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DYNAMIC BEHAVIOURAL MODELING, SIMULATION AND ANALYSIS OF HOUSEHOLD WATER CONSUMPTION IN AN URBAN AREA: A HYBRID APPROACH

Muhammad Saad Qaisar Alvi
Imran Mahmood
Fahad Javed
Asad Waqar Malik

Center for Research in Modeling, Simulation & Vision (Crimson)
School of Electrical Engineering and Computer Science
National University of Sciences & Technology
Sector H-12, Islamabad, 44000, PAKISTAN

Hessam Sarjoughian

Arizona Center for Integrative Modeling & Simulation (ACIMS)
School of Computing, Informatics, and Decision Systems Engineering
699 S. Mill Avenue
Arizona State University, Tempe, AZ, 85281, USA

ABSTRACT

Pakistan is rapidly becoming a water stressed country, thus affecting people's well-being. Authorities are faced with making drastic water conservation policies toward achieving effective management of available water resources and efficient water supply delivery coupled with responsible demand side management. Due to the lack of modern water metering in Pakistan, water consumption is not being accurately monitored. To achieve this goal, we propose a hybrid modeling and simulation framework, consisting of: (i) Agent-Based Modeling (ABM) paradigm that deals with the behavior and characteristics of individuals and (ii) System Dynamics(SD) paradigm that accounts for water flow dynamics. Our approach provides dual-resolution expressiveness suitable for replicating real-world urban infrastructure scenarios. The key objective of the research is to assist authorities to understand and forecast short-term and long-term water consumption through examining varying patterns of water consumption in different climates and thus improving demand side water usage dynamically subject to water supply availability.

1 INTRODUCTION

United Nations Sustainable Development Goals (UN-SDGs) has released a report to achieve sustainable development goals for cities and communities (Sustainable Development Goals 2018). Basic necessities such as water, energy, healthcare, sanitation, and education are required to be made available at the doorsteps of the individuals to achieve this target (Guterres 2017). Domestic water consumption constitutes a major part of urban water demand but with the growth of population and the continuous rise in the inflow of urban population the urban areas are facing a drastic decline in available water quantity and quality (Linkola et al. 2013). Pakistan is at the 17^{th} position in the list of countries, which are facing extreme water scarcity and health crisis due to unsafe drinking water (Altaf 2017). As the size of the human population is increasing day by day, it is being suggested that by the year 2025 the population of Pakistan will get doubled (Iqbal 2010). This continuous rise in the inflow of urban population intensifies the services like delivery of safe water, waste management, energy, health, school facilities and public safety to their critical limits, and impends the availability of critical resources for having a resilient and sustainable urban infrastructure (Moon 2016). In order to help improve water governance, a dynamic modeling and simulation framework can help develop strategies/policies for preventive demand side management as well as better planning for supply and resource management (Linkola et al. 2013).

1.1 Water Supply and Management

Water supply and management is becoming a major issue due to climate change, depletion of natural resources and rapid urbanization. It is crucial for the water regulatory authorities to be able to forecast the future demand and propose a resilient and sustainable infrastructure for effective water management (Butler et al. 2016). In most parts of the urban regions of Pakistan, there are no proper metering of water and regulatory authorities have limited data on water consumption and required water supply. Installing Smart water meters requires significant funding and time commitment. There is, therefore, an urgent need to forecast with as much as possible the exact household water demand, in order to best manage available water resources and delivery. This requires system analysis for combined demand and supply. Many existing approaches propose the analysis of water resources planning and management through modeling and simulation (Berglund 2015).

Modeling and simulation enables us to replicate a real world system for suitable risk-free dynamic experiments (Borshchev 2013). Simulation models of water consumption deals with modeling of individual's characteristics and water consumption behavior as agents, as well as the modeling of external environment, supply processes and water flows as system dynamics. These external factors have significant importance in analyzing interdependent behavioral aspects (Olmo 2009). Modeling and simulation of domestic water consuming entities and water resources help in analysis and management planning of water resources. It provides a control over consumption by predicting the tasks which are necessary for satisfying the volumetric flow usage. Modeling water consumption of different consumers such as *domestic, industrial* and *agricultural sectors* (Khoso et al. 2015), helps in forecasting water demand by analyzing activity-based consumption and by gaining the insights of the demand dynamics (Linkola et al. 2013).

In this paper, we propose the development of behavioural simulation model for household water consumption at a dual resolution (i.e., Macro and Micro level) using hybrid approach. Our hybrid approach combines (i) Agent Based Modeling (ABM) to model individuals' water consumption behavior at a micro level, and (ii) System Dynamic (SD) approach to aggregate the modeled behavior of a population in an urban area, at macro level in order to forecast short-term and long-term water demand. The goal of this research is to develop a framework for the regulatory authorities, that can help in monitoring of water resources, plan effective supply of water at household level and forecast short-term and long-term water consumption demand. It further aids in gaining insights of the behavior patterns of water consumption in different areas, and improve the performance of the water supply process through demand side management.

2 RELATED WORK

Many existing approaches propose the analysis of water resources planning and management through modeling and simulation, at various levels of abstraction.

2.1 Agent Based Modeling (ABM)

An agent-based model (ABM) is a class of models meant for simulating the actions and interactions of autonomous agents, both individual or collective entities, with a view to assessing their effects on the system as a whole (Bonabeau 2002). Application of Agent Based Modeling (ABM) provides microscopic insights about water systems to explore complex behavior over time. Microscopic models help in simulating real-world problems with greater accuracy, as these take into account many small details that can produce minor deviations from the actual result if not considered. Williamson explores leakages in domestic water consumption scenarios (Williamson 2001). Similarly, Berglund discussed different case studies to demonstrate the use of reactive and active agents for simulating water resources planning problems (Berglund 2015). Schwarz, et al. proposed ABM for analyzing water saving innovation diffusion in an urban environment (Schwarz and Ernst 2009). The modeling of water consuming entities and water resources at domestic level is an essential part of studying this behavior, as proposed by (Zaher and Badr 2016). Linkola et al. 2013 proposed a model of household water consuming behavior. The model simulates hourly water using activities of individuals in a house, the results suggested that different household types (i.e. households having different demographic characteristics) produced different water consumption patterns (Linkola et al. 2013). Darbandsari et al. 2017 proposed an urban household behavioural model applied to the western area of Tehran metropolitan in, Iran for finding the best effective water consumption management policies under different climate conditions (Darbandsari et al. 2017). Koutiva and Makropoulos proposed an approach to analyze water demand behavior by modeling socio-economic characteristics of urban area, using statistical mechanics. They integrated a social simulation model and an urban water management tool in order to forecast the future domestic water demand (Koutiva and Makropoulos 2016). Meso simulation fills the gap between micro and macro simulation. This category deals with modeling individual's interaction and behavior at lower levels of detail. Furthermore, in Meso water consumption simulation, agents can be generated with some characteristics and behavior of household water consumption; however, minute details such as age group of a person and other factors can be ignored in this kind of simulation (Szczeniak ands Piniewski 2015).

2.2 System Dynamics Modeling

System dynamics (SD) is a macro simulation approach, used in understanding the behaviour of complex systems over time using stocks, flows, feedback loops, and time delays (Forrester 1995). SD works on a higher level of abstraction (i.e., fewer details). The system entities exclude the microscopic details and instead only represent some key aspects of a real-world system at *aggregate* abstraction levels. These models do not take into consideration the behavior and characteristics of individual people but instead focuses on modeling the household water consumption (Athanasiadis et al. 2005). Ganjidoost et al. 2015 proposed the application of system dynamics modeling approach for studying a network of water distribution and wastewater entities. They proposed casual feedback loops between the physical infrastructure with finance and consumer/public policy sectors. This framework aims to optimize strategic-level asset management decisions (Ganjidoost et al. 2015). Palmer, proposed a system dynamics model that includes the impact of households receiving water and sanitation services where rainwater harvesting is an alternative water supply (Palmer 2014). Park, et al. proposed a system dynamics model of water supply using causal feedback loops between the management of water pipes and their effect on water pricing (Park et al. 2015).

2.3 Hybrid Modeling

The proposed hybrid modeling approach integrates Agent-Based Modelling with System Dynamics to leverage the potential of both paradigms. ABM focuses on microscopic details of the system whereas SD aims to aggregate the modeling details at a macro level. The former provides the advantage of capturing essential details at entity level models that mimic human behavior and characteristics such as the age groups of people and consumption habits. ABM, however, suffers from performance issues, especially when dealing with large-scale populations. The latter has an edge in building large-scale models that can be simulated for very long timescales. It also helps in modeling the nonlinear continuous behavior of a complex system over time such as the quantity of water consumed in a particular activity, but it lacks expressiveness for entity-level behaviors.

In our observation, most of the existing simulation models focus either on agent-based or system dynamics modeling, but not both. We, therefore, propose a hybrid model based on the combination of ABM and SD. The ABM paradigm is used to model the agents, such as persons, houses, and the neighborhoods as entities using state-charts while the SD paradigm is used to model complex behavior of water supply and management using stocks and flows.

3 PROPOSED HOUSEHOLD WATER SIMULATION AND ANALYSIS FRAMEWORK

This section provides the technical details of our proposed household water consumption modeling, simulation and analysis framework. It consists of three modules:

3.1 Agent Module

To describe our Agent module, we use the seven elements of the ODD protocol, as outlined in Grimm et al. 2010.

3.1.1 Purpose

The model is design to predict the amount of water consumed by different individuals in a house during 24 hours and generate a household demand profile.

3.1.2 Entities, State Variables and Scales

The Agent module consists of a number of agents: (i) Persons, (ii) Households and (iii) Neighborhoods. The water consumption behavior of an individual, in a typical urban house at hourly (or lower) resolution is modeled using State chart, as shown in Figure 1. The states are representing major water consumption activities in a household.

Household water consumption depends on the type of the person. Persons can be of different age groups, employed, or stay in their houses. Water will only be consumed in a household activity during the time periods people are in their houses, which depends on the type and age of the person. Infants stay in their houses throughout the day and hence utilize water. Children, however, who go to their schools, consume their household water once they are back from their schools. Similarly, teens go to their schools and colleges and their unavailability duration is slightly greater than the children. Adults, on the other hand, need to spend most of their time outside to earn a living for their family. Elders are mostly retired people and spend most of their time in their houses so their water utilization is more as compared to other age groups (Linkola et al. 2013). The availability and consumption behaviour is represented in Table 1.

Table 1: Availability Probability of Different Age Groups.

Agent type	Availability	Behavior
Infant (1-5)	Mostly at home	Water consumption is carried throughout the day
Child (6-12)	Spend a small amount of time outside the house	Water consumption is comparatively less as compared to infants
Teen (13-19)	Spend half of their time in school or college	Water consumption only occurs once they are in home
Adult (20-59)	Spend most of their time in work places	Water consumption is very low as compared to other age groups
Elders (60 and above)	Mostly retired persons and spend most of their time in home	Water consumption is highest amongst other age groups

The temporal resolution is set on hourly basis. In this paper, the spatial modalities of the house and the neighborhood are neglected (and will be catered in future). We calculate the water use of individuals, households and the neighborhood through the summation of individual water use per unit time.

3.1.3 Process Overview and Scheduling

The behaviour of each individual in a house is modeled using a State chart where (i) ***States*** represent different activities and (ii) ***Transitions*** trigger these activities based on some stochastic patterns including probability of occurrence, time of occurrence and the activity duration. Transition occur at discrete (integer) time periods. These transitions are guarded by the utilization factor of different activities (e.g., "Taking Shower" may be restricted to a maximum of 3 times a day for each individual). The behavior of water consumption of a person is represented by the state-chart in Figure 1. When a person enters into an activity, it triggers the outflow of the corresponding activity in the house component by assigning a non-zero consumption rate, which causes the flow of water from the roof-top tank and simulates water consumption. We assign ***timeout*** probability functions to different activities. The timeout causes an activity and the water flow to stop.

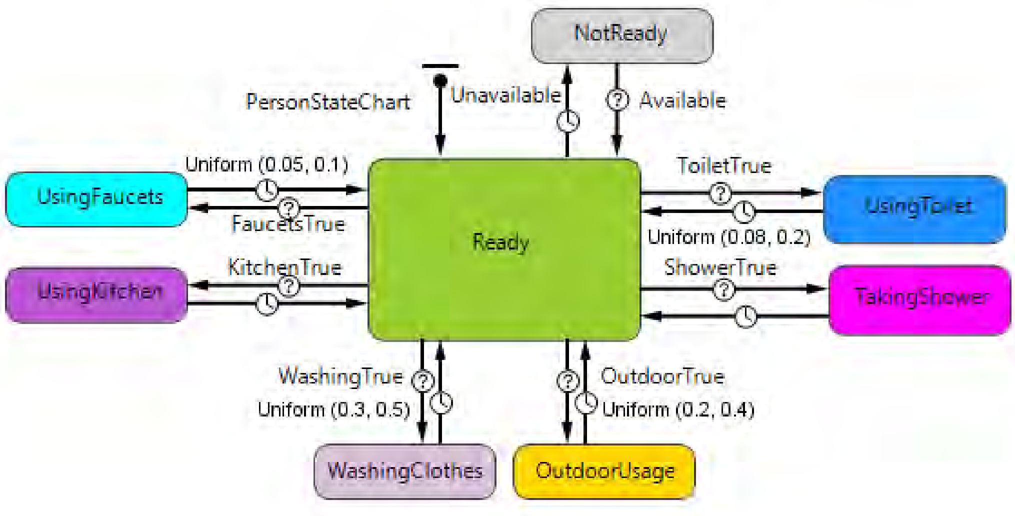

Figure 1: Person Statechart.

Every household's water consuming activity has different times of occurrence, for different water consuming activities which are triggered with some probability of occurrence (Funk and DeOreo 2009). The probabilities as shown in Figure 2. These probabilities are based on California Single Family Water Use Efficiency Study (Andrew and DeOreo 2011). The purpose of the study was to obtain current water use information on representative samples of single-family customers in California. Another study presents the percentages of water consumption in different activities (Alaton et al. 2002).

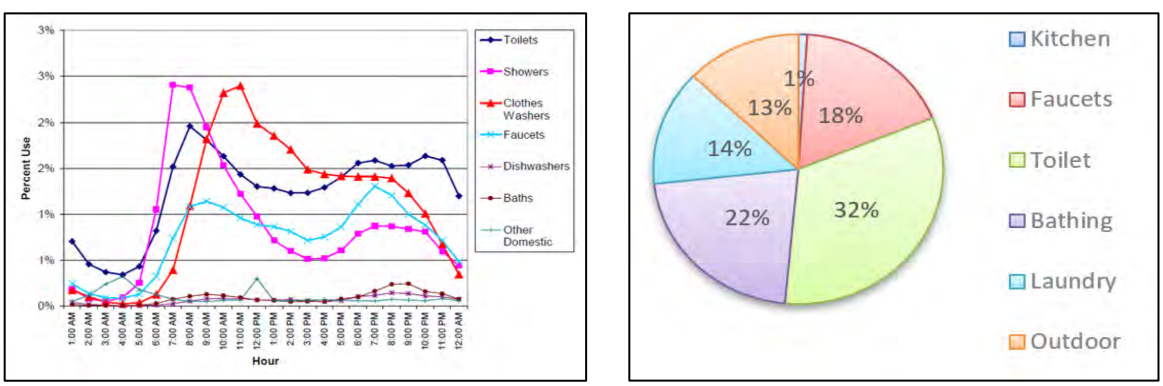

Figure 2: (a) Hourly Probability of water use (b) Percentage of Water Utilized in different activities.

Our proposed framework is based on these general guidelines and represents households for an arbitrary urban area. However, the framework can be calibrated for a specific location by adjusting the probability tables. A modeler can also incorporate typical norms of a society to localize the model behaviour. E.g., in Muslim countries people perform ablution (*wudu*) five times a day or obligatory bathing on Fridays. Similarly, the model can incorporate exogenous variables such as temperature, weather, seasons, power outages. According to (Alaton et al. 2002) energy and water consumption vary with variation in temperatures in households, workplaces, neighborhood, etc.

3.1.4 Design Concepts

- Emergence: An aggregate water consumption behaviour emerges from the interactions of individual agents with the household water system. It is desirable to explore methods to develop cooperative agent behaviour which results into optimal use of water when the water supply is limited (and will be catered in future).
- Adaptation: We use calibration technique to adapt the behaviour of agents in order to optimize their daily water use based on given empirical dataset.
- Fitness: Agents do not interrupt each other's activities.
- Prediction: Probability functions are used to predict agent decision.
- Sensing: Daily temperature data is used along with the original probability function for temperature sensitive activities (e.g., taking bath and outdoor water use).
- Stochasticity: Probability distributions with discrete values are assigned to model the duration of activities.
- Collectives: House represent a group of individuals; Neighborhood represents a group of houses.
- Observation: The outflow of water from different activities are measures over time.

3.1.5 Initialization

The model initializes with a given number of houses in a neighborhood and a uniformly distributed population of individual's in each house. Model starts at time=00:00 AM and runs for 24 hours at an hourly resolution.

3.1.6 Input Data

Table 2 shows the key inputs required to run the model:

Table 2: Model Inputs.

Initial Parameters	No. of Persons in a House No. of Houses in a Neighborhood
Availability Probability	Infant, Child, Teen, Adult, Elder
Probability of Occurrence	Kitchen Faucets Washing Clothes Bathing Toilet Outdoor 24 hours (1:00 AM – 12:00 AM)
Activity Duration	Kitchen Faucets Washing Clothes Bathing Toilet Outdoor
Consumption Rates	Kitchen, Faucets, Washing Clothes, Bathing, Toilet, Outdoor
External Variables	Hourly Temperature 24 hours (1:00 AM – 12:00 AM)

3.1.7 Sub Models: None

3.2 System Dynamics Module

We use System Dynamics approach to model the House components, which consists of stocks and flows. Water reservoirs are modeled as stocks and consumption of water in a house is modeled as flows as shown in Figure 3. A typical house will have a random number of individuals (person agents) and thus may have a demand profile different from other. A neighborhood (an array of houses) will have an aggregate demand over time. There are different household water consuming entities in a house and the nature of water consumption in different household entities vary dynamically. When an individual enters into a state and initiates water consumption, the rate of consumption is switched from 0 to a positive value, which causes a flow from a municipal water tank through a household water tank to the corresponding consuming activity. When the agent stops an activity due to timeout, the consumption rate value is switched back to zero, hence stopping the flow. Since the house component aggregates multiple individuals in a house, according to the random occupancy, the flows can handle parallel water consumption activities. The consumption rates are shown in Table 3. The time resolution of this model is set on hourly basis so that the daily water consumption of different types of people in different houses can be observed on a time scale of 24 hours. Figure 4 shows an integration of house agents in the form of a neighborhood.

Table 3: Consumption Rates for different activities.

Activity	Gallons/Hour
Faucets	0 - 9.3
Kitchen	0 - 10.1
Laundry	0 - 3.4
Outdoor	0 - 18
Shower	0 - 24.4
Toilet	0 - 8.8

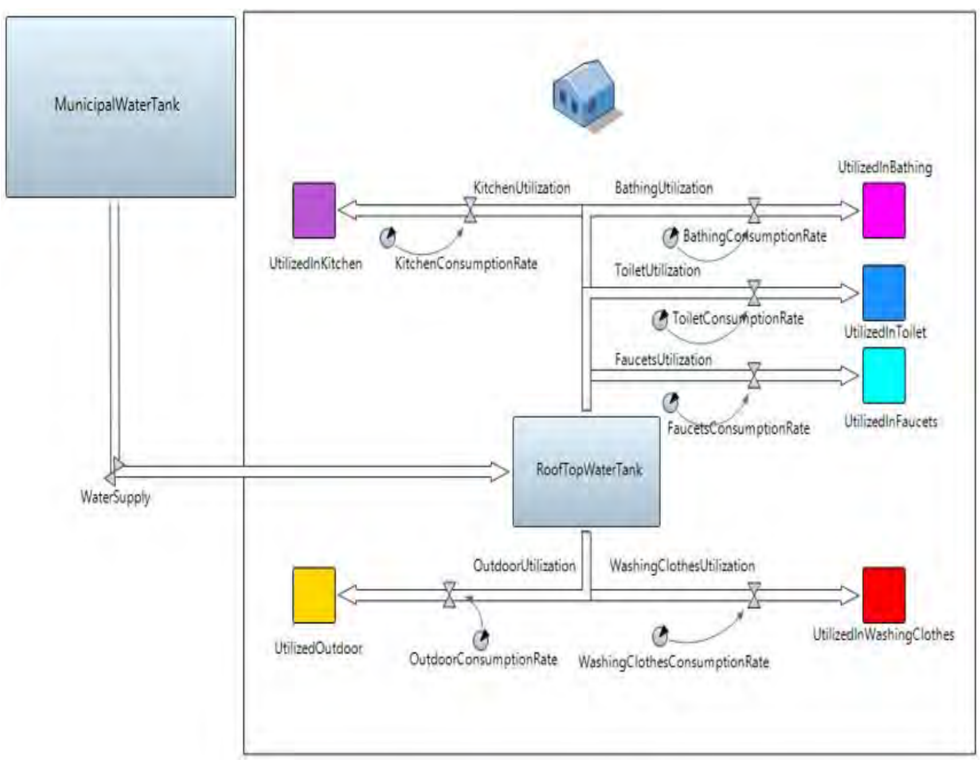

Figure 3: Stock and Flow diagram of water consuming entities in a typical house.

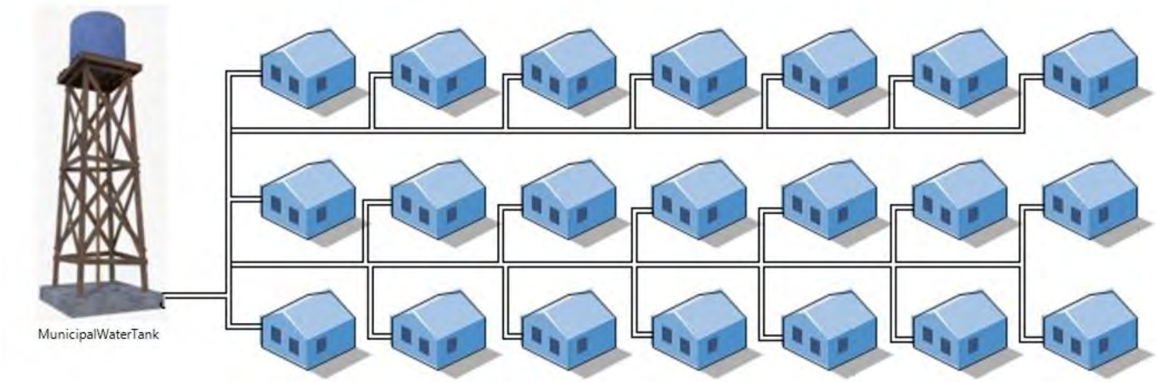

Figure 4: Array of Houses in a typical urban infrastructure.

3.3 Hybrid Approach Architecture

There are three architectures to implement multi-method modeling in Anylogic as shown in Figure 5:

1. In which both agent environment and System Dynamics are modeled at the same level. Entities and elements are visible and can be accessed and manipulated by by both ABM & SD layer during the simulation.
2. In which the entire SD model is built inside the agent body. Entities and Elements are local to a single agent.
3. In which the entire SD model is built inside the agent body. Entities and Elements are local to a single agent.

We use (1) in which both Persons (ABM) and Household water system (SD) are modeled inside a house using *Parallel method*. During the simulation any person can manipulate the flow of water in the SD layer by entering into a water consumption activity.

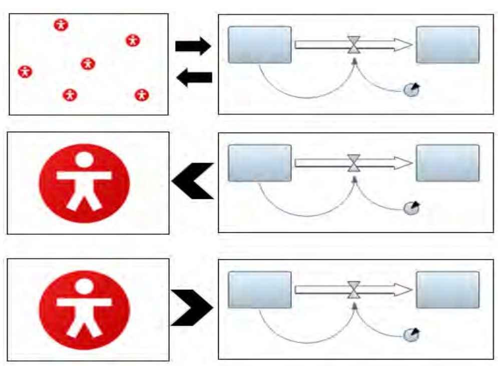

Figure 5: Hybrid Approach Architectures.

3.4 Visualizations and Analysis Module

Water regulatory authorities such as Capital Development Authority (CDA) may utilize the visualization dashboard. It provides visualizations of the daily, weekly, monthly or yearly water consumption profiles of the specified area and will help in monitoring and management planning of water resources. This module allows the users to initialize the simulation with a given number of houses and the minimum, maximum population of each house. Similarly it will allow an input for configuring water consumption rates of each activity, time durations and utilization factors. Our framework takes key parameters as inputs such as probability tables, consumption rates and time. Fine tuning of our framework will help regulatory authorities in effective water supply and management. Figure 6 shows the visualization and analytics framework process.

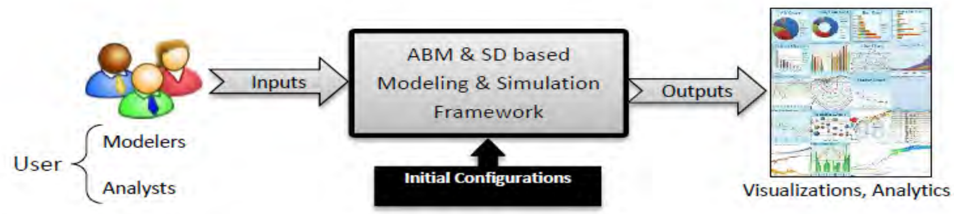

Figure 6: Visualization and Analytics Framework.

4 RESULTS AND DISCUSSION

We ran a simulation of 10 runs for one household of 10 persons (with different types) over a period of 24 hours. Figure 7 shows the average utilization of water consumption of different activities. In another experiment, we ran a simulation of 10 runs for the water consumption of a typical neighborhood of 10 houses. Figure 8 shows time plot of this simulation experiment for an average daily water consumption for a period of 30 days. Figure 9 shows a monthly aggregate of average water consumption of 10 houses for a year.

Figure 7: Water Consumption of a household [X-axis = Hour of the day, Y-axis = Gallons].

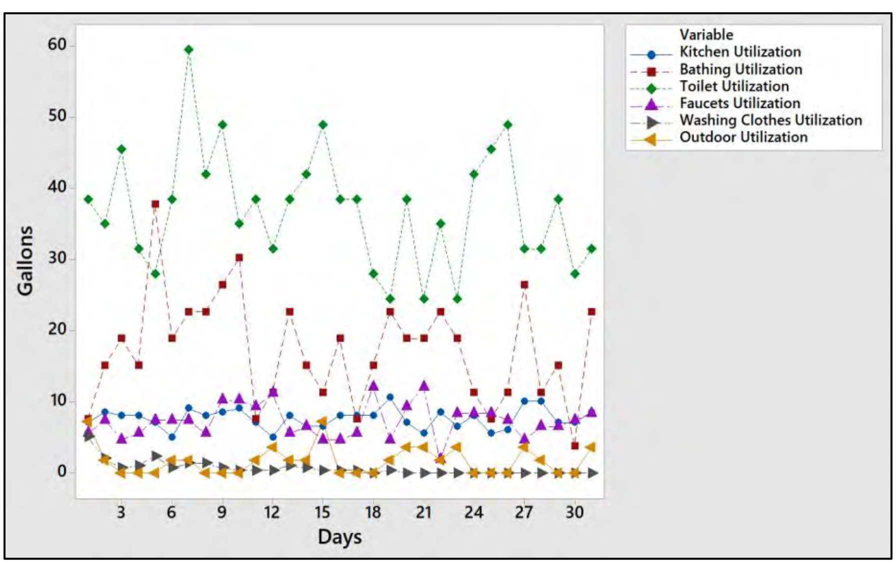

Figure 8: Average daily Water Consumption of 10 houses for a period of 30 days.

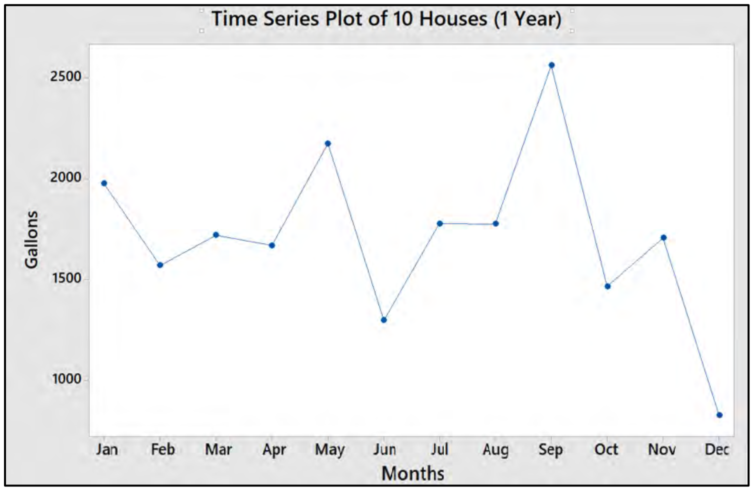

Figure 9: Average Yearly Water Consumption of 10 houses.

These results suggest that the maximum amount of water is utilized in toilets, while least amount of water is utilized in outdoor activities. It also shows a direct correlation of temperature with the water consumption, since there is a steep rise of consumption from the month of April till September. Whereas in June & July, due to monsoon season and heavy rains the temperature drops and eventually the water consumption is reduced. Also in winter the water consumption is decreased.

We use the Anylogic University Researcher Edition (8.2.4) (Anylogic, 2018) for the development and the execution of the household water consumption simulator. The hardware and OS specifications are: DELL OptiPlex 3046 Intel(R) Core(TM) i7-6700 CPU @ 3.40 GHz, RAM: 8GB, Windows 10 Education.

5 CONCLUSIONS AND FUTURE WORK

In this paper, we propose a modeling, simulation and analysis framework for household water consumption in an urban area using a hybrid ABM and SD approach. Our framework allows the modeler to analyze and forecast household water demand. This framework consists of three modules: (i) AB module which is used to replicate a person's behavior and characteristics, (ii) SD module which allows the modeler to replicate complex and dynamic behavior of water flow from a specific household water consuming entity, and (iii) Visualization and analytics module which allows the modeler to analyze and forecast demand and supply of water in an urban infrastructure.

The simulation framework will help develop strategies/policies for preventive demand side management as well as better planning for supply and resource management. This research work is in progress. We are developing an observational technique to collect real-time data on water consumption using Internet Of Things (IoT) kit. This will help in the validation and calibration of a model with actual data. Once the simulation framework is validated for the behavioral analysis of water consumption in the domestic sector, it should be straightforward to extend to other sectors including industrial, commercial and agricultural using our component-based modeling approach. And eventually can be deployed as a decision support system. We further aim to extend the framework to support supply-side modeling at multiple levels of resolution and incorporate water supply management processes under various scenarios of urban infrastructures.

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AUTHOR BIOGRAPHIES

MUHAMMAD SAAD QAISAR ALVI is currently pursuing his Masters in Information Technology at the Department of Computing, School of Electrical Engineering and Computer Science, National University of Sciences and Technology (Pakistan). He is serving as a Research Assistant at CRIMSON. He can be reached at malvi.msit15seecs@seecs.edu.pk.

IMRAN MAHMOOD is currently working as an Assistant Professor at the Department of Computing, School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Pakistan. He is serving as the Director of the Center for Research in Modeling and Simulation (CRIMSON). His current research interests are in applied modeling, simulation, analysis and formal verification of complex systems. He can be reached at imran.mahmood@seecs.edu.pk.

FAHAD JAVED is the Lakshmi Mittal Harvard South Asia Institute fellow. He completed his Ph.D. and MS in Computer Science from LUMS, Pakistan. His research interests are in the modeling and simulation of socio-economic impact of smart grids. He is currently working as Assistant professor at NUST, Pakistan. He can be reached at fahad.javed@seecs.edu.pk.

ASAD WAQAR MALIK received his PhD degree in Computer Software Engineering from the NUST, Pakistan. He served as a Research Scholar at Georgia Institute of Technology, and North Dakota State University, USA. He is an assistant professor at the NUST School of Electrical Engineering and Computer Science, Pakistan. His research interests include parallel and distributed simulations, cloud computing, vehicular and large-scale networks. He can be reached at asad.malik@seecs.edu.pk.

HESSAM S. SARJOUGHIAN is an Associate Professor of Computer Science and Computer Engineering in the School of Computing, Informatics, and Decision Systems Engineering (CIDSE) at Arizona State University (ASU), Tempe, AZ, and co-director of the Arizona Center for Integrative Modeling & Simulation (ACIMS). His research interests include model theory, poly-formalism modeling, collaborative modeling, simulation for complexity science, and M&S frameworks/tools. He is the director of the ASU Online Masters of Engineering in Modeling & Simulation program. He can be contacted at hessam.Sarjoughian@asu.edu.