Behavioral Modelling of Household Water Consumption for Effective Water Supply and Management

By

Muhammad Saad Qaisar Alvi

00000118946

Supervisor

Dr. Imran Mahmood

Department of Computer Science

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Information Technology

Approval

It is certified that the contents and form of the thesis entitled "Behavioral Modeling of Household Water Consumption for Effective Water Supply and Management" submitted by Muhammad Saad Qaisar Alvi have been found satisfactory for the requirement of the degree.

Advisor: Dr. Imran Mahmood

Signature: ____________________

Date: ____________________

Committee Member 1:

Dr. Asad Waqar Malik

Signature: ____________________

Date: ____________________

Committee Member 2:

Dr. Anis ur Rahman

Signature: ____________________

Date: ____________________

Committee Member 3:

Dr. Arsalan Ahmad

Signature: ____________________

Date: ____________________

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material, which to a substantial extent, has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author's Name: Muhammad Saad Qaisar Alvi

Signature: ____________________

Acknowledgment

I pay my gratitude to Allah almighty for His blessings guidance without which I could not have completed this task. I am thankful to Dr. Imran Mahmood for guiding and encouraging me to complete my thesis. His timely and efficient contributions helped me shape the thesis into its final form and I express my gratefulness for his sincere supervision all the way.

I am also thankful to Department of Computing, and the teachers for providing me with an academic base, which enabled me to complete this thesis.

I would like to thank my parents who have provided me every comfort of life and their utmost affection and support that made me reach where I am today.

I would specially like to thank Major Talaat Khurshid (Retd) for proof reading of my thesis.

Publications

M. Alvi, I. Mahmood, F. Javed, A. Malik, H. Sarjoughian, "Dynamic Behavioral Modeling, Simulation and Analysis of Household Water Consumption in an Urban Area: A Hybrid Approach", *Proceedings of the 2018 Winter Simulation Conference,* Gothenburg, Sweden.

[Submitted on 15th April 2018, Under Review]

Table of Contents

Certificate of Originality **1-3**
Acknowledgment **1-4**
Publications **1-5**
Table of Contents **1-6**
List of Abbreviation **1-7**
List of Tables **1-8**
List of Figures **1-9**
Abstract **1-10**
Chapter 1 Introduction **1-1**
1.1 WATER SCARCITY 1-1
1.2 CHALLENGE 1-2
1.3 PROBLEM DOMAIN 1-2
1.4 PROBLEM STATEMENT 1-3
1.5 SOLUTION DOMAIN 1-3
1.5.1 Modeling and Simulation 1-3
1.5.2 Water Simulation 1-3
1.6 SOLUTION STATEMENT 1-4
1.7 KEY CONTRIBUTIONS 1-4
1.8 RESEARCH IMPACT 1-4
1.9 THESIS ORGANIZATION 1-5
1.9.1 Chapter 2: Background 1-5
1.9.2 Chapter 3: Literature 1-5
1.9.3 Chapter 4: Methodology 1-5
1.9.4 Chapter 5: Simulation and Results 1-5
1.9.5 Chapter 6: Conclusion and Future work 1-5
Chapter 2 Background **2-6**
2.1 WATER SUPPLY AND MANAGEMENT 2-6
2.2 HOUSEHOLD WATER SIMULATION 2-7
2.2.1 Household water Simulation Models 2-7
2.3 HOUSEHOLD WATER SIMULATION TOOLS 2-9
2.3.1 AnyLogic 2-9
Chapter 3 Literature Review **3-11**
3.1 WATER SUPPLY AND MANAGEMENT 3-13
3.2 HOUSEHOLD WATER SIMULATION 3-13
3.2.1 Micro Simulation 3-13
3.2.2 Marco Simulation 3-14
3.2.3 Meso Simulation 3-14
3.3 AGENT BASED MODELING 3-14
3.4 SYSTEM DYNAMICS MODELING 3-15
3.5 OUR PROPOSED FRAMEWORK IN THE STATE OF THE ART 3-16
Chapter 4 Methodology **4-18**
4.1 AGENT BASED MODELING 4-18
4.2 SYSTEM DYNAMICS MODELING 4-21
4.3 VISUALIZATIONS AND ANALYTICS 4-23
Chapter 5 Simulation and Results **5-25**
5.1 SIMULATION 5-25
5.2 RESULTS 5-25
Chapter 6 Conclusion and Future Work **6-29**
6.1 CONCLUSION 6-29
6.2 FUTURE WORK 6-30
References **6-31**

List of Abbreviation

ABM	Agent Based Modeling
SD	System Dynamics
UN- SGDs	United Nations Sustainable Development Goals
M&S	Modeling and Simulation
WHO	World Health Organization
MAF	Million Acre Feet
IoT	Internet of Things
SM	Smart Metering

List of Tables

Table 1: Literature Review 3-11
Table 2: Availability Probability of Different Age Groups 4-18
Table 3: Consumption Rates for Different Activities 4-22
Table 4: Pseudo code 4-24

List of Figures

Figure 1: Change in water scarcity in the world (year 2010-2050) [1]..........................1-2
Figure 2: Modeling & Simulation Tool Visualization... 2-10
Figure 3: Graphical Simulation Output [19] 2-10
Figure 4: State Chart of a Person 4-20
Figure 5: Probability of Household Water Utilization [40] 4-20
Figure 6: Percentage of Water Utilized in Different Household Activities 4-21
Figure 7: Stock and Flow Diagram of Water Consuming Entities in a Typical House 4-22
Figure 8: Array of Houses in a Typical Urban Infrastructure................................... 4-22
Figure 9: Visualization and Analytics Framework 4-23
Figure 10: Water Consumption of a Typical Household with 1 Person 5-25
Figure 11: Water Consumption of a Typical Household with 10 Person 5-26
Figure 12: Average Daily Water Consumption of 10 houses (Islamabad, Pakistan) for a Period of 7 Days 5-26
Figure 13: Average Daily Water Consumption of 10 houses (Islamabad, Pakistan) for a Period of 30 days 5-27
Figure 14: Average Yearly Water Consumption of 10 houses (Islamabad, Pakistan) for a Period of 1 year 5-27
Figure 15: Annual Temperature of Islamabad (Pakistan) 5-28
Figure 16: Average Yearly Water Consumption of 50 houses (Islamabad, Pakistan) for a period of 1 year... 5-28

Abstract

Pakistan is rapidly becoming a water stressed country, thus affecting people's well-being. Authorities are faced with making drastic water conservation policies towards 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, due to which we are unable to monitor and manage our water resources efficiently. Smart meters are very expensive, installation of smart meters in an urban infrastructure of a country like Pakistan is not possible at this level. To achieve this goal, we propose a hybrid modeling and simulation framework, consisting of: (i) Agent-Based Modeling (ABM) paradigm that takes into account 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 commensurate with water supply availability and to gain insights of the behavior patterns of water consumption in different areas and improve the performance of the water supply process through demand side management. Furthermore, we propose a low cost solution to smart water meter, we propose to develop an IoT kit that will help in collection of water consumption data at entity level. Once water starts to flow through some entity the water flow sensors will signal the kit and will record the quantity as well as the time for which the water was consumed from that entity. Finally, we will be able to generate the demand of water at household as well as that of an urban area and will be able to validate our model.

Keywords: *Agent-Based Modeling, System Dynamics Modeling, Hybrid Modeling*

Chapter 1

Introduction

This chapter provides the information about the topic which is being studied. It describes the definitions and concepts of household water consumption simulation and some preliminaries to get an understanding about this thesis.

Household water consumption simulation is playing a very vital role in simulating household water utilization of a large population or a large urban infrastructure. 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 drastic decline in water quantity and quality. 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. In order to overcome this water scarcity and provision of safe and healthy water to society, we have proposed a framework that will help the water regulatory authorities in overcoming water scarcity and strengthening water governance.

1.1 Water Scarcity

According to a report by World Health Organization (WHO), half of the world population will be living in water stressed areas by the year 2025 [1]. Pakistan, being rich in natural resources, needs to conserve its natural resources. Pakistan is at 17^{th} position in the list of countries which are facing extreme water scarcity and health crisis due to unsafe drinking water [2]. Due to global warming, the condition of Pakistan's natural resources is getting into a new shape, the total available surface water is around 153 Million Acre Feet (MAF) and total land reserves are around 24 MAF. It is assessed that the population of Pakistan will be doubled by the year 2025 and it is expected that Pakistan will face a shortage of 31 MAF by the year 2025, which is a great threat to Pakistan's economy and stability [3].

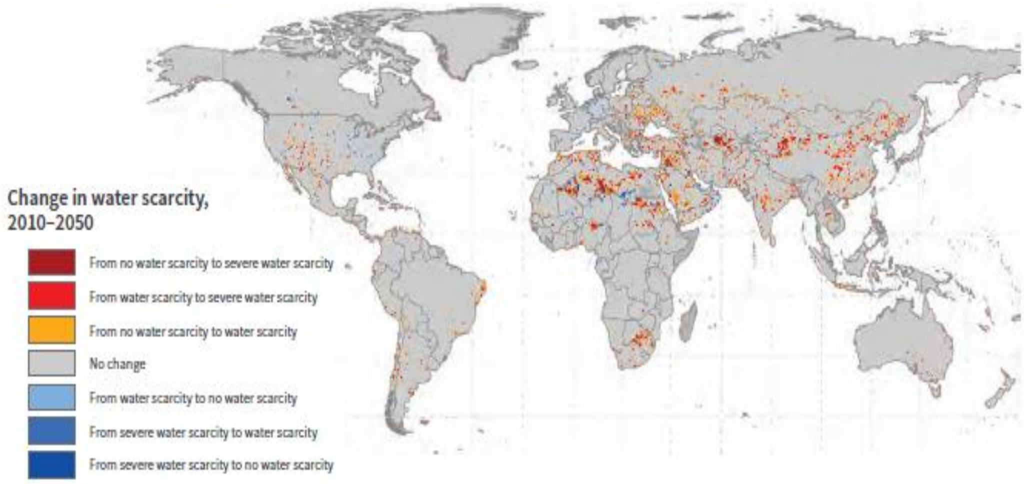

Figure 1: Change in water scarcity in the world (year 2010-2050) [1]

1.2 Challenge

Pakistan ranks 17th in the list of water stressed countries; this water stress is mainly due to Indian obstruction on western rivers. United Nations (UN) report suggests that Pakistan will be facing an extreme water scarcity in the near future [4]. United Nations Sustainable Development Goals (SDGs) were published in the year 2015 with the main objective of transforming the world by the year 2030; it has a total of 17 goals with interrelated targets. The total number of targets that need to be achieved by the year 2030 is 169. All 17 goals are a challenge in themselves A single thesis cannot cover all the 17 goals, but can only target a single goal or a part thereof. We will focus mainly on the development of sustainable cities and communities, which is basically goal number 11 of UN SDGs [5].

1.3 Problem Domain

As the size of human population is increasing day by day, it is being suggested that by the year 2025 the population of Pakistan will get doubled [6]. However, our natural water resources such as rivers and ground water reservoirs will not be able to sustain levels corresponding to the increase in the population. With the increase in population, the water resources are depleting which is giving birth to water scarcity. To save ourselves from this water scarcity, while we need to take measures to conserve our natural resources, we also ought to know as to what our actual requirement is. We need to forecast the demand of water and supply the required amount of water to the end users. If water demand is not forecasted now and if we leave the society at its own, the day is not far away when our urban areas will become similar to Thar desert, where there is no water even to drink. These conditions will lead to poor health and sanitation and ultimately death of human race.

1.4 Problem Statement

The need of the hour is to estimate required amount of water for a particular sector of an urban infrastructure, which leads us to the formulation of our problem statement which is listed below:

“Analysis and estimation of water requirement for household usage and providing required amount of water to a particular sector for an urban infrastructure without smart water metering is a challenging task.”

1.5 Solution Domain

We give a brief overview of the solution to the above mentioned problem in our thesis.

1.5.1 Modeling and Simulation

Modeling and Simulation (M&S) is a technique in which we can model real world scenarios as we cannot afford to find right solution by experimenting with real world objects. Building, destroying or making changes may be too expensive, dangerous or impossible. In modeling and simulation, we can even commit mistakes which, if done in real life scenarios can give devastating results. We can undo things, go back and forth in time, basically it provide a risk-free world where we can find our direction from problem to its solution [7].

1.5.2 Household Water Consumption Simulation

Water consumption simulation is of great importance, as water in consumed in various areas such as homes, industry, agriculture and livestock and in order to study one of these areas, water consumption simulation can prove its worth in this regards. As our area of study is domestic or household water consumption, a water consumption simulation system can help in monitoring and managing household water consumption activities and help water regulatory authorities in effective management of water resources and delivery of required water to end users.

1.6 Solution Statement

It is not possible for us to study utilization of household water in such a large urban infrastructure, where there are different family sizes, people belong to different age groups and water consumption activities of every individual vary as per different routine of an individual. Modeling and simulation plays an essential role in modeling this real-world scenario in virtual world with some abstractions to analyze the consumption of water at household level and forecast the required amount of water that needs to be delivered to the end user in an urban infrastructure.

A hybrid modeling technique consisting of Agent-Based (AB) and System Dynamics (SD) modeling was used to develop a framework for analyzing water consumption activities in a house. AB and SD water simulation and analysis framework uses Anylogic built-in features and library to simulate household water utilization.

1.7 Key Contributions

We propose a hybrid agent-based and system dynamics household water consumption simulation and analysis framework that encompasses (i) model person, state of a person and houses as agents, because every individual is different from the other and similarly water consumption activities of an individual also vary (ii) model the reservoirs, overhead water tank and other water consuming entities (such as faucets, shower, toilet, dish washing, outdoor water utilization etc.) in system dynamics, as consumption of water is dynamic in nature. SD modeling best models the utilization of water in various household water consumption activities (iii) Developed front end using Anylogic for the regulatory authorities to best monitor and fulfill the water demand of the end users.

1.8 Research Impact

Our proposed framework will help water regulatory authorities in overcoming water scarcity with an effective management of water resources. It will provide better insights for the regulatory authorities to forecast the future water demand of an urban area, which will lead to good health and sanitation conditions of a society. It will also help in attaining the title of sustainable cities and communities and will ultimately lead to transforming the world by achieving sustainable development goals.

1.9 Thesis Organization

The organization of the thesis is as follows:

1.9.1 Chapter 2: Background

Chapter 2 provides brief overview of household water consumption simulation and experiments for the analysis of insights of water supply and management. Moreover, few water consumption simulation models and preliminary concepts used in methodology chapter have also been discussed.

1.9.2 Chapter 3: Literature

This chapter explains the work done so far which is related to household water simulation and analysis framework. The formulation of the thesis and the novelty of the thesis lie in identifying the research gap from the literature already published. The identification of the direction of research is also one of the sanctions of literature.

1.9.3 Chapter 4: Methodology

Our proposed simulation and analysis framework has been presented in this chapter. Moreover, the tool used for the development of framework and built-in libraries of the tool used for developing the model, are presented here. Furthermore, the input parameters required to drive the framework are also presented in this section.

1.9.4 Chapter 5: Simulation and Results

The functionality of our proposed framework is described in this section. The inputs which the framework requires and the output which our framework provides, the simulation of our frame work and the visualizations which our framework provides are all presented in this chapter.

1.9.5 Chapter 6: Conclusion and Future work

The tasks completed during the course of this thesis are presented in this chapter. The conclusion of our work and the future work which is to be carried out is presented in this chapter.

Chapter 2
Background

This chapter provides the information about the topic which is being studied. It describes the definitions and concepts of water consumption simulation and some preliminaries to get an understanding about this thesis.

2.1 Water Supply and Management

Water supply and management is becoming a major issue due to climate change, depletion of natural (water) 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 [8]. In most parts of the urban regions of Pakistan, there are no proper authorities to meter water and regulatory authorities have no data on water consumption and required water supply. Installing Smart water meters requires significant funding and time commitment. It is therefore an urgent need to forecast the exact household water demand, in order to best manage available water resources. 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 [9].

Modeling and Simulation enables us to replicate a real-world's system for suitable risk-free dynamic experiments [10]. Simulation models of water consumption deal with modeling of individual's characteristics and water consumption behavior as agents, as well as the modeling external environment, supply process and water flow as system dynamics. These external factors have significant importance in analyzing behavioral aspects [11]. 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 consumed. Modeling water consumption of different consumers such as: domestic, commercial, industrial and agricultural sectors, helps in forecasting water demand by performing activity-based consumption and reveals insights of the demand dynamics [12].

2.2 Household Water Consumption Simulation

"Household water consumption simulation is the process of simulating the flow of water in different household water consuming entities. It also helps in monitoring and effective distribution of water resources [13]."

In the past few years, efforts have been made to simulate the flow and behavior of water utilization in household activities. Virtualizations of human characteristics to simulate water consumption in house is widely used to create models and frameworks that can help in attaining the required demand supply curve of water utilization in a particular house. It also helps in forecasting water demand for the future, which ultimately helps in designing an urban infrastructure. It is becoming a prevalent area of interest for the researchers and stake holders of urban development, as water is of great importance in an urban infrastructure. Safe and healthy drinking water, sanitation, healthcare and education are the building blocks of an urban infrastructure where a lack of even a single factor can lead to devastating results. Water consumption simulation is also playing an important role in development of smart household water utilization entities such as smart shower, smart faucets etc. These entities help in conservation of water and hence pave the way to a sustainable and a resilient urban infrastructure.

Household water simulation deals with modeling of individual's behavior and characteristics as well as the building characteristics and external environment as these are important factors to develop realistic models. Water utilization depends mainly on behavior, characteristics and external factors. These external factors have a significant importance in analyzing behavioral aspects [14].

2.2.1 Household Water Consumption Simulation Models

Some household water consumption simulation approaches are described below by mentioning how water is simulated and what factors are the driving force of household water simulation in an environment. Three major household water simulation and modeling approaches are discussed below.

2.2.1.1 Agent-Based Modeling Approach

Agent Based Modeling ABM is used to create malleable perception of the real world. Agent-based models are mostly composed of: (i) number agents; (ii) decision-making heuristics; (iii) adaptive processes; (iv) interaction and (v) environment. The term agent based is significantly important as these models are micro models, meaning thereby these incorporate all the characteristics of an entity taking into account every single detail that may be necessary for proper functioning of the system. For example, if we are trying to replicate human behavior, it will take into account all the characteristics of a human such as its age, weight, height, his nature of job and other related factors. In view of all this, experiments with the ABM allow us to improve our intuition and understanding of the overall domestic water system [15].

2.2.1.2 System Dynamics Modeling Approach

System Dynamic is a mathematical modeling technique for modeling complex systems. System Dynamics is one of the aspects of system theory and deals with dynamic behavior of complex systems [16]. Elements of System Dynamics are stocks, flows and feedback loop systems. Stock and flow help in analyzing the system in a quantitative term; stock is the term used for any entity that diminishes or accumulates over time and flow accounts for the rate of flow. A complex system such as an eco-system or a mechanical system can be represented by causal feedback loop. There are two types of reinforcement in causal loop systems - positive reinforcement and negative reinforcement. These reinforcements create a balance in the system by depleting some factors from the system and by accumulation of some of the factors in the system while the overall system remains in equilibrium.

2.2.1.3 Hybrid Modeling Approach

Hybrid modeling approach is used when we need to take advantage of more than one modeling technique. Agent base paradigm is used to create models that mimic human behavior and characteristics such as the age group of person, his hours of work and ethical values of the society. System Dynamics paradigm will help in modeling the nonlinear behavior of complex system over time such as the amount of water consumed in a particular activity over a period of time can only be modeled using system dynamics modeling paradigm. Moreover, hybrid paradigm takes into account all the characteristics which are directly or in directly involved in consumption of water. Model developed using hybrid paradigm will be more accurate and precise as compared to a model developed using a single paradigm [17].

2.3 Household Water Consumption Modeling Tools

Different tools have been developed to simulate household water consumption. These tools allow modelers to model virtual environments for experimentation, effective management and forecasting of household water utilization and demand.

2.3.1 AnyLogic

AnyLogic is a versatile modeling and simulation tool developed by The AnyLogic Company [18]. It allows modeler to model complex systems with conformity and accuracy because of the built-in libraries provided by Anylogic. It supports agent-based, discrete event, and system dynamics simulation methodologies. Anylogic is used to simulate wide range models such as manufacturing, supply chain and logistics, health care, business processes, aerospace, safety and security and many other real world scenarios.

AnyLogic is a simulation tool with graphical interface that allows modeler to quickly model complex environments. Anylogic Simulation environment provides both a user friendly Integrated Development Environment (IDE) as well as an efficient simulation engine. We can also develop complex hybrid models with the combination of discrete event, agent-based and system dynamics [10]. Anylogic provides user-friendly interface, Java-based development environment and a set of multipurpose component libraries, which all together help in making modeling process robust. It also facilitates modeler to integrate simulations with external environments.

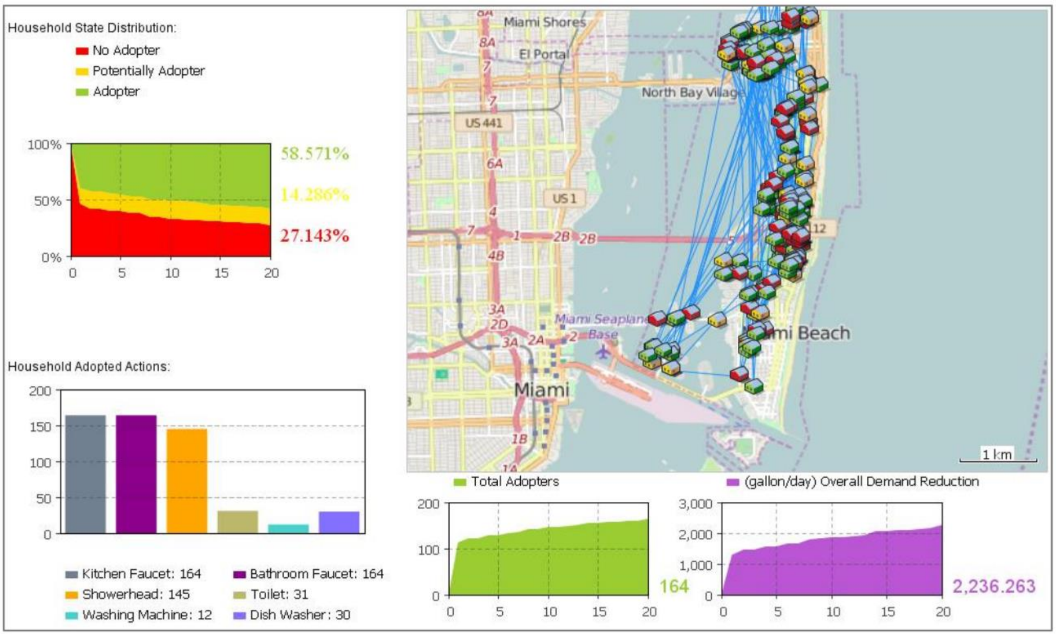

Figure 2: Modeling & Simulation Tool Visualization

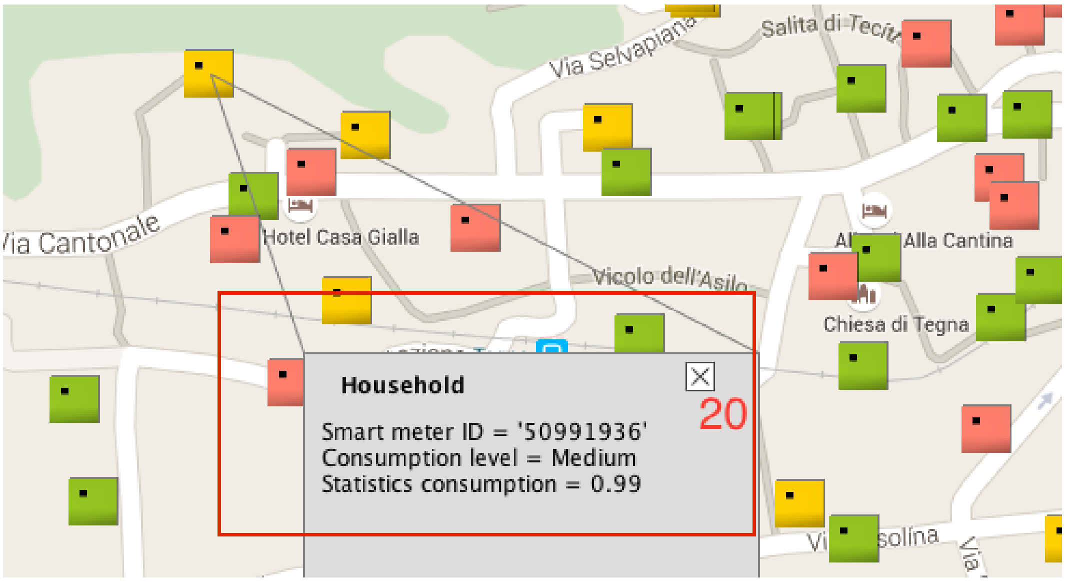

Figure 3: Graphical Simulation Output [19]

In this research we are using Anylogic simulation software for the development of our proposed framework. Its rich features help us to build complex simulations robustly. We can design custom agents in Anylogic using agent-based paradigm whereas other complex systems of the model can be modeled using system dynamics paradigm.

Chapter 3
Literature Review

This chapter explains how related is our work with that of others. Moreover, it also contributes in the understanding and development of the area of research.

Table 1 summarizes different research clusters of the literature reviewed during the course of literature reviewed. Details of the papers are described later.

Table 1: Literature Review

Author (s)	Category	Paper Description	Key Features
[20]	**Water Supply & Management**	Explained the advantages of calibration in modeling	Described statistical measures of goodness of fit, continuous calibration can remove biasness from the system. Continuous calibration provides better representation of typical annual flow
[8]		A framework that logically relates the emerging threats, the intervening water system and its impact on social, economic and environmental consequences	Key features are graphical illustration of used interventions and how they are related to other components in the framework
[21]		A framework which takes into account water resources and management of these resources to overcome water stress in an urban infrastructure.	Describes strategic management of water resources to overcome water stress by taking into account economic activities, geographical and financial limitations.
[14]	**Household Water Consumption Simulation**	Stochastic activity based energy and water consumption	Describes the engineering design of model that caters occupant's energy related and water consumption needs and activities of occupants
[13]		Intelligent Software Simulation of Water Consumption in Domestic Homes	Proposed a software solution which aims at reducing the water consumption according to daily basic activities and needs. The management is about predicating the task which must be allowed to satisfy most of the daily tasks while conserving water
[12]	**Agent Based Modeling**	Provides a framework which simulates hourly water using activities of occupants in behavioral context	Provided a framework which works on micro level simulation because it takes into account the characteristics of a person, ranging from availability to household water consumption

			behavior.
[22]		Provide an agent based framework while integrating different sub models	It adopted and integrated social sub model, models of urban dynamics, water consumption, technological and opinion diffusion making it an agent based model which is in turn linked to geographical information system
[23]		The paper integrates and simulates two modeling tools i.e., social simulation model and an urban water management tool	The integration of Urban Water Agents Behavioral Model (UWAB) and Urban Water Optioneering Tool (UWOT) provides better understanding of the system by changes and incremental adjustment of management decision based on learning outcomes
[24]		An agent-based framework to provide a reliable support for the decision making processes for water conservation	Agent based modeling using interactive components to simulate complex system. A powerful tool to help setup rules based on timings of flow, water demand and environmental concerns
[25]		An agent-based model to predict water demand of the future using stochastic behavior and feedbacks	Developed a model for regulatory authorities to predict water demand by using two agent roles; (i) government agent and (ii) household agent
[26]	**System Dynamics Modeling**	Proposed a strategic level asset management decision support system using causal feedback loop systems	Developed a decision support system using causal feedback loop system for stakeholders to evaluate various water management strategies
[27]		Micro level system dynamics simulation tool for water management	A model that performs micro level simulation by taking into account factors such as income, water price, leakage using causal feedback loop system to solve water management problem
[28]		Development of the Kirkwood water demand system model for water management	K-DEM model proposed a framework for policy analysis in light of the issues being faced by the municipality
[16]		A framework that will provide a sustainable urban infrastructure using system dynamics modeling	A system dynamics model that takes into account social, economic, environmental and life-style factors to effectively deal with the complexities of an urban infrastructure
[17]	**Hybrid Modeling**	Developed a hybrid Agent-Based Model DAWN for evaluating water pricing policies	A hybrid model that takes into account residential water demand, social influence and pricing policies

3.1 Water Supply and Management

Water supply and management is becoming a big issue in this era; due to many reasons such as climate change, depletion of natural resources and urbanization. Water, being a very important entity for existence of human life, calls for drastic measures to take this problem into account. It is the need of the time that water regulatory authorities should be able to forecast the future demand and be able to propose a resilient and a sustainable infrastructure in order to provide reliable water management. Regulatory authorities need to look into the factors which are responsible for variation in water consumption These factors may be social, economic or environmental [8]. Water management may also include waste water treatment, water reuse and water billing as per units of water consumed and also per the unit of waste generated [29].

3.2 Household Water Consumption Simulation

Simulation and modeling enables us to choose the right constructs of the modeling language and to replicate a real world system for suitable risk-free dynamic experiments [30]. The modeling of domestic water consuming entities and water resources and the simulation of these can help in monitoring and management of water resources. It is basically a software solution for monitoring and management of water resources. It provides a control over consumption by predicting the tasks which are necessary for satisfying the volumetric flow consumed [13]. This can help the regulatory authorities in providing water without any interruption which can satisfy a large number of tasks without undue use. We can also go into details by adding a number of variables and parameters. We can take into account details such as activities of users and in which activity how much water is being consumed, behavior and characteristics of users, time of an activity, hourly water utilization in an activity etc. Yannou et al. proposed that all these factors, when taken together, can produce a framework which will produce the results that are much close to the original results and help in forecasting future demand [14].

3.2.1 Micro Simulation

Microscopic models help in simulating real-world problems with such accuracy that the results generated by these models are very much close to actual results, as these take into account every small detail which can produce minor deviations from the actual result if not considered. For example, in case of water simulation, if we cater for leakage, Williamson propose that it can produce much better results that are much close to the actual results [31].

3.2.2 Marco Simulation

Macro simulation works on abstract level as it does not take into account small details. It abstracts all the details, focuses on modeling a real world system which can produce similar results in simulation. Athanasiadis et al. propose that these models do not take into consideration the behavior and characteristics of a person, instead they only focus on modeling the household water consuming entities [32].

3.2.3 Meso Simulation

Meso simulation fills the gap between micro and macro simulation. This category deals with modeling individual's interaction and behavior at a lower level of detail. According to Szczeniak et al. in meso water simulation, agents can be generated with some characteristics and behavior of household water consumption, however, small details such as age group of a person and other minute factors can be ignored in meso simulation [33].

3.3 Agent Based Modeling

An agent-based model (ABM) is a class of models meant for simulating the actions and interactions of autonomous agents - either individual or collective entities, with a view to assessing their effects on the system as a whole [34]. 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. Agent based modeling is a modeling paradigm in which individuals, their interaction with each other and their environment are represented as an agent [35]. ABM offers a toolkit for behavioral science which can help in developing models as to how individuals interact and what is the behavior and organization which materialize from these interactions. Williamson explores leakages in domestic water consumption scenarios [31]. Similarly, Berglund discussed different case studies to demonstrate the use of reactive and active agents for simulating water resources planning problems [9]. The modeling of water consuming entities and water resources at domestic level is an essential part of studying this behavior, as proposed by Zaher, et al. [13]. Linkola, et al. 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 [12] . Darbandsari, et al. proposed an urban household behavioral model applied to the western area of Tehran metropolitan in Iran for finding the best effective water consumption management policies under different climate conditions [36]. 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 [23]. 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. In Meso water 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 [33]. Gala proposed a framework that integrated GIS and socio-economic information databases on the metropolitan area of Valladolid. They illustrated ABM as an integrative paradigm. They proposed that an increase in population does not necessarily increase water consumption by the same proportion. They also analyzed the impact of external pressure of behavior diffusion on water consumption which concluded that if behavior diffusion is combined with technological diffusion it can contribute a lot in water saving [22].

3.4 System Dynamics Modeling

System dynamics (SD) is a macro simulation approach used in understanding the nonlinear behavior of complex systems over time using stocks, flows, feedback loops, and time delays [37]. SD works on a higher level of abstraction (i.e., lesser details). It aggregates the system entities by excluding the microscopic details and only incorporating key aspects of a real world system. These models do not take into consideration the behavior and characteristics of individual people, instead focuses on modeling the household water consumption [32].

Ganjidoost, et al. proposed the application of system dynamics modeling approach for studying a network of water distribution and wastewater collection. 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 [26]. Palmer, et al. proposed a system dynamics model which included impact of household receiving water and sanitation services. It proposed rainwater harvesting as an alternate to water supply [28]. 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 [38]. Complex systems can be developed using system dynamics modeling.

3.5 Hybrid Modeling

Hybrid modeling approach is used when we need to take advantage of more than one modeling technique. Agent base paradigm is used to create models which mimic human behavior and characteristics such as the age group of person, his hours of work and ethical values of the society. System Dynamics paradigm will help in modeling the nonlinear behavior of complex system over time such as the amount of water consumed in a particular activity over a period of time which can only be modeled using system dynamics modeling paradigm. Moreover, hybrid paradigm takes into account all the characteristics which are directly or in directly involved in consumption of water. According to Athanasiadis et al. models developed using hybrid paradigm are more accurate and precise as compared to a model developed using a single paradigm [17].

3.6 Our proposed framework in the State of the Art

Hybrid modeling approach integrates Agent-based modeling with System dynamics to exploit the potential of both paradigms. ABM focuses on microscopic details of the system whereas SD aims to aggregate the modeling details at macro level. Former provides the advantage of capturing essential details at entity level models that mimic human behavior and characteristics such as the age group of person, consumption habits, ethical values of the society etc., however it suffer from performance issues specially when dealing with large-scale population. Latter has an edge in building large-scale long-term models and helps in modeling the nonlinear continuous behavior of 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, either most of the existing simulation models focus on agent based modeling or on system dynamics modeling, but not on both. We, therefore, propose a hybrid model based on the combination of ABM and SD. ABM paradigm is used to model the agents, such as persons, houses and the neighborhoods as entities using state-charts. While, SD paradigm is used to model complex behavior of water supply and management using stocks and flows.

Hybrid modeling approach is used when we need to take advantage of more than one modeling technique. Agent based paradigm is used to create models that mimic human behavior and characteristics such as the age group of person, his hours of work, ethical values of the society etc. System Dynamics paradigm will help in modeling the nonlinear behavior of complex system over time. The quantity of water consumed in a particular activity over a period of time can only be modeled using system dynamics modeling paradigm. Moreover, hybrid paradigm takes into account all the characteristics which are directly or in directly involved in consumption of water. Model developed using hybrid paradigm will be more accurate and precise as compared to a model developed using a single paradigm [32].

Chapter 4
Methodology

In this chapter we propose a hybrid Agent-Based Modeling (ABM) and System Dynamics (SD) approach in developing the proposed simulation framework.

Our proposed framework is composed of three modules

1. Agent Based Modeling
2. System Dynamics Modeling
3. Visualizations and Analytics Module

4.1 Agent Based Modeling

Agent Based 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 the Figure 4. Major water consumption activities in a household are kitchen, faucets, laundry, bathing, toilet and outdoor usage. Water consumption activities follow some stochastic patterns including probabilities of occurrence, time of occurrence and average duration of these activities. We also modeled different types of persons: infant, child, teen, adult and elder. We include the probability of person's availability in the house during 24 hours. The availability and consumption behavior is represented in Table 2.

Table 2: 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

Household water consumption depends on the type of the person. Person can be of a different age group, employed or can remain in their houses. Water consumption in a house varies with the state of the person. Water will only be consumed in a household activity if person is available in the house, 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 in their homes 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 [12].

Utilization of water in household activities is carried out with some probabilities of utilization. Every household's water consuming activity has different times of occurrence as different water consuming activities are triggered with some probability of occurrence [39]. The behavior of each individual is modeled using a state chart, where: (i) States represent different activities; (ii) Transitions are guarded by the conditions of the occurrences of activities and time-out durations of each activity. When a person is consuming water, his state transits to the corresponding activity state. An individual can either be idle or performing some water consuming activity, but an individual can only switch to one water consuming activity at one time. The behavior of water consumption of a person is represented by the state-chart in Figure 4. When a person enters into an activity, it triggers the rate of consumption of the respective activity in the house component and assigns a non-zero consumption rate, which causes the flow of water from the roof-top tank and simulates water consumption.

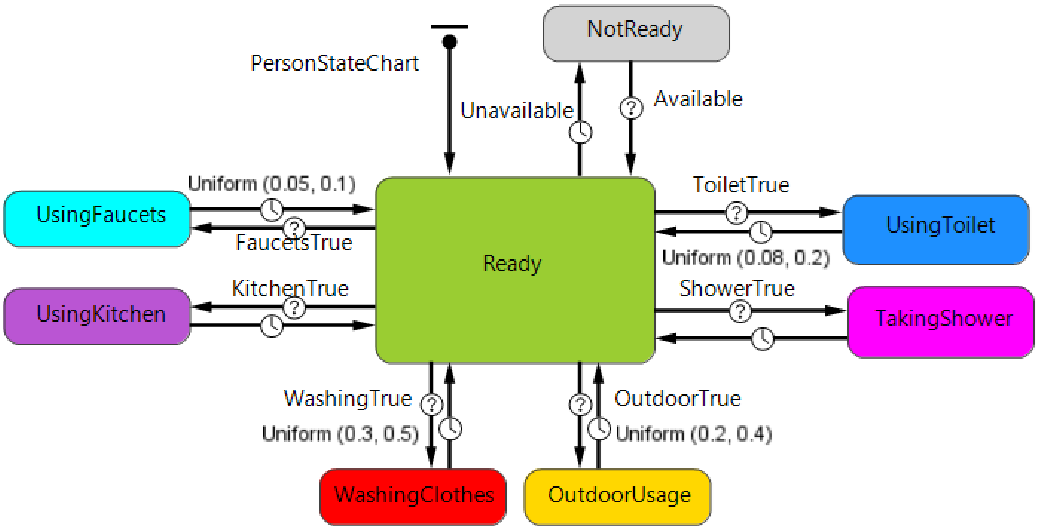

Figure 4: State Chart of a Person

Each water consuming entity has different water consuming probability and the time duration. The probabilities are as shown in Figure 5. These probabilities are based on California Single Family Water Use Efficiency Study (Andrew & 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 as shown in Figure 6.

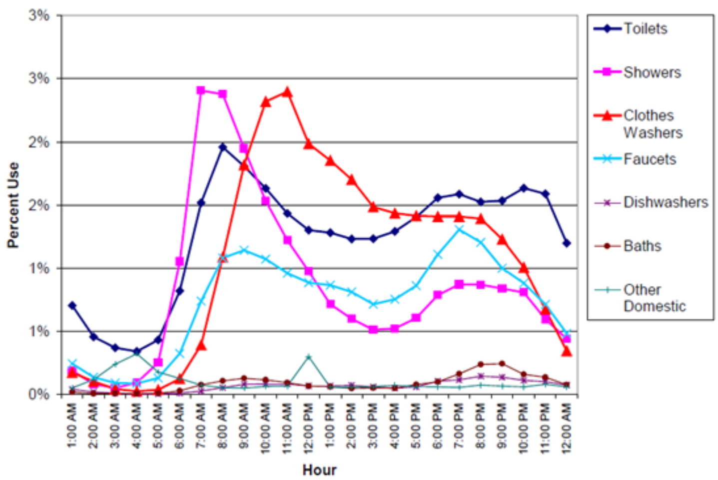

Figure 5: Probability of Household Water Utilization [40]

Similarly there are other factors too that account for the consumption of water in a house such as the norms of the society, type of the house one is living in and the architecture of the house. In our framework we have also included maximum number of times a household's water consumption can be carried out like some activities which occur on weekly basis such as outdoor water utilization and laundry.

We have made our model sensitive to temperature by incorporating temperature into it. According to [41] energy, water consumption varies with variation in temperatures in households, work places, neighborhood, etc. Therefore water consumption is directly dependent on temperature. All these factors are incorporated in our framework for the prediction of water consumption over a period of time.

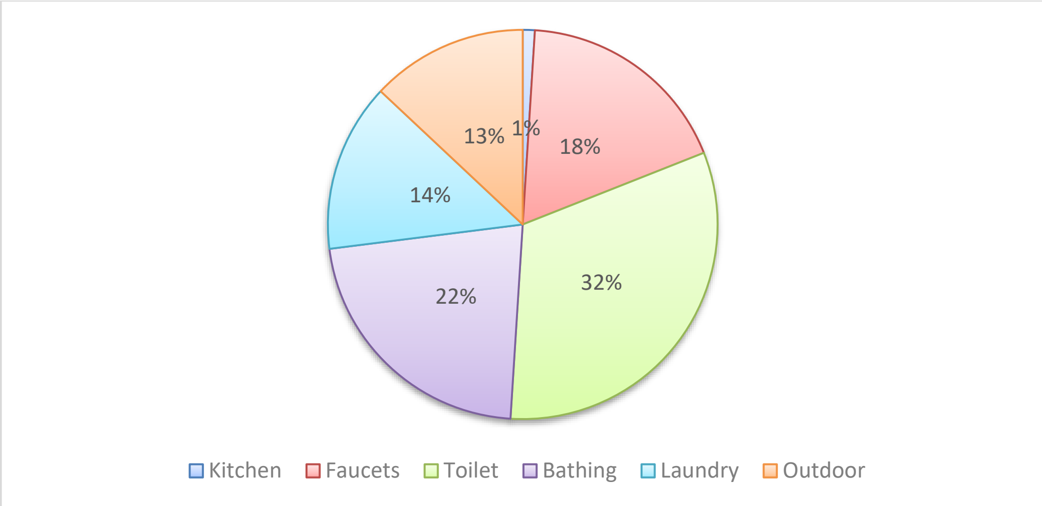

Figure 6: Percentage of Water Utilized in Different Household Activities

4.2 System Dynamics Modeling

We use System Dynamics approach to model the house components, which consist 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 7. A typical house will have a random number of individuals (person agents) and thus may have a demand profile different from another house. 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 varies 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 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 8 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

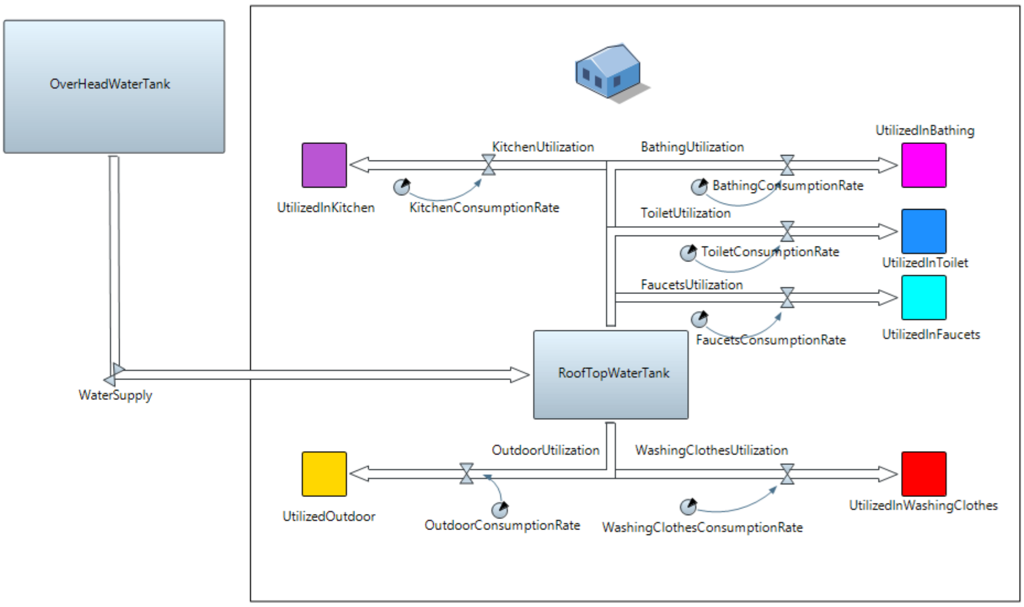

Figure 7: Stock and Flow Diagram of Water Consuming Entities in a Typical House

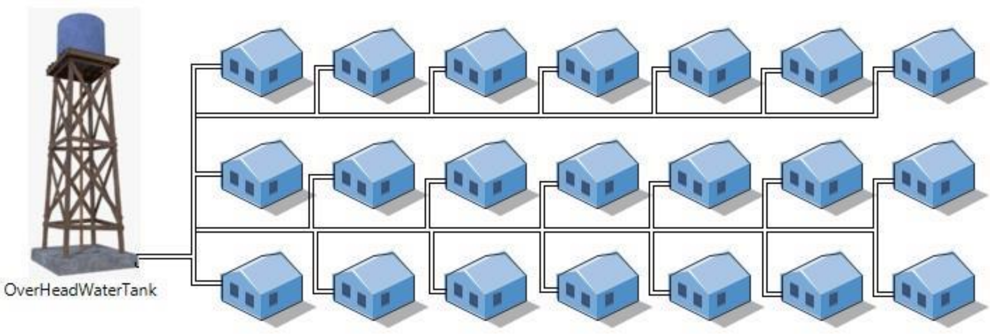

Figure 8: Array of Houses in a Typical Urban Infrastructure

Each water utilization activity is controlled by some parameters; parameter values are linked to person states. Whenever a person enters a specific state, parametric values come into action and water is consumed from the water tank of the house. Each household water utilization activity has a specific time duration for which the activity is carried out, after that particular time the system switches its state either from that activity to another activity or it switches to idle state where no water utilization is carried out.

4.3 Visualizations and Analytics

Water regulatory authorities such as Capital Development Authority (CDA) will be provided with the visualization dashboard. It will provide visualizations of the daily, weekly, monthly and yearly water consumption profiles of the specified area and will help in monitoring and management planning of water resources. This module will allow 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 9 shows the visualization and analytics framework process.

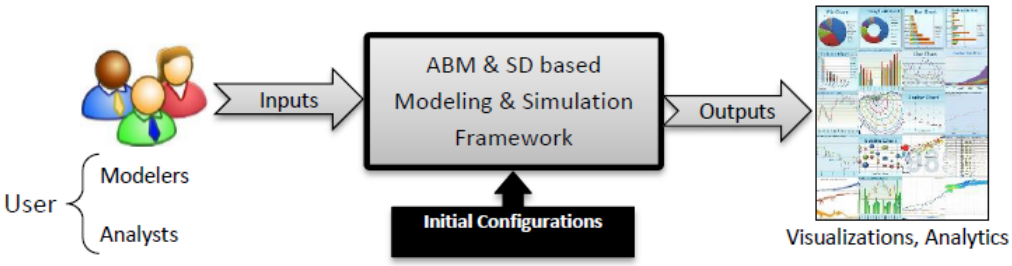

Figure 9: Visualization and Analytics Framework

We use Anylogic Software [42] for the development of the household water consumption simulator.

Anylogic provides built-in plots and charts to visualize output at run time. These plots and charts are linked to inputs via some parameters or functions and we can also edit graphically these outputs charts, plots or histograms in Anylogic editor. Final output is displayed as Model User Interface at run time.

Table 4: Pseudo code

```
Algorithm 1: Behavioral Household Water Consumption

Input: P, H, T ▷No of Persons, No. of Houses, Temperature data
Output: TotalConsumption

For i= 1 to P Length
   p ← P[i]
   PersonType ← GetPersonType(p)  ▷Types = {Infant, Child, Teen, Adult, Elder}
   Availability ← RandomTrue(AvailiabilityProbability(PersonType))
   If Availability = True then
      Activity ← RandomTrue(ActivityProbability(PersonType))
         If Activity = Bathing & T > 18° C
      ConsumptionRate ← GetWaterConsumptionRates(Activity)
      ActivityConsumption ← ConsumptionFlow(ConsumptionRate)
         end If
      TotalConsumption = Sum (ActivityConsumption)
   end If
Return TotalConsumption
```

Chapter 5

Simulation and Results

In this section, we demonstrate the functionality of our proposed framework. We simulate the scenario of household water utilization in an urabn infrastructure, to help regulatory authorities in forecasting water demand and effective management of water resources.

5.1 Simulation

Initially we ran a simulation of 10 runs for one house of 10 persons (with different types) over a period of 24 hours to visualize the pattern of consumption of different household water consuming entities. Once the utilization pattern was recognized we ran simulation of 10 runs each for a period of 1 week, 1 month and 1 year respectively. Initially the population of houses was kept 10 houses in each simulation and finally we simulated our frame work for a simulation of 10 runs for a population of about 50 houses in order to generate and forecast the demand profile of an urban infrastructure. Results of the simulations are discussed in the following section.

5.2 Results

Figure 10 shows the average utilization of water consumption of different activities of a single house with 1 occupant.

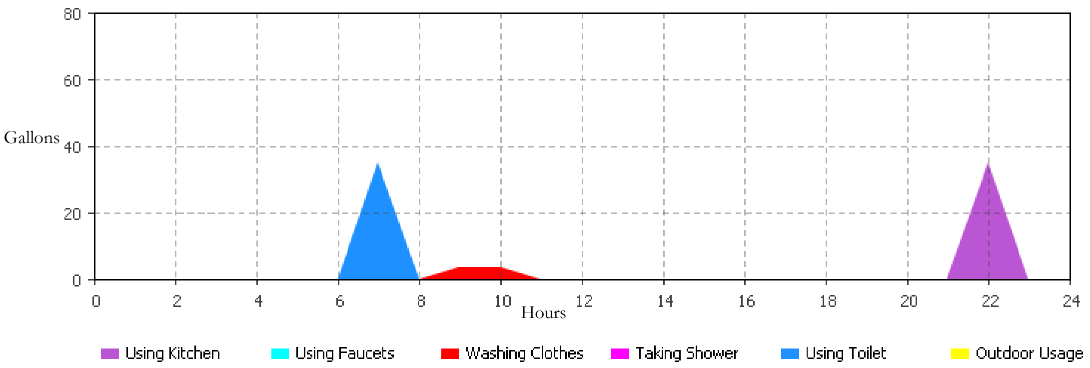

Figure 10: Water Consumption of a Typical Household with 1 Person

Figure 11 shows the average utilization of water consumption of different activities of a single house with 10 occupants.

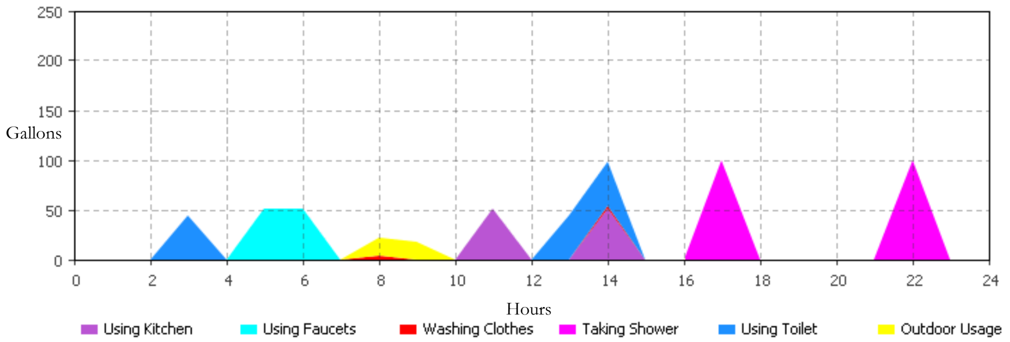

Figure 11: Water Consumption of a Typical Household with 10 Person

It can be seen in the graph that water consuming entities in different household occur at different times of the day as each activity has a different probability of occurrence and a different value of gallons consumed per hour. Maximum water is consumed in toilet activity as the frequency of toilet utilization is maximum. Shower/bathing is the second largest water consuming activity. Similarly, water consumption is minimum in case of laundry and outdoor utilization.

Once we have observed the pattern of water consumption in a single house over a period of 24 hours, we extend our model to simulate our framework over a period of one week as shown in Figure 12.

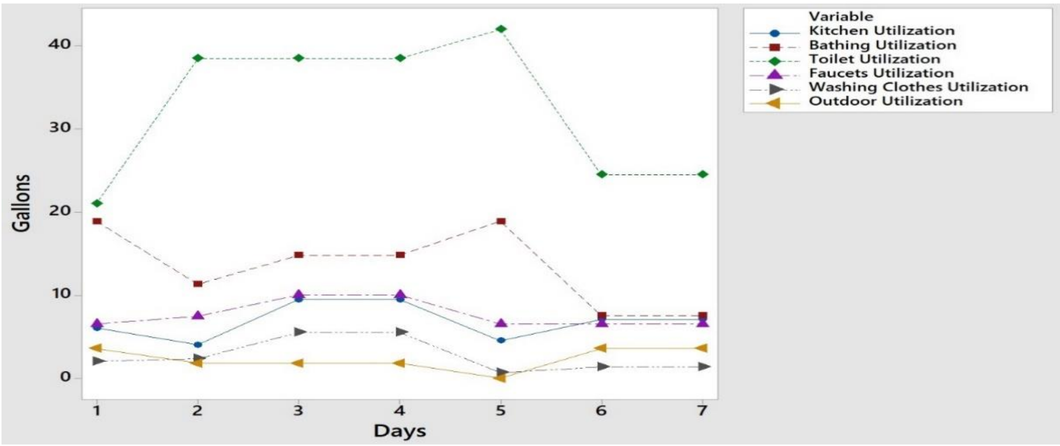

Figure 12: Average Daily Water Consumption of 10 houses (Islamabad, Pakistan) for a Period of 7 Days

Similar pattern is observed in the plot of water consumption generated over a period of one week. It is evident from the plot that maximum quantity of water is consumed in toilet and bathing activities respectively. Similarly, minimum water is consumed in laundry and outdoor water utilization activities.

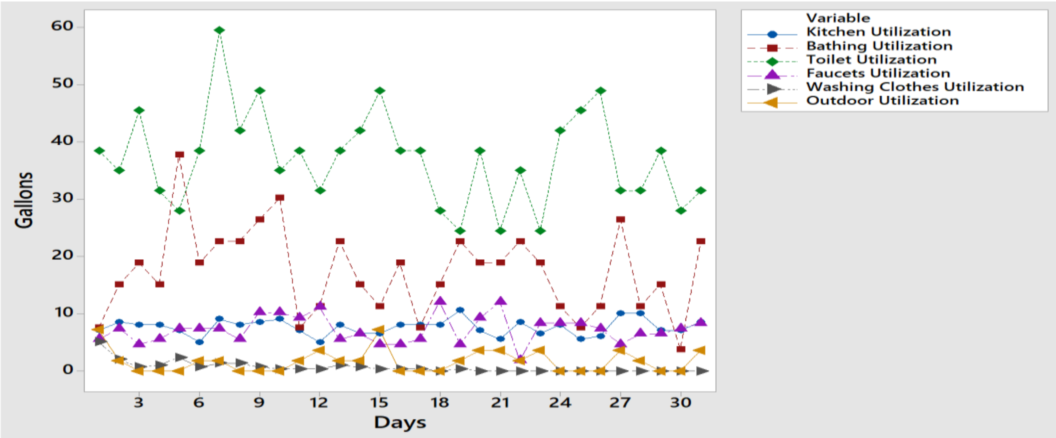

Figure 13: Average Daily Water Consumption of 10 houses (Islamabad, Pakistan) for a Period of 30 days

Similarly, we ran our simulation for 10 runs, the number of houses in each run were kept 10 to generate the water consumption graph of a month as shown in Figure 13. Same pattern was observed in the monthly graph of water consumption as it was in daily and weekly graph.

Once the pattern was recognized, we aggregated the activity wise water consumption to early consumption in order to get the demand profile of an urban infrastructure. Figure 14 shows the average yearly water consumption of 10 houses.

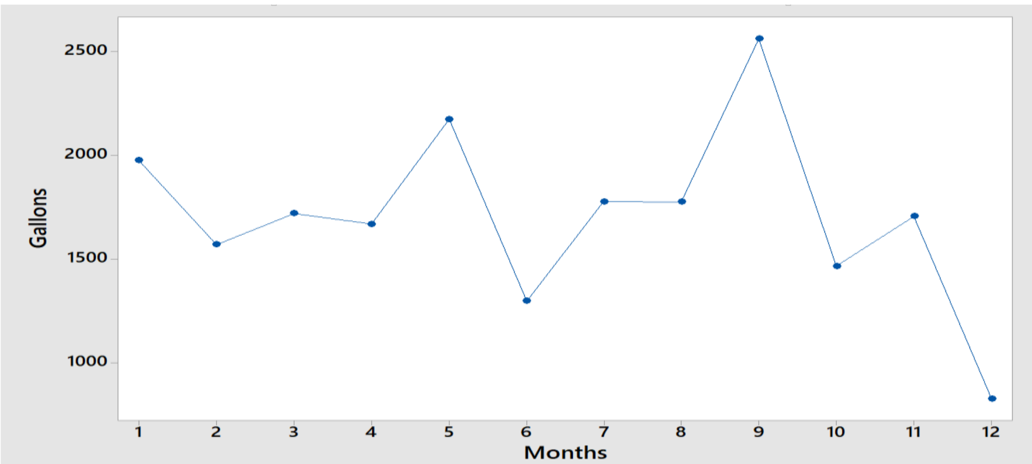

Figure 14: Average Yearly Water Consumption of 10 houses (Islamabad, Pakistan) for a Period of 1 year

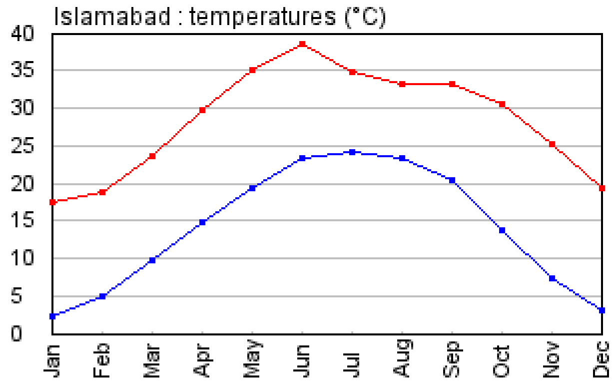

Figure 15: Annual Temperature of Islamabad (Pakistan)

It is evident from Figure 15 that water consumption increases with the increse in temperature. The decrease of water consumption at noon is due to the reason that person or persons are not availble in the house. As soon as a person is available in house, the water consumption tends to increase with the increase in temperature.

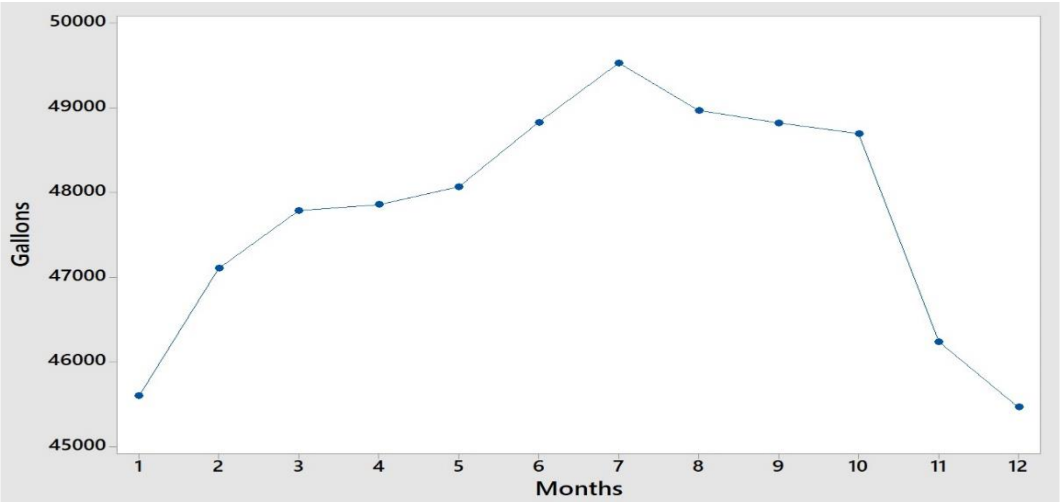

Figure 16: Average Yearly Water Consumption of 50 houses (Islamabad, Pakistan) for a period of 1 year

It can be seen in Figure 16 that once we run the simulation for more than 1 runs for a period of year, simulation results start to get better and simulation curve fits on the temperature curve. Figure 15 shows the annual temperature of Islamabad (Pakistan).

Chapter 6

Conclusion and Future Work

This chapter provides the discussion, conclusion and future work of the thesis.

6.1 Conclusion

In this chapter, 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. Our framework which 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 (iii) Visualization and analytics module which allows the modeler to analyze and forecast demand and supply of water in an urban infrastructure.

It can be analyzed and proved through this framework as to which water consuming entity contributes to which extent in the utilization of household water. It can be seen in all the graphs, whether they are on daily, weekly or monthly basis; the activity which is contributing the most towards water utilization is toilet utilization and bathing respectively. Maximum quantity of water is utilized in toilet due to frequency of its use, toilet is utilized from 10 to 12 times in a typical house. As far as the utilization of bathing/shower is concerned, the shower head remain open for 10 to 12 minutes on an average because of which this much quantity of water is utilized in bathing activity. On the other hand, minimum utilization consists of laundry and outdoor utilization, the reason behind this is again the frequency of use. As laundry and outdoor utilization take place only once or maximum twice a day, hence due to this reason these activities have minimum water consumption. The simulation framework will help develop strategies/policies for preventive demand side management as well as better planning for supply and resource management.

6.2 Future Work

In future, we will be developing an observational technique to collect real-time data of water consumption using Internet of Things (IoT) kit. This will help in the validation and calibration of model with actual data. Once the simulation framework is validated for the behavioral analysis of water consumption at domestic sector, it can be easily extended to other sectors including: industry, commerce and agriculture, using our component based modeling approach. Eventually, it 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.

References

[1] T. U. N. W. W. D. Report, "Nature Based Solution for Water," UN Water, Brasilia, 2018.

[2] M. Altaf, "Water crisis in Pakistan," Pakistan Observer, Turbat, 2017.

[3] UNESCO, "Water and Jobs," United Nations World Water Development Report, Perugia, 2016.

[4] A. R. Iqbal, "WATER SHORTAGE IN PAKISTAN – A CRISIS AROUND," ISSRA Papers, Islamabad, 2010.

[5] A. Guterres, "Sustainable Development Goals Report," United Nations, Portugal, 2017.

[6] W. H. Organization, "Drinking Water," WHO Media centre, Geneva, 2017.

[7] Y. B. Moon, "Simulation Modeling for Sustainability : A Review of the Literature," *Mechanical and Aerospace Engineering ,* pp. 1-18, 2016.

[8] D. Butler, S. Ward, C. Sweetapple, M. Astaraie-Imani, K. Diao, R. Farmani and G. Fu, "Reliable, Resilient and Sustainable Water Management: The Safe & SuRe Approach," *Global Challenges,* pp. 1-15, 2016.

[9] E. Z. Berglund, "Using Agent-Based Modeling for Water Resources Planning and Management," *Journal of Water Resources Planning and Management,* vol. 141, 2015.

[10] A. Borshchev, The Big Book of Simulation Modeling:Multimethod Method Modeling with Anylogic, Anylogic North America, 2013.

[11] J. M. P. Olmo, "An agent-based model for domestic water management in Valladolid metropolitan area," *Water Resources Research,* 2009.

[12] L. Linkola, C. J. Andrews and T. Schuetze, "An Agent Based Model of Household Water Use," *Water,* vol. 5, pp. 1082--1100, 2013.

[13] R. Zaher and G. Badr, "Intelligent Software Simulation of Water Consumption in Domestic Homes," *UKSim-AMSS 18th International Conference on Computer Modelling and Simulation,* 2016.

[14] B. Yannou, Y. Leroy, T. Zaraket and E. Chapotot, "Activity-based simulation of households energy and water consumptions," *Hal Archives,* 2017.

[15] A. Facchini, A. E. Rizzoli, C. Rottondi, C. Valeri, A. Castelletti, A. Cominola, M. G. liani, S. Denaro, A. Alsaha, J. N. and P. Lazaridou., "ABM SIMULATOR FOR WATER CONSUMPTION A first prototype Project," 2015.

[16] I. Winz, "A System Dynamics Approach to Sustainable Urban Development," *Proceedings of the 2005 System Dynamics Conference,* vol. 12, no. 2, p. 153, 2005.

[17] I. N. Athanasiadis, A. K. Mentes, P. A. Mitkas and Y. A. Mylopoulos, "A Hybrid Agent-Based Model for Estimating Residential Water Demand," *Simulation,* vol. 81, no. 3, pp. 175-187, 2005.

[18] "Anylogic Simulation Software," [Online]. Available: http://www.anylogic.com/. [Accessed January 2017].

[19] A. Facchini, A. E. Rizzoli, C. Rottondi, C. Valeri, A. Castelletti, A. Cominola, M. Giuliani, S. Denaro, A. Alsahaf, J. Novak and P. Lazaridou, "ABM SIMULATOR FOR WATER," FP7-ICT-2013-11, 2015.

[20] U. Shamsi and J. Koran, "Continuous Calibration," *Journal of Water Management Modeling,* vol. 25, pp. 1-9, 2017.

[21] R. I. McDonald, K. Weber, J. Padowski, M. Flörke, C. Schneider, P. A. Green, T. Gleeson, S. Eckman, B. Lehner, B. Lehner, T. Boucher, G. Grill and M. Montgomery, "Water on an urban planet: Urbanization and the reach of urban water infrastructure," *Global Environmental Change,* vol. 27, no. 1, pp. 96-105, 2014.

[22] M. Gala, "An agent-based model for domestic water management in Valladolid metropolitan area," *WATER RESOURCES RESEARCH,* vol. 45, 2009.

[23] I. Koutiva and C. Makropoulos, "Modelling domestic water demand: An agent based approach," *Environmental Modelling & Software,* vol. 79, pp. 35-54, 2016.

[24] M. Akhbari and N. S. Grigg, "A Framework for an Agent-Based Model to Manage Water Resources Conflicts," *Water Resources Management,* vol. 27, no. 11, pp. 4039-4052, 2013.

[25] X. C. Yuan and Y. M. Wei, "Urban Household Water Demand in Beijing by 2020 : An Agent-Based Model," *Water Resources Management,* p. 2967– 2980, 2014.

[26] A. Ganjidoost, C. Haas, M. Knight and A. Unger, "A System Dynamics Model for Integrated Water Infrastructure Asset Management," in *Proceedings of the 33rd International Conference of the System Dynamics Society*, Cambridge, 2015.

[27] S. Park, V. Sahleh and S.-y. Jung, "A System Dynamics Model for the Simulation of the Management of a Water Supply System," in *2nd International Conference on Geological and Civil Engineering*, Singapore , 2015.

[28] C. G. Palmer, "Using System Dynamics to Explore the Water Supply and Demand Dilemmas of a Small South African Municipality," in *32nd International Conference of the System Dynamics Society*, Delft, 2014.

[29] A. Bahri, Integrated Urban Water Management, Stockholm: TEC Background Papers, 2012.

[30] A. Borshchev, The Big Book of Simulation Modeling. Multimethod Modeling with AnyLogic 6, United States, 2013.

[31] P. Williamson, "An Applied Microsimulation Model: Exploring Alternative Domestic Water Consumption Scenarios.," *Springer Berlin Heidelberg,* 2001.

[32] I. N. M. A. K. M. P. A. &. M. Y. A. Athanasiadis, "A Hybrid Agent-Based Model for Estimating Residential Water Demand," *Simulations,* pp. 175-187, 2005.

[33] M. Szczesniak and M. Piniewski, "Improvement of the Hydrological Simulations by Applying Daily Precipitation Interpolation Schemes in Meso Scale Catchments," *Water,* pp. 747-779, 2015.

[34] E. Bonabeau, "Agent-based modeling: Methods and techniques for simulating human systems.," in *Proceedings of the National Academy of Sciences*, 2002.

[35] J. Schank, "Agent-Based Modeling," 2010.

[36] P. K. R. &. E. S. M. Darbandsari, "An Agent-based behavioral simulation model for residential water demand management: The case-study of Tehran, Iran," *Simulation Modelling Practice and Theory,* vol. 78, pp. 175-187, 2017.

[37] J. W. Forrester, "The beginning of system dynamics," *McKinsey Quarterly,* pp. 4-17, 1995.

[38] S. Park, V. Sahleh and S.-y. Jung, "A System Dynamics Model for the Simulation of the Management of a Water Supply System," in *2nd International Conference on Geological and Civil Engineering* , Singapore, 2015.

[39] A. &. D. W. B. Funk, "Embedded Energy in Water Studies. Boulder: Aquacraft, Inc. Water Engineering and Management," 2009.

[40] F. Andrew and W. DeOreo, "Embedded Energy in Water Studies Study 3: End-use Water Demand Profiles," Aquacraft, Inc., California, 2011.

[41] P. D. B. &. S. D. Alaton, "On Modelling and Pricing Weather Derivatives," *Applied Mathematical Finance,* pp. 1-20, 2002.

[42] R. f. A. S. M. S. T. &. Solutions, "Anylogic.," 2018. [Online]. Available: https://www.anylogic.com/.

[43] S. Shams, "Water scarcity in Pakistan – A bigger threat than terrorism," Islamabad, 2107.

[44] G. Domínguez, "Water scarcity 'is Pakistan's worst nightmare'," 2015.

[45] J. BASHIR, "Severe water crisis," Voice of People, Pakistan Observer, Lahore, 2017.

[46] UN-Habitat, "Urban Infrastructure and Basic Services , Including Energy Issue Paper on Urban Infrastructure and Basic Services , Including Energy," *Habitat III Issue Papers,* vol. 2015, no. May, pp. 0-9, 2015.