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Agent Based Modelling in Digital Twins for Household Water Consumption Forecasting

***Abstract**. The continuous increase in urban population due to migration of mases from rural areas to big cities has set urban water supply under serious stress. Urban water resources face scarcity of available water quantity, which ultimately effects the water supply. It is high time to address this challenging problem by taking appropriate measures for the improvement of water utility services linked with better understanding of demand side management (DSM), which leads to an effective state of water supply governance. We propose a dynamic framework for preventive DSM that results in optimization of water resource management. This paper uses Agent Based Modeling (ABM) with Digital Twin (DT) to model water consumption behavior of a population and consequently forecast water demand. DT creates a digital clone of the system using physical model, sensors, and data analytics to integrate multi-physical quantities. By doing so, the proposed model replicates the physical settings to perform the remote monitoring and controlling jobs on the digital format, whilst offering support in decision making to the relevant authorities.*

***Streszczenie.** Ciągły wzrost liczby ludności miejskiej spowodowany migracją mas z obszarów wiejskich do dużych miast poważnie obciążył miejskie zaopatrzenie w wodę. Miejskie zasoby wodne borykają się z niedoborem dostępnej ilości wody, co ostatecznie wpływa na zaopatrzenie w wodę. Najwyższy czas zająć się tym trudnym problemem poprzez podjęcie odpowiednich działań na rzecz poprawy usług wodociągowych połączonych z lepszym zrozumieniem zarządzania popytem (DSM), co prowadzi do efektywnego zarządzania zaopatrzeniem w wodę. Proponujemy dynamiczne ramy prewencyjnego DSM, które skutkują optymalizacją zarządzania zasobami wodnymi. W niniejszym artykule wykorzystano modelowanie oparte na agentach (ABM) z cyfrowym bliźniakiem (DT) do modelowania zachowania populacji w zakresie zużycia wody iw konsekwencji prognozowania zapotrzebowania na wodę. DT tworzy cyfrowy klon systemu za pomocą modelu fizycznego, czujników i analizy danych w celu zintegrowania wielofizycznych wielkości. W ten sposób proponowany model replikuje fizyczne ustawienia do wykonywania zadań zdalnego monitorowania i kontrolowania w formacie cyfrowym, oferując jednocześnie wsparcie w podejmowaniu decyzji odpowiednim organom.I (**Modelowanie agentowe w cyfrowych bliźniakach do prognozowania zużycia wody w gospodarstwach domowych**)*

Keywords: Water Resources; Water Supply; Water System Dynamics; Agent-Based Modelling (ABM); Digital Twin (DT); Demand Side Management (DSM).
Słowa kluczowe: Zasoby wodne; zaopatrzenie w wodę; Dynamika systemu wodnego; modelowanie agentowe (ABM); Cyfrowy bliźniak (DT); Zarządzanie popytem (DSM).

1. Introduction

Human behavior modelling of domestic water utilization gives us insights of water consumption patterns in different communities. Having better understanding about water consumption details in line with the requirements of the community, helps relevant agencies to futuristically plan water supply accordingly. The demand and supply of water is a growing concern around the globe, and it is leading to alarming situation in some of the thickly populated urban cities. This paper presents a Digital Twin (DT) based system that replicates the real environmental settings to generate the household data for water consumption employing Agent Based Modeling (ABM) for making improved assessment about the demand of water consumption.

DT is used to optimize domestic water demand that is a complex problem to optimize as it depends on wide range of factors, from interrelated natural parameters, average household economy, social demographics to sustainability. Domestic water modelling is an approach to model household water consumption based on human behavior centric approach that consequently incorporates human pattern involved in the domestic water consumption and in this way the collected information is effectively used to assess the current as well as futuristic water demand. A water consumption simulation system can help in monitoring and managing household water consumption activities which can essentially guide the water regulatory authorities for efficiently managing water resources and ensuring smooth water supply to end users. [1].

Studying utilization of household water consumption in a large urban infrastructure is practically infeasible due to different family sizes of households having residents of varying age group and different water consumption patterns as per their unlike daily routine. Further, there are various other socio and ethnic factors which also effect the water consumption activities of a household and makes it a difficult task of assessing precise water demand for an urban community. Therefore, modelling and simulation plays an essential role in dealing with this situation and virtually depicts a real-world scenario with some level of abstractions to analyse the consumption of water at household level. The modelling and simulation based system forecasts the required amount of water that needs to be delivered to the end user in an urban infrastructure [2][3][4]. Thus, we propose a framework, which employs DT, ABM and AnyLogic [5] to virtually simulate the settings of real world scenario, to capture the water consumption data for domestic households in urban community, make more accurate assessment of current water demand and forecast the expected increase in the demand. ABM based water simulation and analysis uses AnyLogic's built-in features and library to simulate household water utilization. ABM replicates the real time settings involving human behavior and other characteristics such as age group, hours of work, and ethical values of the society etc. Whereas, DT takes into account all the characteristics, which are directly or indirectly involved in consumption of water. The proposed framework extends assistance to the water regulatory authorities in dealing issues linked with water governance, assessing future water demand and handling water scarcity. Thus, a model developed using hybrid paradigms is more accurate and precise compared to a model based on single paradigm [6].

The rest of the manuscript includes literature review in section 2, proposed framework including the implementation details are presented in section 3, section 4 discusses obtained results and finally conclusions are drawn in section 5.

2. Literature review

Ensuring smooth water governance has become a challenging issue with increasing urban population. Further, it is also linked to many factors such as frequent climate catastrophes, depletion in water resources and inefficient water supply management without considering the correct water demand.

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 time to not only have fair assessment of the current water demand but relevant regulatory authorities should be equipped with advance system to be able to apprehend the future water demand and propose the resilient and sustainable infrastructure accordingly, 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 linked to the social, economic or environmental settings prevailing in an urban locality [4] [6]. Water management also includes waste water treatment, water reuse and water billing as per units of water consumed and also per unit of waste generated [7]. Simulations and modelling based solutions are capable to replicate a real-world scenario using parametric settings that enables to perform experiments having close resemblance with real world environment. The simulation based experiments take the values of domestic water consumption and then determine the actual demand, which ultimately extends improved level of monitoring and management of water resources. This simulation based computer program performs efficient monitoring of water resources, as it has the capability to predict the water consumption and then addressing the volumetric water flow. 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 [8]. This helps the regulatory authorities in providing water without any interruption which satisfies a large number of tasks without undue use. This takes into account details such as the activities of users and the amount of water being consumed, behavior and characteristics of users, time of an activity, hourly water utilization in an activity etc. Yannou et al. [9] proposed that all these factors, when collectively taken into consideration, enables the framework to produce more improved results for forecasting the future water demand

Agent-based Modeling (ABM) refers to a group of models, which enables to capture the activities and dealings of autonomous agents, considering their individual as well as collective impacts [10]. ABM is considered as a well-known method, which extracts the microscopic details about water governance and extends sufficient information to investigate complexities involved in human behavior. Such microscopic models are widely used and they effectively cater the minor details exiting in real world problem, in order to produce results which are more relevant and accurate for a real world problem. The capability of dealing with minor details of a real world problem makes such models an appropriate choice for studying the problems of water governance and many other real world problems that involves human behavior. ABM is considered as a modelling measure whereby individuals, their interaction with each other and their environment are represented as agents [11]. ABM offers a toolkit for behavioural science which can help in developing models as to how individuals interact with organizations, and materialize the needful services from these interactions. For the purpose Williamson [12] has presented a work which investigates the leakages generally found in water consumption scenarios of domestic household.

Similarly, Berglund [13] also presented a work, which shows the interaction of active and reactive agents involved in water resource planning. In another study [14], the water consumption behavior has been analyzed at domestic level, encompassing the consuming entities, which is essential for studying once human behavior is to be studied. Linkola et al. in [10] has proposed a model which determines water level consumption of a household in a bid to determine the water consuming behavior, on the basis of hourly water consumption and considering the social demographics of domestic household. The study shows, that different households having different social demographics possess varying water consumption pattern. The work presented by Darbandsari and Kerachian [15] proposed to exploit the behavioral characteristics of urban households in Tehran, considering it as a pilot city of Iran for developing improved water consumption policies, considering varying climatic conditions.

Modeling Domestic Water Demand (MDWD) [16] is an approach based on considering socio-economic characteristics in order to analyze water demand behavior of urban areas through applying intuitive statistical mechanics. The work proposed to integrate simulation based model and another tool used for water management to precisely calculate the water demand for future in an urban area employing ABM. Galan et al. [17] proposed a framework that integrated Geological Information System (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 analysed the impact of external pressure of behavioural diffusion on water consumption. Wanderbeg, et al. [18] proposed a system dynamic (SD) based model that extends a strategy offering improved water management for semi-arid area of Brazilian Northeast. The study focuses to explore complex level interactions involved at micro level in a water supply system.

Fuertes et al. [19] proposed a DT based approach for drinking water distribution system (WDS). Building a DT involves considering parameters settings, which virtually or physically exist in the problem domain. It includes the range of parameters such as data transmission, storing, conversion, protection, etc. Further, advanced Artificial Intelligence (AI) algorithms are applied for pre-processing and data analytics. The DT in this work is shown capable to optimize and adapt to external changes by suggesting operational settings once validated by simulations.

Kaur et al. [20] proposed a new direction in the research field of remote monitoring, viewing and controlling on a digital format, based on using the modern concepts of DT, Internet of Things (IoT), and AI. Authors proclaim that these new technologies would reshape the future vision for study of human behavior in the context of resource management in the current globalized world. DT has been recently evolved and known for one of the effective methods, which efficiently replicates the physical model and extends remote monitoring and controlling of resources. It makes a good choice for enterprises worldwide, for modelling jobs. DT depicts the living picture of the physical model, which has the capability to incorporate the operational changes that are continuously carried in the system through changing real time data received from devices and IoT sensors. The data acquired from such wide variety of devices is consequently used for predicting the future demand.

Alves et al. [21] proposed a DT based technology where changing data is collected from sensors and eventually a system is developed. This system offers smart ways of water management that provides initial building measures for cyber physical system (CPS). It provides a digital platform for agriculture related stakeholders to better apprehend future needs of agriculture farms. Such studies specifically supports the farmers to better prepare the required resources and procure needful equipment in lieu of future needs. Observing the performance of such systems, which gather the data of soil probes, the frequency of soil probes can be increased along with adding more sensors and controlling devices so that DT may operate at optimum level. Anagnostou and Simon [22] presented a model that operates using distributed computing environment, where simulation program depicts a large scale system or large models distributed in such a way that divided components are executed on separate computers. Consequently, the system is more reusable with increased processing speed, improved level of data consistency and privacy.

3. Proposed framework

An abstract view of the proposed framework is shown in the Figure 1 given below. The proposed framework develops a behavioral simulation model for household water consumption employing (i) ABM to model individual's water consumption behavior at a micro level and (ii) DT approach to model a large number of water consuming entities. The framework effectively replicates the real world settings, which estimates the water consumption of households considering varying factors and simulates the water consumption scenarios in an urban environment. This leads to the development of a system, which estimates the water consumption quantity as per number of water-consuming entities in an urban locality.

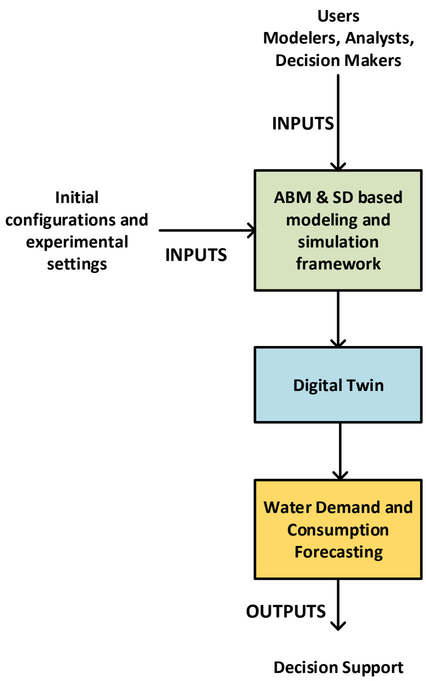

Fig.1. Block diagram of the proposed framework

The main goal of this research is to develop a framework that extends monitoring of water resources and helps in planning of water supply at household level. The objective is achieved through employing simulation and modeling capabilities of ABM, which are consequently used to develop a digital twin for replicating the real world settings in virtual scenarios. A range of actors, which involves users, modelers, analysts and decision makers collectively provide the parametric values comprising of initial settings as an input to the ABM module of the proposed framework. The initial configuration are stochastically updated to virtually devise different scenarios for encompassing maximum number of settings to cater the estimates of water consumption in an urban locality. Finally, a digital twin operates that collects the data from the sensors attached in a water supply system. Once enough data is collected through simulations based on a virtual copy of the real system, then a holistic view is developed by analytics and decision makers for better understanding the water consumption demand and foreseeing the stress on the available water resources.

The proposed frame work finally extends the valued information and forecasting, which supports the decision makers of relevant authorities to take appropriate measures for fulfilling the current and future water demand of an urban locality.

3.1 ABM Module

ABM covers all the general water consumption activities of households considering the factors such as, number of persons living in a household belonging to different age groups, income level, occupancy time, household type etc. Figure 2 shows the graphical representation of ABM module. ABM uses AnyLogic that stochastically computes the population of actors, which simulates the number of persons living in a household, number of household in a neighborhood, the time dependent water consumption patterns linked to the different age groups of the persons living in a household, socio and ethnic factors etc. ABM covers the transition of activities related to any level of water consumption in a household, which is carried out in a time bound fashion. Once an activity is timeout, it is accordingly recorded and collected data is used in the simulation. For calculating the measure of an individual's susceptibility to change, certain degree of randomness in the consumption behavior of a household, number of households in a neighbourhood and transition of activities, is incorporated. A continuous process proffers the collection of data for water consumption, from wide range of activities, which generally occur in an urban household living, as shown in Figure 3.

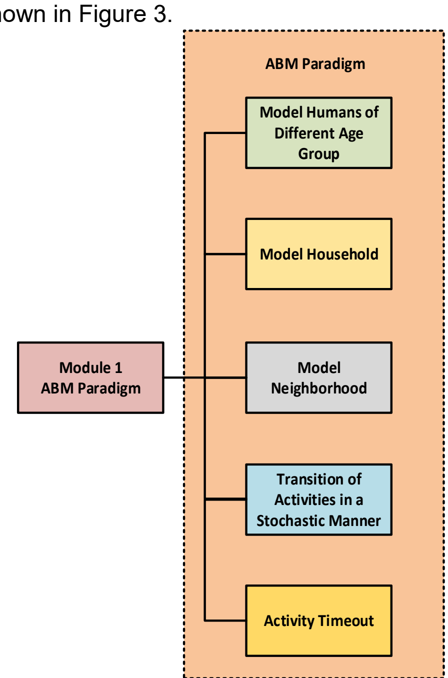

Fig.2. ABM Module of proposed framework

Different factors are considered to appropriately acquire the information from a household, which may closely reflect the real consumption of water. For, the Figure 3 pictorially represents a broad view of water consumption activities, considered in the experimentation. Water consumption is triggered by probability of occurrence of water consumption activities. The water consumption activities are recorded to collect the required data for simulations with the help of sensors, considering the probability and time dependency factors.

3.2 Water consumption algorithm

The water consumption in different household activities directly depend on the age group, income, education level, occupancy and house type, etc. Algorithm 1 presented below considers the human behavioral water consumption and takes input as number and types of persons, number of houses, water availability probability and water consumption rates in a typical household. A house is initialized by some parametric variables to generate the profile of water consumption demand for a household. It is to be noted that different households would generate different initial parameters which are largely based on the factors discussed earlier. Therefore, their total water consumption would be different. In our simulations, we have chosen these values randomly based on a random sampling technique.

Algorithm 1: Behavioural Household Water Consumption
Inputs:
Persons, House, Availability Probability, Water Consumption Probability, Water Consumption Rates
Output:
Household Water Consumption
Initialize Persons, House
Type ⟵ *GetPersonType( )*
Probability ⟵ *GetProbability(Type)*
P=RandomTrue(Probability(Type))
if *(P==True)*
then
if *(GetPersonAvailability( )==True)*
then
Consumption ⟵ Probability
GetWaterConsumptionProbability( )
ConsumptionRate ⟵ *GetWaterConsumptionRates( )*
HouseholdWaterConsumption ⟵ *GetTotalWaterConsumption()*
return Household Water Consumption

The Mathematical expression to calculate the probability is given by:

$$P_i = \frac{\exp\frac{I_i}{U}}{\left\{\exp\frac{-I_i}{U}\right\}\left\{\exp\frac{-I_i}{U}\right\}} \qquad (1)$$

if $X < P_i \Rightarrow O_i(t+1) = -O_i(t)$

if $X > P_i \Rightarrow O_i(t+1) = O_i(t)$

where: P_i : is the probability of an individual entity; I_i : is the exerted social impact; U : is the Utilization of water in a household water consumption; X: is a randomly selected number from a uniformdistribution of [0; $O_i(t)$: is the attitude of the household agent/entity. Using P_i, we compute the W_c, which is the total water consumed per capita/person by using the following equation:

$$W_c = \sum_{i=1}^{n} P_i * W_a * W_r \qquad (2)$$

Where: W_a: is the water consumed in a particular activity per capita; W_r: is the water consumption rate per capita.

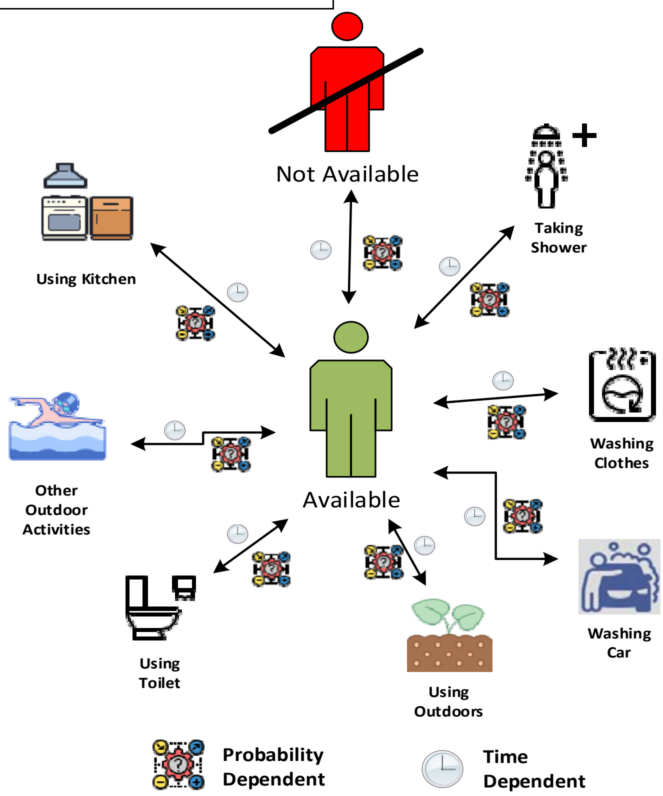

Fig.3. ABM module state diagram showing water consumption activities in a household

3.3 Data Collection of Water Consumption

For the validation of model, we require data of water consumed in households of urban settings. Some urban areas install water meters which is very expensive. So, we propose a low-cost solution for installation of IoT based water consumption monitoring kit. IoT water monitoring kit is installed for generating the demand profile of a neighborhood and that helps in validation of the proposed framework. Figure 4 shows the IoT based water consumption monitoring kit. It comprises of a time and flow monitoring sensor, along with the control valve assembly, and an IoT module capable of transmitting the sensor data. An IoT based water monitoring kit is installed at consumer level for data collection. The attached sensor, to the consumption monitoring kit, provides the data for the household and neighborhood water consumption. Such an advanced controller kit is better than other electrical methods proposed in literature [24].

3.4 Digital Twin and Forecasting

Furthermore, DT is flexible technology which adopts itself to continuously updating real time data that is collected from various IoT sensors and devices. This all lead to forecast the water demand. Such technologies pave the way for the development of a system, which extends great benefits and ease of water management for the relevant regulatory authorities. DT provides a virtual copy of the real system that simulates the real world environment and identically behaves like its real world counterpart. It leverages the technologists to develop a system in digital environment that offers great support to decision makers of the water regulatory authorities for improved water governance. The proposed framework provides dynamic information on a dashboard, which presents the current state of affairs in a real time system and thus guides to take appropriate measures in terms of adding more monitoring and controlling devices. In this way the framework analyzes the behavioral patterns involved in water consumption and fine tunes the parameters which may lead to improvement in the performance of water supply system through DSM.

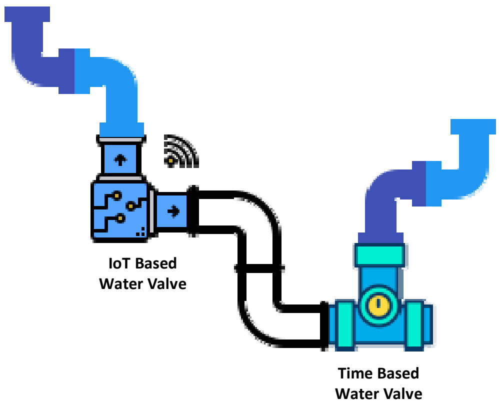

Fig.4. IoT based water consumption monitoring kit

4. Results and discussion

The proposed DT based framework is implemented using Anylogic, whereby a number of simulations are developed to model the household water consumption. The computational specification of the machine used for running simulations are OptiPlex 3047 Intel Core-i7 CPU with a clock speed of 3.40 GHz and onboard system memory of 16 Gb.

Comprehensive experimentation is performed to exploit the collected data for generating the results through simulations. Ten runs of the simulation for 500 houses in an urban area was performed for a period of one year. The results are collected for annual water consumption in an urban area by taking the average of 10 simulation runs and plotting their values over the time series graph as shown in Figure 5.

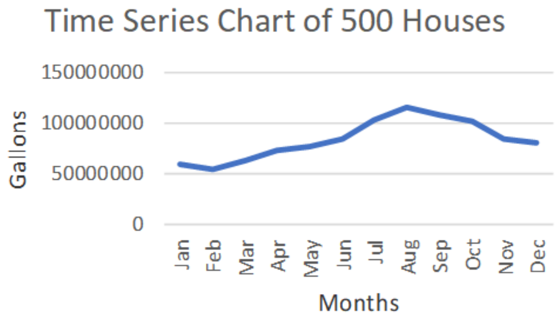

Fig. 5. Simulation Result of 500 Houses

The results shown in Figures 6-9, represent the water consumption for households in urban locality. All graphs are drawn taking the average of ten simulation in each case. The number of households which are considered for experimentation ranges from 500, 1000, 10000, 50000 to 100000.

Figure 5 shows that whilst considering 500 households of an urban locality, the maximum water consumption is approximately 12 million gallons in the month of August in that year. Further the graph also shows, the trend of water consumption in the beginning and end of the year.

In order to effectively demonstrate the consumption of a small town, we have carried out extensive simulations. In Figure 6, it is observed that when 1000 households are considered, there is not major deviation in the water consumption trend. However, the total water consumption for 1000 household is approximately 200 million gallons in the month of July. Furthermore, considering a bigger population of 10000 households, does not show a major deviation in the water consumption trend. The month of July still remains the month with highest approximate water consumption. To give a more realistic picture and and incorporate real life scenarios in our experimentation, we Increase the population size of households to 50000 in figure 8. Again, it can be observed that the water consumption pattern depicts an unchanged behaviour and the results are predictable. It shows that generally the months of summer in a certain urban locality involves higher water consumption. Whereas, the start and end of a year does not as such involve any abrupt change in the water consumption pattern. Mostly it is observed that with the commencement of winter season towards the end of the year, the water consumption starts decreasing. In case where 100000 households are considered, as shown in Figure 9, July and August are shown as months involving maximum water consumption. Thus, it is observed that all the simulations result depict the maximum water consumption in the months of summer, which is usually the case in urban settlements in most of the countries around the globe. Thus, the proposed digital twin using agent-based modelling gives realistic results. Moreover, the increase in population size has not as such shown any major deviation in the results. Therefore, the obtained results represent a holistic view of water demand and consumption in an urban locality. The proposed framework seems effective enough, to compute indoor as well as outdoor water consumption and determines the nature of water requirements of a specific household neighbourhood. This way, the proposed framework can be utilized to compute the water consumption estimates for toilet use, kitchen, washing etc in a household, household neighbourhood and in an urban locality.

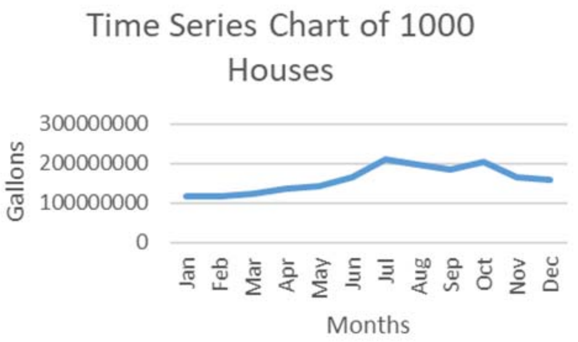

Fig.6. Simulation Result of 1000 Houses

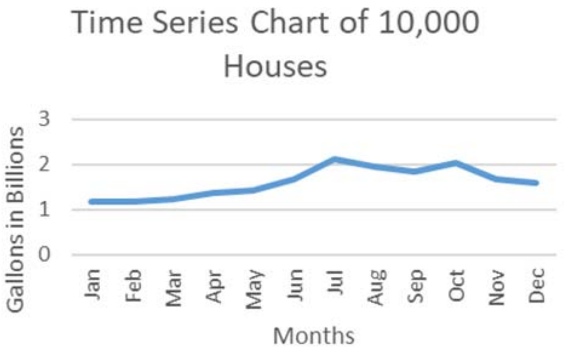

Fig.7. Simulation Result of 10000 Houses

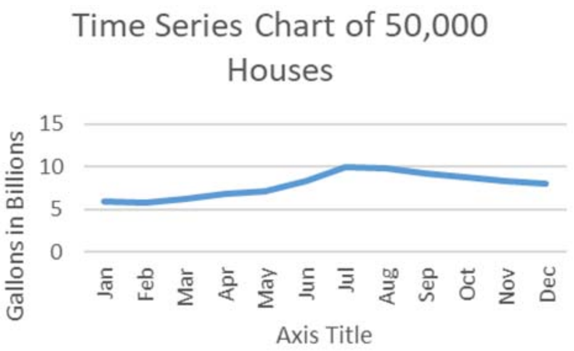

Fig.8. Simulation Result of 50000 Houses

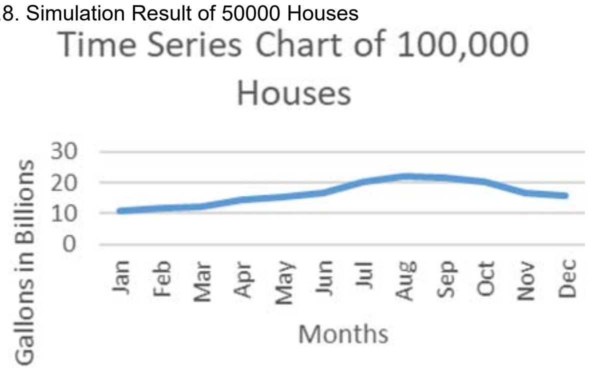

Fig.9. Simulation Result of 100,000 Houses

6. Conclusion

This work present a model that is a hybrid form of DT and ABM. Both the used technologies have proven significance in analyzing human behavioral patter, and resource management, respectively. The proposed model is developed using simulation & modeling techniques, for monitoring and evaluating the water consumption at domestic household level in urban locality. The proposed framework utilizes ABM's capabilities to simulate the human behavior involved in water consumption activities in specific household neighborhood. DT virtually simulate the various real world scenarios with the help of actual settings that closely replicates the real environment and consequently results are obtained which extend useful information for improved water governance. Such a framework is equally useful in forecasting the water demand, realizing the behavioral pattern of domestic households in urban areas. The information acquired with regards water consumption, monitoring and evaluation, and forecasting consequently provide assistance to relevant stakeholders in concerned authorities for effectively fulfilling the demand, leading to improved water governance.

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