hansen *et al.* 2017). (2) Demand changes – future demand is dependent on several factors, for this study one key factor, PG, is selected. (3) Solutions – three options were selected for the study: no management action (NMA); a CA – constructing a new reservoir on Big Cottonwood Creek; and a decentralized alternative (DCA) – RWH.

As noted above, the DST was built in *GoldSim* and included the creation of a dashboard (Figure 5). This DST

can be executed in deterministic or stochastic simulation mode for the time period of 1981 to 2060. Although the model uses a daily simulation time step, the results are aggregated to monthly or annual scales for ease of analysis.

Here, brief descriptions of SLC-IWRM components (following Figure 5) are provided. It should be noted that not all components were used for the study of centralized versus decentralized options.

Water demand

In this module, users may modify scenarios based on changing per capita indoor demand, outdoor demand, and temporal pattern of outdoor water consumption. The projection of future demands is based on deterministic increases or a stochastic simulation. When stochastic simulation is selected, the model runs with stochastic inputs and will use Monte Carlo simulation to generate probabilistic outputs. Behind the dashboard, stochastic inputs are provided, which have been developed with appropriate distribution functions. Therefore, users need to specify the

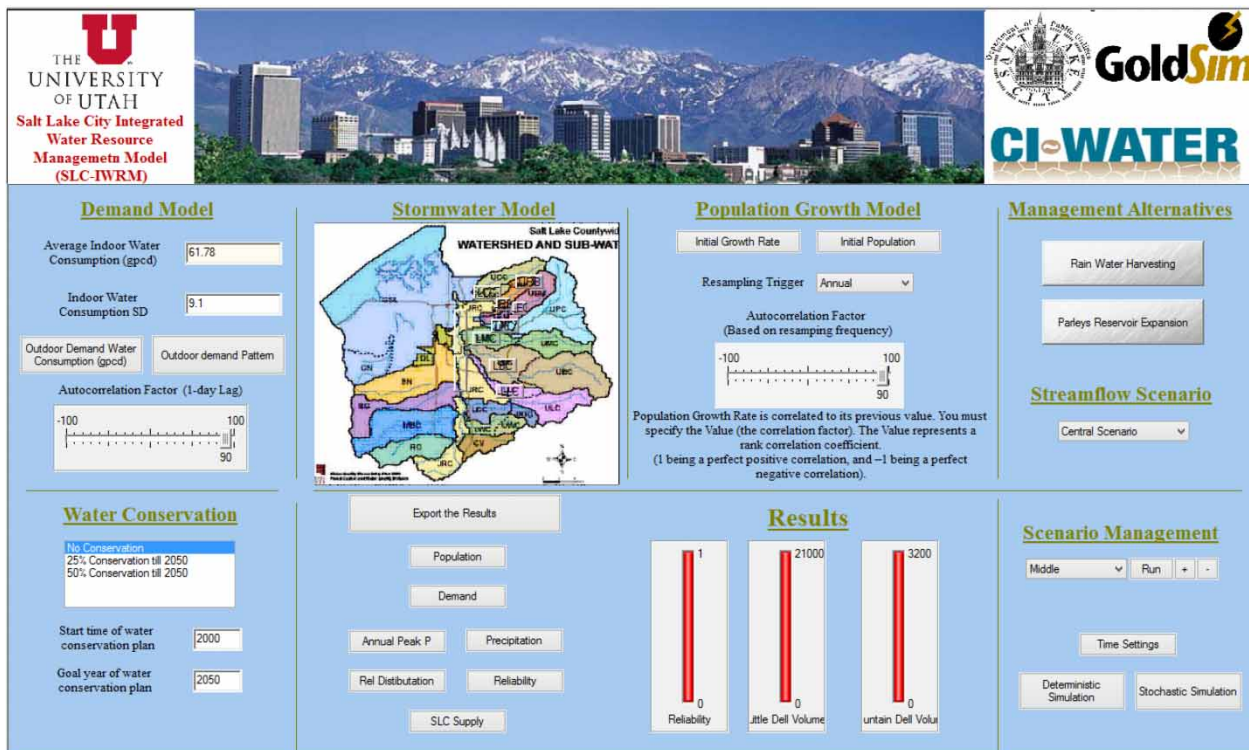


Figure 5 | The SLC-IWRM tool interface.

mean, standard deviation, and autocorrelation for triggering lag of resampling.

Water conservation

An important management alternative for SLCDPU is future conservation practices to decrease per capita water demand. The dashboard empowers the user to select conservation goals and the implementation timing of practices in the form of percent reduction in water demand with time.

Stormwater model

This module is based on coupling SWMM for Salt Lake County to *GoldSim* to provide detailed stormwater management modeling in SLC-IWRM. Users can alter SWMM by changing input parameters at the sub-catchment level in a user interface provided in the DST.

Centralized infrastructure alternative

For this project, the main infrastructure solution is a 21 Mm³ (17,000 AF) reservoir that was proposed long ago for construction on Big Cottonwood Creek. To accompany this reservoir, the WTP is expanded proportionally from

0.15 million cubic meters per day (MCMD) (40 million gallons per day, MGD) to 0.45 MCMD (120 MGD) (Hooton 2015). Users can change the characteristics of the proposed reservoir, as well as change the operating rules and geometric properties.

Rainwater harvesting

The decentralized management alternative considered for this study is to capture and store rainwater in on-site cisterns and use later for outdoor demand. To represent RWH in the SLC-IWRM tool, the SWMM-*GoldSim* coupling is further coupled with a RWH model created in *GoldSim* (Figure 6). The size of the cistern may be selected as one or two storage containers with maximum capacity of 0.38 m³ (100 gallon) (an amount that does not require registration in Utah) or the size may be up to 9.5 m³ (2,500 gallon) with registration (Utah Division of Water Rights 2015). The number of cisterns is derived based on the total number of housing units in different townships in the SLCDPU service area (Table 1). For the study, it is assumed 50% of the housing units are equipped with cisterns, with 35% having 200 gallon capacity and the remainder having 2,000 gallon capacity.

The impact of RWH can be analyzed across the system using the SLC-IWRM. For example, capturing rainwater

Jordan River Subbasin

Rainbarrel Numbers
200 Gal 2,500 Gal

Percentage of roofs from Imperv area

LCC Subbasin

Rainbarrel Numbers
200 Gal 2,500 Gal

Percentage of roofs from Imperv area

LRB Subbasin

Rainbarrel Numbers
200 Gal 2,500 Gal

Percentage of roofs from Imperv area

LEM Subbasin

Rainbarrel Numbers
200 Gal 2,500 Gal

Percentage of roofs from Imperv area

LPC Subbasin

Rainbarrel Numbers
200 Gal 2,500 Gal

Percentage of roofs from Imperv area

Total RWH used for outdoor demand (Gal)

Total WTP used for outdoor demand (Gal)

2 containers with the maximum size of 100 gallons each on-site
Price: ~ \$200 each one

Underground storage and the law permits up to 2,500 gallons in one container.
Price: ~ \$2500-\$3000

Figure 6 | Rainwater harvesting dashboard built in GoldSim.

Table 1 | Total number of housing units in different townships and rainwater cisterns for RWH

Township	Housing units, 2010	Selected cisterns for RWH	
		200 gallon	2,500 gallon
Salt Lake City	80,724	30,272	10,091
Mill Creek	26,203	9,826	3,275
Holladay	10,537	3,951	1,317
Cottonwood Heights	13,194	4,948	1,649

may decrease the volume of water processed in WTPs, increase bypasses from WTPs, and result in modified discharges downstream (e.g., to the Jordan River in SLC). Users may change the number of cisterns in each sub-catchment and vary the implementation strategy by changing the percentage of rainwater serviced by RWH.

Population change

This module enables users to change population projections into the future. Users can keep the population constant or change it by specifying a growth rate. Also, users may use uncertainty analysis based on selecting a stochastic PG. In the case of stochastic simulation, users change the initial population and PG rate for the township areas in the model. Moreover, users decide the resampling trigger and its associated autocorrelation.

Deterministic/stochastic simulation

Users may choose deterministic simulation or use Monte-Carlo simulation. In deterministic simulation, rates and factors are represented using mean values. In Monte-Carlo simulation, stochastic elements are based on pre-defined probability distributions. Therefore, the model may represent uncertain elements and be used to simulate uncertain future conditions. The number of realizations and other stochastic or deterministic simulation properties (e.g., time period, simulation time step) can be changed by the user.

Scenario management

Users can add, modify, remove, or save scenarios. The scenarios are built when any change is made in parameters

related to climate, population, and management action. The values are stored and results can be viewed individually or with other scenarios.

Results presentation

Selected results (e.g., reliability, vulnerability, population projection, demand projection) are displayed in the dashboard. Other results can be viewed in daily, monthly, and annual summaries. Stochastic simulation results can be seen for different realizations, as well as summarized using a statistical analysis (probability of uncertain bounds). Users with access to the model can view or export all or selected scenarios results.

Multi-criteria decision analysis

In addition to vulnerability and reliability, a package in *MATLAB* provides results from the calculation of the WSPI (Goharian *et al.* 2017). The WSPI offers joint information about the estimated reliability and vulnerability for different scenarios by forming joint probability distributions between reliability and vulnerability using Copula functions. WSPI varies between 0 to 1, where 0 indicates the least favorable performance by the system and 1 demonstrates the best performance of the system. This package is available on *GitHub* for public use (<https://github.com/erfangoharian/WSPI>).

RESULTS

Vulnerability factors

Table 2 reports the results of the key factors included in the vulnerability calculation for the four major water supply sources of SLCDPU. The results are shown for the NMA, CA, and DCA management alternatives for all projected climate conditions. The severity of failure for all sources increases from the WW to HD climate projections under all management alternatives. However, implementing Argenta Dam decreases the severity of failure in comparison with the RWH implementation. DCA has less effect on the severity because the stored volume in cisterns is much

Table 2 | Vulnerability factors' values for different water sources under different scenarios

Water supply source Climate condition	City Creek			Parleys			Big Cottonwood			Little Cottonwood		
	HD	M	WW	HD	M	WW	HD	M	WW	HD	M	WW
Vulnerability factors	Argenta Reservoir											
Severity	0.07	0.03	0.01	0.06	0.02	0.00	0.06	0.02	0.00	0.05	0.02	0.00
Potential severity	0.04	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.04	0.00
Exposure	0.23	0.05	0.00	0.40	0.12	0.00	0.15	0.00	0.00	0.11	0.00	0.00
WSACI	9.82	9.61	9.15	7.97	6.98	6.26	0.98	0.96	0.93	0.00	0.00	0.00
	No management											
Severity	0.13	0.09	0.05	0.10	0.07	0.04	0.10	0.07	0.04	0.09	0.06	0.04
Potential severity	0.10	0.12	0.13	0.02	0.06	0.09	0.47	0.46	0.48	0.17	0.20	0.32
Exposure	0.23	0.05	0.00	0.40	0.12	0.00	0.15	0.00	0.00	0.11	0.00	0.00
WSACI	9.82	9.61	9.15	7.97	6.98	6.26	0.98	0.96	0.93	0.00	0.00	0.00
	Rainwater harvesting											
Severity	0.12	0.08	0.04	0.10	0.07	0.03	0.10	0.07	0.03	0.08	0.06	0.03
Potential severity	0.11	0.11	0.14	0.02	0.06	0.09	0.46	0.43	0.46	0.18	0.18	0.32
Exposure	0.23	0.05	0.00	0.40	0.12	0.00	0.15	0.00	0.00	0.11	0.00	0.00
WSACI	9.82	9.61	9.15	7.97	6.98	6.26	0.98	0.96	0.93	0.00	0.00	0.00

smaller than the reservoir. The severity values for DCA are not improved under the HD scenario, which indicates the distributed cistern solution has not received sufficient precipitation to fill storage capacity. Conversely, the observation is improved for RWH under the WW climate projection. Although Argenta Dam reduces the severity (magnitude of failure) to zero (under WW climate projection), RWH produces a significant reduction in severity. Results also show that implementing Argenta Dam on Big Cottonwood Creek not only decreased the severity of failure on this source, but also supported the whole system and reduced the magnitude of failure in other sources too.

As noted, Argenta Dam can reduce water shortage failures under the WW climate condition, and, because of this, the potential severity would be zero in these conditions. Of the four water sources, the greatest improvement in potential severity occurs for Big Cottonwood Creek because this creek has the highest volume of available water compared to the other sources. This observation indicates potential severity is important for selecting the location of developing or expanding new infrastructure. Potential severity reflects not only the decrease in use of one source (e.g., Big Cottonwood Creek), but also the storage and/or use of water from other

sources because it is not bypassed. The zero potential severity of Parleys Creek, while the Argenta Dam is added to the system, verifies this point. Thus, optimizing designs in individual sub-systems considering severity and potential severity factor, and analyzing their interactions yields superior results in an integrated system. Although RWH can reduce the severity, it has a small effect on potential severity. RWH may also, in some cases, increase potential severity in sources without reservoir structures. The water which was supplied by the treatment plant no longer will be used, substituted by RWH, and as a result water will be bypassed from WTPs and leads to increased potential severity in the system. Table 2 indicates that even though the exposure and WSACI factors vary under different climate conditions, they are not changed by implementation of management alternatives, i.e. these two factors are not influenced by infrastructure solutions. However, adding a new water supply source can increase WSACI for other sources.

Reliability and multi-factor vulnerability assessment

After estimating the individual factors affecting vulnerability, the reliability and vulnerability measures are

calculated based on Goharian *et al.* (2015, 2016). The overall vulnerability and reliability of the system are presented in Figure 7 for different management alternatives and under different climate conditions.

Figure 7(b) shows that implementing the CA alternative reduced the vulnerability of the SLC water system. The least vulnerable condition in the system occurred for the WW climate projection with the presence of the Argenta Reservoir. This figure illustrates that HD condition, regardless of implementing any management alternative, placed the system in a vulnerable condition. The same vulnerability values of WW and M scenarios for NMA and DCA, verified that DCA offered no additional benefit to the system in terms of improving the vulnerability. However, for NMA and DCA, wetter conditions offered higher reliability (Figure 7(a)). These two points indicate that although implementing DCA can reduce the failure events due to DCA's small capacity of storage, no additional benefits compared to NMA are expected from DCA, especially under the WW and M climate conditions. However, if the weather condition would be HD, DCA offers some slight improvement in management of water system. These figures clearly suggest that the system is more responsive to the implementation of the CA under different types of climate conditions. It can also verify that supply-side management alternatives can improve the system's performance under the HD condition, but there is a need for demand-side practices during M and WW climate conditions when there is less capacity in the system to provide additional water supply.

This was caused by the pace of PG and change in timing of snowmelt leading to failures even if the water available is not changed significantly. In terms of reliability, although wet climate conditions offer a more reliable water system, the enhancement trend had higher rates for the CA.

Water system performance index

As shown in the previous results above, it is difficult to fully comprehend and report the performance of the water supply system by considering reliability or vulnerability independently. Basing a decision on one indicator can sometimes lead to adverse consequences. For example, one may overestimate or underestimate performance of the system (as shown in Figure 7). While reliability shows improvement from HD to M and from M to WW, the vulnerability of the system was nearly unchanged for WW and M conditions. A decision based on vulnerability would lead to no action, and thus an unreliable system. Therefore, reliability and vulnerability do not always have similar behavior. An indicator simultaneously representing information about reliability and vulnerability would be useful. While Figure 7 shows the reliability and vulnerability of different management alternatives, Figure 8 presents the combined indicator of WSPI for these scenarios. Goharian *et al.* (2017) used Copula functions to develop a joint probability distribution between reliability and vulnerability marginal distributions. Here, by analysis of the time series of reliability and vulnerability, the Frank Copula function

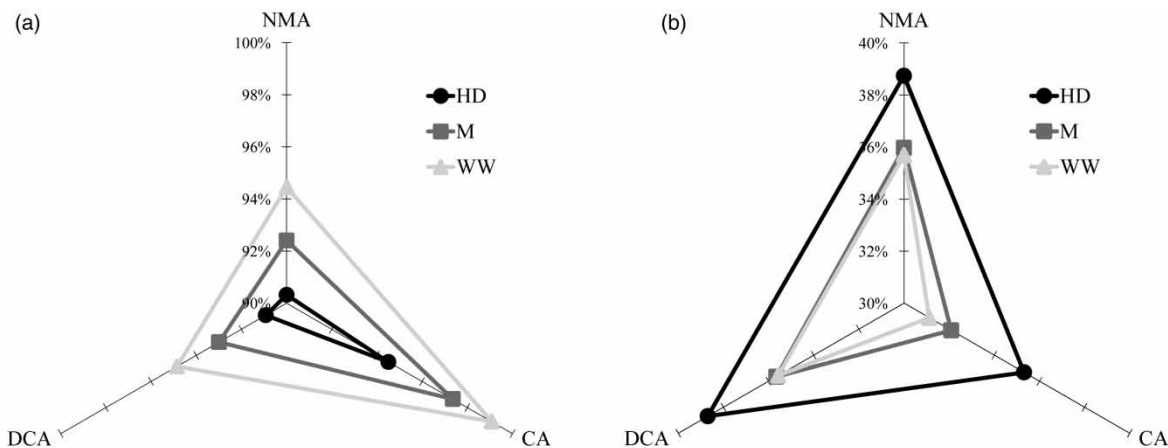


Figure 7 | Comparison of different scenarios based on (a) reliability and (b) vulnerability.

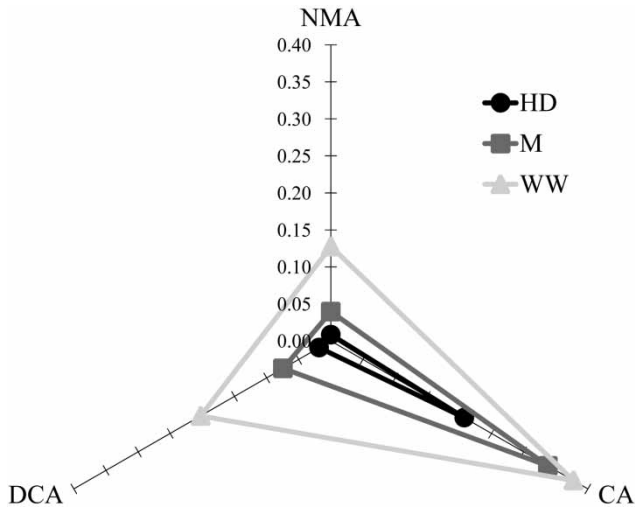


Figure 8 | WSPI results for different management scenarios and climatic conditions.

was selected as the best fit for the joint probability distribution. Then, WSPI for different sets of reliability and vulnerability from Figure 7 were estimated based on the cumulative density function of joint probability. Figure 8 depicts the WSPI values for NMA, CA, and DCA management alternatives under HD, M, and WW climatic conditions. As shown in Figure 8, regardless of climate condition, CA option offered a better performance in the system. It is important to note how the difference between WSPI of NMA and DCA was decreased for WW and HD climatic conditions. It suggests that under warmer and wetter climate conditions, RWH is an appropriate alternative for managers, but that in the HD condition implementing RWH is not a prudent alternative.

SUMMARY AND CONCLUSION

The primary contribution of this paper is to present an integrated, computer-based, and generic framework to couple urban water-related models into a DST for urban water management. Challenges of creating a DST and integrated modeling framework, which are discussed in this study, are: (1) involving stakeholders in the model and DST development process; (2) representing complex and interconnected relationships between water resources system components; (3) developing a DST to process outcomes and support the decision-making process; and (4) hydroinformatics barriers

such as availability, accessibility, and compatibility of model and DST. The core section of the framework to develop the decision-support tool includes a system-dynamics and Monte-Carlo based software called *GoldSim* which provides a flexible water system simulation model. These challenges are overcome using *GoldSim* and tailored solutions. The challenges are addressed by solutions, which form the framework: (1) appropriate dialog, consistent communication, effective knowledge and information exchange, and skills transfers between researchers, water managers, and stakeholders through GMB and participatory simulation processes; (2) SD and object-oriented programming approaches to integrate sub-models and represent complex behavior of the system; (3) simultaneous vulnerability and reliability assessment using a new and joint probability-based performance index, WSPI; and (4) data transfer across the ODBC compliant databases, across the sub-models by developing DLLs, shared library in *GoldSim* to develop and control the connections, internal clocks for sub-models, and open-access and online available tool for different group of users.

The simulation core tool is connected to database management tools, external models, and a post-processing component. Moreover, the underlying methodology was designed to enable the tool to interface and operate with input from a variety of sources and formats, e.g., text, database, sensor, external model. A range of management actions, climate projections, and PG realizations are arranged into a set of scenarios for analysis. The tool estimates multiple user-defined output variables and time series, pre-defined performance metrics, and ultimately the WSPI for different management, climate, and PG scenarios. The tool can be operated deterministically or stochastically and can be modified to a wide range of extensible applications for various stakeholder groups including researchers, decision makers, and the public.

In this paper, the SLC-IWRM DST was demonstrated for a study of the effectiveness of management actions across a range of climate projection conditions for SLC, Utah, USA. The tool was applied to compare the performance of SLC water system under three management conditions: no action, centralized (a reservoir), and decentralized (RWH) for three future climate conditions (HD, WW, and middle tendency). The demonstration was designed to illustrate the

trade-offs between centralized and decentralized solutions across a range of climate conditions. The results indicated the performance of the water system may be improved by implementing either management alternative, but the impact depends on the climate conditions.

Through this project, managers are able to test alternative solutions, analyze 'what if' scenarios, and explore results and reactions of components within the system. Incorporating different performance indicators, which are presented within the tool, eases the comparison between different scenarios, and supports decision makers to evaluate proposed solutions. Consequently, the main outcome and message of this research is optimized design and management of connected components in a water system in isolation leads to inefficient performance of the whole system. Alternatively, whole-system thinking and integrated management of urban water systems tends to result in more diverse benefits for the system as a whole.

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