Supporting Regional Water Sustainability Decision-Making through Integrated Modeling

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***Abstract*—Water sustainability in cities has become a priority concern due to growing city populations and climate change. This is particularly important for cities that face severe water challenges, such as the twin border cities of Ciudad Juarez, Chihuahua in Mexico, and El Paso, Texas, USA. While the municipal utilities and government make immediate decisions about water sourcing, pricing, and use, both are public agencies, subject to democratic participation and decision-making. An integrated platform solution may be convenient for stakeholders that interact with multiple aspects of a complex and dynamic system, such as those involved in water sustainability. The Sustainable Water through Integrated Modeling (SWIM) platform provides comprehensible regional water models publicly on the Web that would otherwise only be accessible to domain experts. SWIM leverages future scenario analysis for citizen engagement. This paper presents the motivation, architecture, user interface, and capabilities of SWIM and how it can interoperate with Smart City ICT platforms to enable dynamic systems modeling for decision-making in a Smart City sustainable environment.**

Keywords— water sustainability modeling, water management smartification, stakeholder awareness, decision making, smart city platforms, smart city solution, interoperability.

I. Introduction

The twin border cities of Ciudad Juarez, Chihuahua, Mexico (municipal population over 1.5 million, [1]), and El Paso, Texas, USA (county population over 860,000 [2]), face severe water challenges. They rely on the binational Rio Bravo/Rio Grande River, whose flow will likely decline with climate change, and on two binational aquifers, the Hueco Bolson and the Conejos Médanos/Mesilla Aquifer, whose freshwater storage is declining dramatically [3], [4].

Expert water managers understand elements of key issues. However, the public may be unclear and uninvolved. Even sector-specific managers and users do not consistently consider the entire system's behavior [4]. Envisioning the future is challenging for all concerned due to annual variability, uncertain long-term trends, and the often-hidden character of underground water. A smarter approach would offer tools for addressing the sustainability of this crucial resource. The Sustainable Water through Integrated Modeling (SWIM) platform, available at http://purl.org/swim, was designed to publicly provide comprehensible regional water models on the Web that would otherwise be only accessible to domain experts.

While the municipal utilities and government make immediate decisions about water sourcing, pricing, and use for the two large cities, both are public agencies, subject to democratic participation and decision-making. SWIM fosters the potential engagement between decision-makers and stakeholders by providing a platform where such data can be up-to-date, and novel dynamics can emerge. As defined in [5] "Scenario analysis is the process of evaluating possible future events through the consideration of alternative plausible, though not equally likely, states of the world (scenarios)." SWIM supports scenario analysis with an integrated approach that considers policy and water management impacts on biophysical processes in the context of climate, technology, and population change. SWIM remains relevant and salient by incorporating plausible scenarios influenced by input from a diverse public through stakeholder engagement [4], [6], [7] and allows for potential policy development and action.

This paper is organized as follows: after this section, background information, including the development of SWIM, is presented. A literature review about Information and Communication Technology (ICT) and Smart City applications follows. Next, the SWIM architecture and how it can interoperate with Smart City ICT are described. Last, the SWIM user interface and its evaluation are presented, followed by conclusions and future work.

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II. Background

There are many relevant datasets and multi-purpose models in the Paso del Norte region [8], [9], which is what the region encompassing the two cities is called. However, to the best of our knowledge, they have not previously been integrated into systems models that consider alternative scenarios of the future needed for public policy dialogues. In addition, they are not available on public platforms, i.e., the Web, nor do they address the bicultural nature of the region, i.e., using both Spanish and English and metric and English units.

The regional water system is complex. An accurate representation of the region requires integrating the water system from both the United States and Mexico since the two countries share this resource. It requires integrating cities and agriculture since these two major sectors draw on the same water supplies and, in some cases, exchange water back and forth. It requires integrating surface and subsurface water since the two are linked by both biophysical and anthropogenic exchanges. Scenarios can depict interannual variability and directional climate change that affect river flows entering the region in the north, affecting the two linked aquifers [3]. A drier river means more use of aquifers. Policy options to buffer aquifers from river variability can then be explored using SWIM. Scenario visualization using SWIM effectively represents these cascading effects of climate change and water management policy choices. Having a public platform brings people beyond their narrow geographies and sectors, makes interactive dynamics evident, and helps diverse publics learn about and engage in smart water decisions.

The first version of the platform (SWIM 1.0)[1] was conceived during the USDA-funded project "Sustainable water resources for irrigated agriculture in a desert river basin basing drought and competing demands: From characterization to solutions" (2015-2021). The development of SWIM was done in parallel with the creation of a Hydroeconomic Optimization model for the Paso Del Norte Region [10]. As the model grew in structure, complexity, and resource demand, so did SWIM's capabilities. SWIM initially hosted the Hydroeconomic Model, providing a wide range of features for non-expert stakeholders, such as: i) database persistence of model metadata and scenario executions, ii) a Web-based interface for specifying, executing, and visualizing scenarios, and iii) programmatic access to the model as a service (Maas). SWIM 1.0's architecture can be found in [11], which includes a semi-structured data model that can be reused and extended for additional models and a Service Oriented Architecture (SOA) that was used for the execution of models developed under the General Algebraic Modeling System (GAMS)[2]. The refinement of SWIM 1.0 considered early usability studies [12] and requirement analysis sessions with project collaborators. Integrating more than one model to address water-related questions and interests of diverse stakeholder groups, requires a broader approach beyond a static Web-based platform. The current version, SWIM 2.0, is part of the project "ELEMENTS:DATA:HDR:SWIM to a Sustainable Water Future" funded by the National Science Foundation. SWIM 2.0 provides a human-technology framework for future water projections that integrates semantic-based computational approaches, information technology, and participatory modeling with strong community engagement.

III. Literature Review

Near real-time sensing, data collection and aggregation, analysis and decision-making provide a significant opportunity to develop agile resource management systems to address societal challenges [13]. ICTs and Smart City testbed platforms have made substantial progress in this area.

The OpenCity project implements a testbed incorporating "data collection and processing units, database management, distributed performance algorithms, and real-time data visualization" [14]. This platform includes a Decision Support System (DSS) that uses the Markov decision process (MDP) to model common disruptive scenarios that may occur. The Portunus project [15] presents a complex space-time events collection framework. It provides a layer of abstraction to sensors, actuators, and Smart City events. The architecture comprises a microservice ecosystem with layers for data distribution, authentication, data registry, and logging. The authors present a COVID-19 tracker at the application layer where people can report cases and visualize data from a map on their mobile devices. User-oriented applications use ICT infrastructure to provide elaborate dashboards to monitor Smart City subsystems' key performance indicators (KPIs). KPIs are a representation of values that can facilitate decision-making by government and engaged citizens [16]. Negreiros et al. present an extension to the Smart Campus® living lab cyberinfrastructure with an indicator dashboard for production and use of photovoltaic energy [17].

More sophisticated applications provide custom visualizations and tools to engage citizens and better decision support systems. The Computational Urban Sustainability Platform (CUSP) provides semantic modeling of buildings, the urban environment, socio-technical systems, and smart devices [18]. CUSP displays data and visuals through a 3D Web-based interface using the unity game engine. Kazhamiakin et al. take a step further by implementing a gamification framework for the long-term engagement of smart citizens [19]. Finally, Snap4City is an end-to-end platform designed to involve citizens, ICT operators, and local administrations; it provides a robust software toolset for creating and integrating IoT applications involving IoT devices, data storage, geo-utilities, dashboards, and data analytics. The platform has been widely adopted in many European cities and applied to use cases in urban mobility, emergency response, and event monitoring [20].

Most of the reviewed approaches providing data and models to city residents for decision support seem to be domain or application specific. On the other hand, the Snap4City approach is more flexible for integrating multi-domain solutions and customize GUIs, but these customized GUIs may still be solution dependent. In a Smart City ecosystem, a model-tailored GUI approach may limit the engagement of stakeholders who interact with multiple systems, each with different learning curves. Complementary to the reviewed work, SWIM 2.0 uses commonalities in heterogeneous water-supply models to build a generic interface to explore alternative scenarios, while

[1] https://water.cybershare.utep.edu/

[2] https://gams.com

providing entry points that accommodate different levels of user proficiency and perspectives guided through a 3-step workflow.

IV. Decoupled Sustainability Modeling on the Cloud

A. *SWIM Architecture*

SWIM 2.0 is composed of a decoupled architecture of self-contained microservices. This approach allows specialized services to be called upon independently, increases the number of service-orchestration combinations, and fosters their reuse in other domains and applications. The microservice architecture has been used for developing ICTs and end-to-end solutions in the Smart City domain [20], [21]. In addition, SWIM 2.0 has standardized webservices with the OpenAPI[3] specification. This allows both humans and computers to discover and understand service capabilities. SWIM services are wrapped as Docker[4] containers for rapid deployment and configuration on the cloud or on-site servers with container support.

Fig. 1 provides a layered view of the SWIM 2.0 architecture and potential interconnectivity to ICT infrastructure. The data layer incorporates a polyglot persistence. By polyglot persistence, we refer to the use of multiple data management approaches [22]. NoSQL databases (colored in green) were selected for their schema flexibility and dynamic field types. This facilitates the storage of data from diverse sources (e.g., sensors, data-hubs, model-instances) in shared data collections. From the family of NoSQL, we chose a Document-based data model; implementations of this model use a JSON-like (JavaScript Object Notation) format, which has become highly convenient for developers due to its support in web-based applications. Database instances under the relational model (colored in blue) are used for fixed schemas and a more strict data consistency. An RDF knowledge base (colored in gray, currently in development) stores semantically enriched data to support reasoning capabilities and sharing Linked Open Data.

1) *Workflow Services*

These services enable the orchestration of modeling and transformation services. The swim-broker uses a registry of services for transformation and modeling service metadata[5]. These services can be used to run a modeling service directly or invoke a complex process of composing and executing a workflow in a model-to-model scenario. The workflow-cwl service builds upon the Common Workflow Language (CWL) library for CWL serialization and workflow execution [23].

2) *Modeling Services*

This group of middleware services provides an interface for third-party modeling software or programming languages. Their primary function is to load input data (i.e., a model scenario), execute, and extract modeling results. SWIM currently supports integrating GAMS, Scilab[6], and Python-based models. Instances of each middleware service can be repurposed for any model developed with the supported third-party software and programming languages.

3) *Context Services*

The context services group is a distinctive category that provides services for computer-supported interpretation of scientific model results. The recommender service feeds the model output recommendations to a connected interface according to user roles selected by the users when accessing

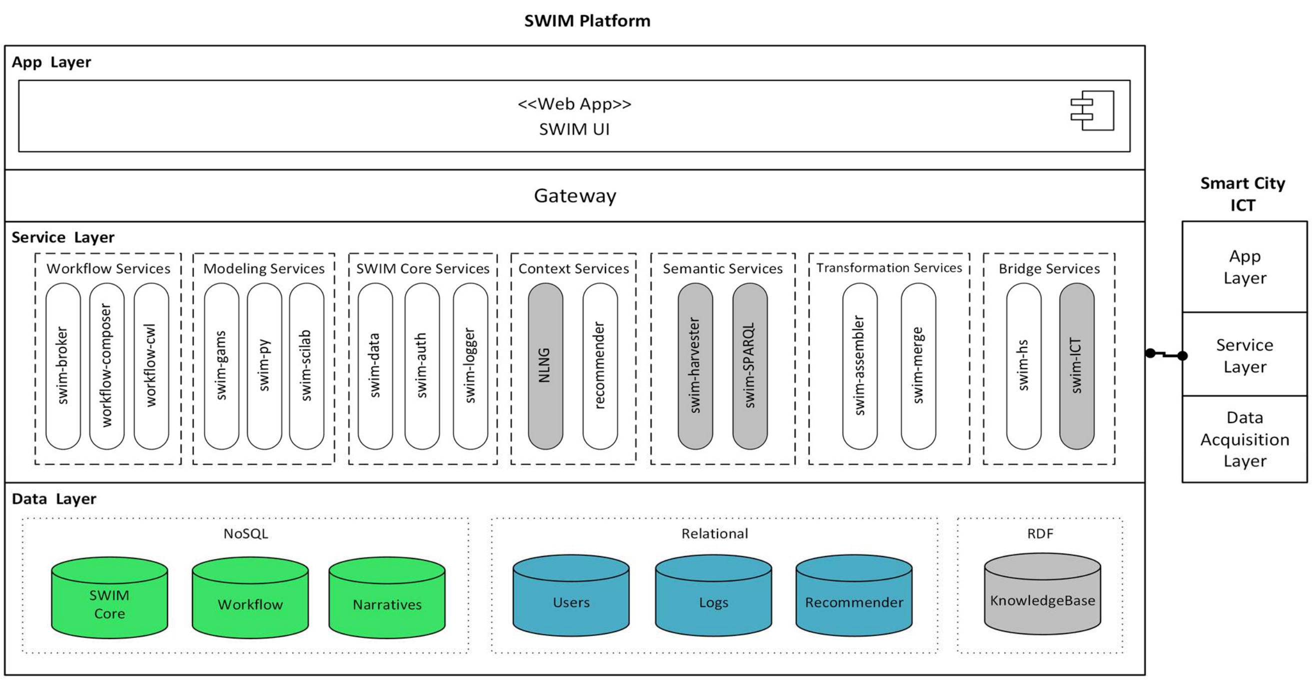

Fig. 1. Layered View architecture of the SWIM platform and proposed high level interoperability with Smart Cities ICT. Artifacts highlighted in gray are in-development or scheduled for future development.

[3] https://spec.openapis.org/oas/latest.html

[4] https://www.docker.com/

[5] https://water.cybershare.utep.edu/resources/docs/en2/backend/swim-broker/

[6] https://www.scilab.org/

SWIM. Under the water domain use case, roles include Urban Residents, Water Managers (i.e., Utility Companies), Policy Makers, and Researchers. These roles were previously identified by Hargrove and Heyman [6]. The Natural Language Narrative Generator (NLNG, currently in development) will provide text-based explanations of modeling output data. The NLNG will leverage trends, behaviors, and context of model results in alignment with a user role's interests.

4) Semantic Services

The semantic services, currently in development, will harvest and expose modeling data using custom and standardized vocabularies. The data-harvester service will be implemented to fetch data from the SWIM Core database and convert data in the form of JSON-LD to Resource Description Framework (RDF) format. The resulting RDF is expected to be stored in a triple store, e.g., an instance of the Allegro Graph Knowledgebase[7]. The SWIM knowledgebase will be exposed through a read-only SPARQL endpoint to answer queries using vocabulary and ontologies in the SWIM linked-data context[8].

5) Transformation Services

Integrating heterogeneous water models and data sources requires data preprocessing to satisfy the requirements of a specific model parameter (e.g., format, resolution, units). These preprocessors are categorized as transformation services. The model-to-model integration capabilities of SWIM uses two independent transformation services; the first extracts and prepares an output of one model as input to the next (swim-assembler) and the second extracts user requested outputs and provenance from the overall modeling results (swim-merge).

6) Bridge Services

SWIM was designed to enable interoperability with other platforms at the service and application levels of the layer hierarchy. The SWIM team collaborated with The Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) to provide seamless connectivity to the HydroShare platform, an online repository for sharing data, models, and code in the water domain [24]. The swim-hs service facilitates the persistence of citable SWIM models and scenarios with third-party platforms following FAIR data principles [25].

B. Interoperability with Smart City ICT

SWIM can potentially host computational models that foster the transformation of cities into Smart Cities. Making SWIM interoperable with Smart City ICTs can enable the delivery of close to real-time data as model inputs. ICT system architectures commonly follow a three-layer architecture [13], also used in SWIM (Fig. 1). Additional artifacts at the service layer of both systems could be integrated to connect, harvest, and transform data for dynamic-model consumption. Access to real-time data by Smart City applications can support informed decision-making in emergency response scenarios.

C. Availability

Published SWIM products are available as open-source code on GitHub and public container images in Docker-Hub. These are listed on the project documentation website[9].

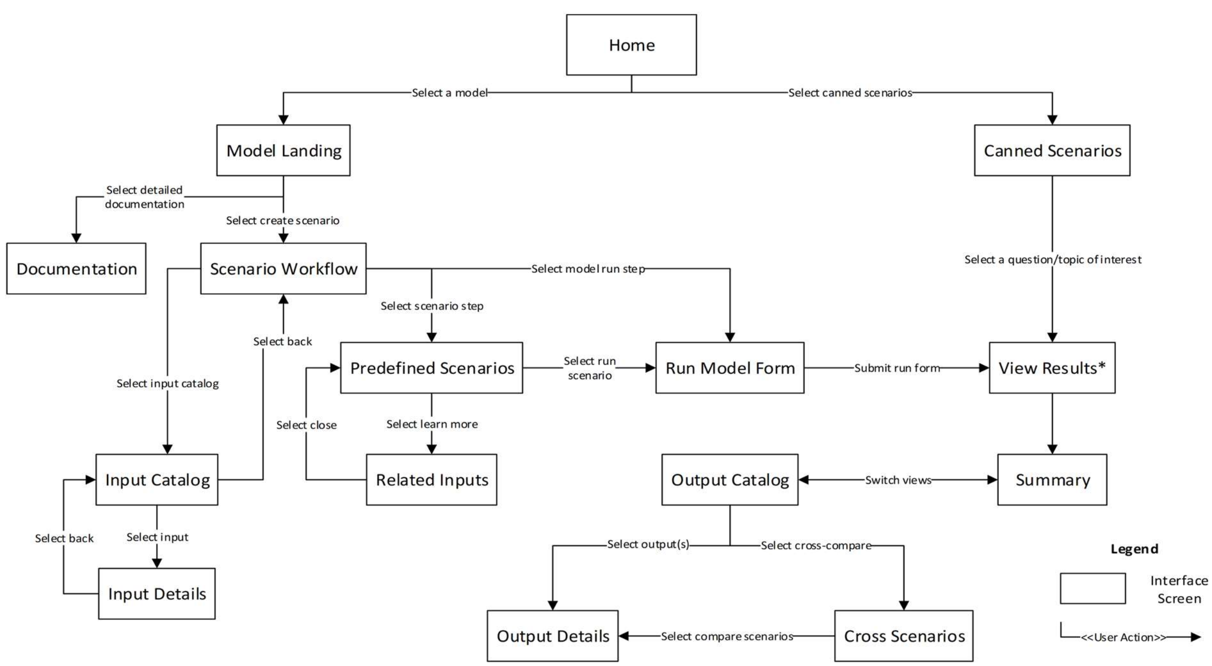

Fig. 2. User flow diagram of the SWIM UI for custom scenario creation and canned scenario selection. *Results are limited to outputs related to the question or topic of interest in a canned scenario.

[7] https://allegrograph.com/

[8] http://purl.org/swim/vocab

[9] https://water.cybershare.utep.edu/resources/docs/en2/source/

V. THE SWIM USER INTERFACE

A. Models and Scenarios

The SWIM user interface (UI) currently provides access to the Water Balance Model (WBM) and the Hydroeconomic Optimization Model (HEM), developed in Scilab and GAMS, respectively. A second version of the Water Balance Model, developed in Python, is also available. The Water Balance Model is a simple aggregated hydrologic model that simulates surface water reservoir storage, river flows, and aquifer storage in the Middle Rio Grande Basin. This model is used to understand how climate change influences regional water availability [26]. The HEM optimizes the distribution of regional water in function of maximizing regional economic benefits. The model is constrained to governing water management policies, storage capacities and sectoral limits to retrieve surface and groundwater. This model has been used for cost analysis exercises of aquifer protection strategies under different climate scenarios [10], and environmental flow schedules [27].

The SWIM UI provides users with entry points through predefined scenarios. A scenario selection loads values that can affect one or multiple model parameters. For example, the selection of a climate scenario loads projected annual water flows to the main storage reservoir under different greenhouse effect scenarios. Water flow values are normalized to consider anthropogenic impairments upstream of the models' start location [28]. The SWIM UI is currently limited to execute one scenario and model at a time. The selection of multiple models and scenarios (e.g., model-to-model and batch executions) is ongoing work as part of the workflow pool of microservices.

B. User Flow

The SWIM UI user flow (Fig. 2) includes two branches for user interaction with models available in SWIM. Starting with the right-hand side branch, users can directly access modeling results as Canned Scenarios. The Canned Scenarios page [10] contains curated questions of interest, each mapped to a model scenario.

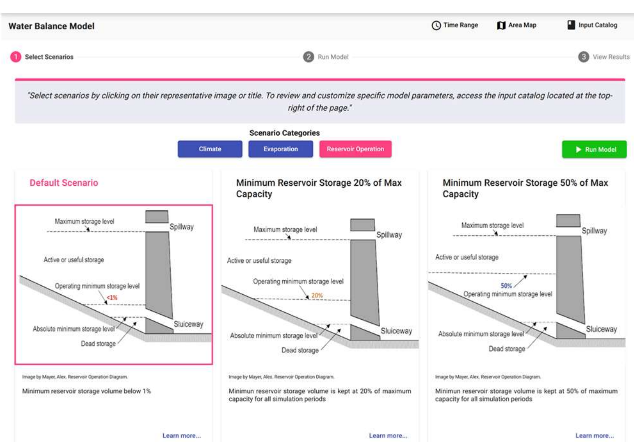

Fig. 3. Screenshot of the "Select Scenarios" step in the SWIM UI modeling workflow using the Water Balance Model.

The results displayed in Canned Scenarios are limited to relevant outputs that help answer the question at hand. Canned scenarios foster users' engagement with limited prior knowledge of water processes (e.g., the general public). Canned Scenarios resulted from knowledge acquired in the preceding USDA project's, including extensive stakeholder consultation about shared and diverse user interests (144 attendees at 10 meetings in two countries [6]). A walkthrough for using a Canned Scenario is available as a "first splash" tutorial[11] on the project website.

Following the left-hand side branch in Fig. 2, SWIM provides access to a generic workflow for custom modeling (Fig. 3). The workflow comprises three steps: 1) Select Scenarios, 2) Run Model, and 3) View Results; optional side options include a) Time-range, b) Area Map, and c) Input Catalog. The 3-step workflow and optional configuration are consistent for all models in SWIM.

After running a model scenario, modeling results are presented as an aggregated summary (i.e., a dashboard) of relevant outputs to a specific user role. The user can then switch to the Output Catalog to browse individual model outputs sorted according to the relevance rank provided by the underlying recommender system. One or many outputs can be selected for data analysis over time. A detailed output view shows metadata, data visualizations (e.g., line-plots, data tables), tools for quick data analysis such as unit change (i.e., metric and English), data comparison plots, and calculation of simple moving averages. Data tables can be exported as a spreadsheet for further analysis. Data visualization design was informed by early face-to-face interviews, discussing output representations with farmers, an important stakeholder group [7].

The Output Catalog features cross-scenario comparison between outputs from a previous scenario execution against outputs of the currently loaded scenario. A walkthrough for creating a custom model scenario is available as a "Dive In" tutorial on SWIM's website[12]. Because many stakeholders are water users/managers in diverse sectors, they have some expertise with water. They can go directly or quickly transition from canned scenarios to custom modeling to explore their questions of particular interest.

C. Evaluation

The SWIM UI was evaluated through a usability study approved by The University of Texas at El Paso Institutional Review Board. This study focused on evaluating the workflow interface to create custom scenarios. Participants were given a brief overview of the interface and a list of tasks to create a custom model scenario using the WBM. After completing the assigned tasks, participants answered a survey divided into the following sections: i) demographics, ii) background, iii) interface design, iv) data presentation, v) workflow evaluation, vi) user impact, and vii) areas of improvement. This study was done in two phases. A recommended number of test users in user experience research is five [29]. This study recruited more than this number of participants to include different types of users in each phase. The first phase comprised one study session held

[10] https://swim.cybershare.utep.edu/en/canned-scenarios
[11] https://swim.cybershare.utep.edu/en/first-splash
[12] https://swim.cybershare.utep.edu/en/second-splash

face-to-face in January 2020, with 15 participants. The SWIM UI was refined based on input from this first session, and the survey was simplified for the workflow evaluation. In the second phase, three sessions were held virtually in September and October 2020, with 11 participants. Two of these virtual sessions were held in English and one in Spanish to address the needs of the bicultural study region. The results of this study are presented below for the face-to-face session (phase one) and the virtual sessions (phase two) separately. For space constraints, we provide results for demographics, background, and workflow evaluation that are the most relevant to this manuscript.

In the face-to-face session, 67% of participants identified as researchers, 13% as educators, 13% as other, and 7% as urban residents. For the virtual sessions, 55% of participants identified as researchers and 45% as students. The top two responses for participants' background in the face-to-face session were Environmental Science and Water Resource Engineering and the top two responses for the virtual sessions were Environmental Science and Ground Water modeling. Other responses mostly included diverse water-related areas. In the face-to-face session, 87% of participants indicated to *have used computer models or other abstractions of a real-world system before,* and 91% in the virtual sessions.

Four sequential workflow tasks (shown in Fig. 4 and Fig. 5) were evaluated according to three aspects: i) ease to find the screen within the workflow to start a task, ii) ease to keep track of user whereabouts within the workflow, and iii) accurate prediction of displayed content to complete a task. In the face-to-face usability session, responses related to these tasks were

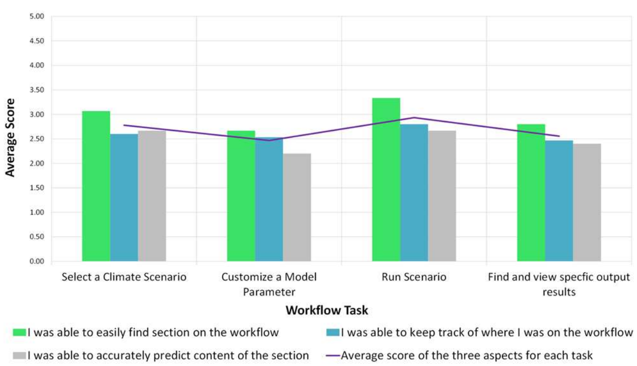

Fig. 4. Workflow task evaluation results from the face-to-face usability session.

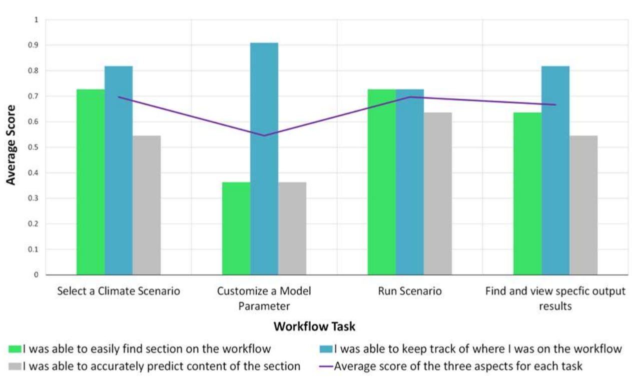

Fig. 5. Workflow task evaluation results from the virtual usability sessions.

collected using a 5-point Linkert-like scale from 1 – *Strongly Disagree* to 5 – *Strongly Agree*. The average of scores in the face-to-face session for each aspect of each task is shown in Fig. 4. In the face-to-face session, the task to *Customize a Model Parameter* was perceived as the most challenging task to accomplish with an average score of 2.47, closer to *Disagree*. The SWIM UI was refined to exclude parameter customization from the main workflow and included it as an optional sidestep. The evaluation scale for the workflow was simplified to a selection of aspects that the participants thought applied for each task. When calculating the average in the virtual sessions, a 1 was assigned to aspects selected and 0 to those not selected. *Customize a Model Parameter* results from the virtual sessions had an average score of 0.54 (Fig. 5) which shows better perceptions for the tracking location aspect in the workflow with an average score of 0.9. However, both the findability and prediction aspects for this task scored 0.36.

The established order of the scenario workflow was evaluated using a 5-point Linkert-like scale from 1- *Strongly Disagree* to 5-*Strongly Agree*. In the face-to-face session 27% of participants *Strongly Agreed,* and *46% Agreed* that *the workflow was appropriate for understanding and completing the overall tasks*. In the virtual sessions, *Strongly Agree* was chosen by 55% of participants and *Agree* by 36%. These results show an improvement in the SWIM UI workflow evaluation when comparing virtual sessions to the initial face-to-face session. We identified an opportunity to improve the SWIM UI for granular customization of modeling scenarios, currently requiring users to modify values in data tables and time series.

VI. Conclusions and Future Work

Smart City platforms can provide a wide range of residents with tailored knowledge and scenarios for analysis by integrating heterogeneous data sources. SWIM enables users access to two features: the behavior of an entire complex system in response to different data inputs and management choices and the ability to consider many alternative water scenarios (including urban supply) based on climate change and management choices. SWIM is particularly suited for understanding cities located in complex, regional socio-environmental systems, which can support informed choices by urban residents and those of surrounding areas.

We describe a decoupled microservice architecture to extend the capabilities of modeling-as-a-service (Maas), and a unified user interface with a generic modeling workflow design that includes multiple elements to support data interpretation.

In this work, we incorporate future-scenario analysis to facilitate the interaction of users with heterogeneous models that is generic enough to accommodate different domains to foster citizen engagement. SWIM 2.0 provides users with canned scenarios as an entry point to the system and uses them as bridge towards developing custom scenarios. The usability study suggests that detailed customization of model scenarios is not a simple task. Additional work can be done to improve data-editing widgets (e.g., sliders, data tables, direct plot manipulation).

Using existing infrastructure, we envision the interoperability of the SWIM platform with Smart City ICT to ingest close to real-time data that can support informed decision-making for a wide range of applications, from planning to event response.

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