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A System Dynamics Modelling of Urban Water Demand Forecasting for Madurai City

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Abstract: Water is important for all kind activities in the present world. Accurate prediction of municipal water demand is critically important to water utilities in fast-growing urban regions for drinking water system planning, design, and water utility asset management. Achieving the desired prediction accuracy is challenging, however, because the forecasting model must consider a variety of factors are Climate, Depletion of Resources, Urbanization, Socio-Economical issues etc., which are not stable in nature. For water demand estimation, Traditional forecasting models such as multivariate regression, time series analysis, and advanced modeling techniques are often applied for short and long-term water demand projections, yet few can adequately manage the dynamics of a water supply system because of the limitations in structures of modeling. System Dynamics modeling has been chosen because it considers the socio-economic factors which are dynamic in nature. It is an iterative technique which helps to arrive at the accurate demand.

The objectives of this study were to thoroughly review water demand forecasting models and propose a new system dynamics model to identify the water demand estimation by addressing the complex Socio-economic factors for long-term municipal water demand forecasts of Madurai City. Some steps of System dynamics modeling process was used in this study, which includes problem articulation, model formulation, model simulation and result validation. System Dynamics simulation results the estimation of water demand by 2040 for the selected study area. The study results indicate that total demand of Madurai city increases in each decade and supply are being insufficient.

KeyWords: water demand, System Dynamics, decision modeling, water management etc…

I.   INTRODUCTION

Urbanization in developing countries has proceeded faster than in developed countries, but the correlation of the rate of urbanization with economic growth has been weaker than in developed countries (United Nations, 2013b). The continuing urbanization and overall growth of the world's population is projected to add 2.5 billion people to the urban population by 2050, with nearly 90 per cent of the increase concentrated in Asia and Africa. At the same time, the proportion of the world's population living in urban areas is expected to increase, reaching 66 per cent by 2050. [World Urbanization Prospects- The 2014 Revision, Highlights, United Nations, New York, 2014]. Urban population growth in some regions of the developing world will be accompanied by the rise of urban poverty. The sprawl has implications for the deterioration of environment – through pollution, increased resource demand, depletion of ground water and encroachment of forest areas, with consequences of climate change. This also has implications for sourcing fresh water and waste water management. (Water Aid).

In all developing countries, the public sector carries the primary responsibility for service delivery in urban areas. Public utilities currently serve up to 95% of the population served through piped network systems. Levels of service vary: Household connections, yard taps, and community water points. In many cases, the failure of public utilities to serve the urban poor and informal settlements is due to city authority laws regarding land tenure, technical and service regulations and city development plans that legally prevents them from serving these areas. (Water Aid). The word "demand" which appears in the title of this report is a technical term in economics. It denotes the quantity of a commodity which will be taken off the market at a particular price. This study is only minimally concerned with water demands in this economic sense. Rather, it primarily focuses on water requirements, needs, and usage; terms which are employed more or less interchangeably herein to denote quantities of water assumed to be largely independent of prices. Clearly, predictions of future water requirements constitute merely a first cut at estimating future demands since they ignore price. The accuracy of such initial estimates as indicators of demand depends to large extent on the costs of supply, which are entirely ignored herein. It does not follow, however, that predictions of future water requirements are of little or no value. Quite the contrary, requirements may be expected to approximately equal demands as long as water remains in relative abundance.

[Donald T. Lauria et al., 1975]

In order to ensure reliable water supply to the residents of a city, an accurate estimate of future water demand is necessary. For many reasons, India have had a central place in global food and water supply and demand projections.

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First one is percentage of population towards urbanization, migration.

Second one is greater economy (Per capita water usage Vs GDP , Urban area, Cultural Vs Geographic location).

Third one is Spatial mismatches between

Population and Water resources

Population and Annual rainfall

Population and climatic conditions.

Human development index and water resources availability.

Total water demand of India by 2025 and 2050 are

22% in 2025 and 32% in 2050. Moreover, the domestic and industrial sectors will account for 54 % of the additional water demand by 2025, and more than 85 % by 2050. (India's Water Supply and Demand from 2025-2050: Business- as- Usual Scenario (BAU))

Predicting and managing urban water demand is complicated by the tightly coupled relationship that exists between human and natural systems in urban areas. This relationship results from multiple interactions between micro scale (individual, household, or parcel level) and macro scale (municipal or regional) processes and patterns. For example, in complex systems, local interactions among individuals cumulate over space and time, generating mesoscale and macro scale variables that in turn feed back to influence or constrain individual choices [Liu et al., 2007; Irwin et al., 2009].

The ability to estimate water demand under multiple climate, population growth, and conservation scenarios is intimately tied to urban hydrological processes and modeling. Peak water demand forecasts influence infrastructure expansion strategies. Many urban areas face similar stresses and will require expansion of water supply and distribution facilities. Ensuring a least cost and reliable infrastructure expansion strategy requires an accurate estimate of the required size and operation of reservoirs, pumping stations, and pipe capacities. [Bougadis et al., 2005].

Accurateprediction of municipal water demand is critically important to water utilities in fast-growing urban regions for drinking water system planning, design, and water utility asset management. Achieving the desired prediction accuracy is challenging, however, because the forecasting model must simultaneously consider a variety of factors associated with climate changes, economic development, population growth and migration, and even consumer behavioral patterns. [Cheng Qi et al., 2011]

A transition in water demand modeling, forecasting, and management depends first on an understanding of the current and historical methods of acquiring and producing knowledge in the discipline. Also required is an understanding of the origin, structure, and limits of this knowledge. This review focuses specifically on examining urban water demand modeling methodologies. Application of water models to water policy and planning is beyond the scope of this paper; it is discussed in greater depth in the water policy literature [Ward, 2007; van de Meene and Brown, 2009; Gober et al., 2010; van de Meene et al., 2010].

Water demand estimations (WDEs) are widely used for future water resource planning because water development projects usually take long periods of time to complete. Accurate WDEs, in principle, can optimize water development efforts. Better planning can alleviate water-related conflicts, reduce environmental degradation, target investments in water infrastructure and help design better adaptation measures. This naturally explains the continuing interest of WDEs and their widespread application to guide development efforts.

For many reasons, India have a central place in global water supply and demand projections. First, constituting more than one-third of the world's population, India is the most populous country in the world. Second, India have huge economy. Economic growth in the recent decades—since the 1980s in India has been remarkable.

1.1 Water Demand Estimation Techniques

Domestic water consumption by households is a principal municipal water demand in urban regions. The first step is to develop accurate and reliable water demand forecast models, especially for assessing peak demand. There are two types of demand forecasting. The first are short-term forecasts, which are used for operation and management. The second are the long-term forecasts, which are required for planning and infrastructure design [Bougadis et al., 2005]. Currently, water managers produce demand estimates using long-term climate trends and the principle of stationary (the idea that natural systems fluctuate within an unchanging envelope of variability) [Milly et al., 2008].

In the past few decades, many approaches have been proposed to forecast short- and long-term municipal water demands. The first are short-term forecasts; Linear regression, Composite model, ANN, Time series analysis, Wavelet denoizing, Monte-Carlo simulation, Fourier series, Multiple regression, Geographically weighted regression, Simultaneous equation demand model, ARIMA, Fuzzy-logic, Agent based approach, Judge mental forecasts, End-use approaches, Econometric time series.

The Second are Long-term forecasts; Regression with Bayesian Entropy, Uni variate time series, System Dynamics, Land use based

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models, IWR-MAIN, PODIUMSIM, Hybrid approach.

System Dynamics modeling has been chosen because it considers the socio-economic factors which are dynamic in nature. It is an iterative technique which helps to arrive at the accurate demand. System dynamics is based on systems thinking, which focuses on the system structure and offers a deeper insight into problems. It can link ecological, human, and social elements of water and energy systems in one modeling platform to investigate their interactions.

1.2 Water Demand Estimation Using System Dynamics

Accodingly, the overall goal of this study is to thoroughly review water demand forecasting models and propose a new system dynamics model to identify the water demand estimation by addressing the complex Socio-economic factors for long-term municipal water demand forecasts of Madurai City. Some steps of System dynamics modeling process was used in this study, which includes problem articulation, model formulation, model simulation and result validation. For formulating the system dynamics model, so many Software are available such as Vensim, iThink, Stella and Powersim. In this study, Vensim PLE software has been used to formulate, simulate the model and to estimate the water demand.

Vensim : Much more powerful, and quite flexible if you have access to using subscripts. If you are working on real big projects this it is good, but the visualization is really old fashioned.

II.   METHODOLOGY

In the view of nature of the problem and available case studies, a tool is designed and checked with reliable data available from the field.
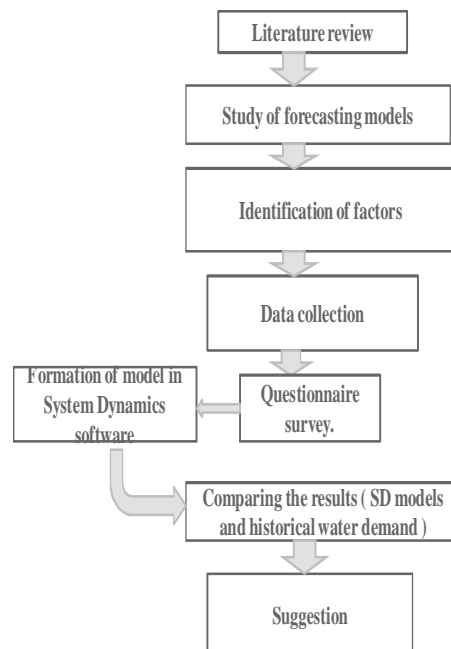

Fig – 1: Methodology

III.   STUDY AREA DESCRIPTION

Madurai City, located in South Central Tamil Nadu, is the third largest city after Chennai and is the headquarters of Madurai District. As the limits of Madurai City Corporation have been extended from 72wards to 100 wards in the year of 2011, the City is required to develop and improve its infrastructure in the added areas. At present, the water supply for the newly added areas does not meet the per- capita water demand required as CPHEEO norms. Hence the Madurai city corporation had proposed to execute a Water Supply Scheme for the newly added areas under the Jawaharlal Nehru National Urban Renewal Mission (JnNURM II) scheme or under Integrated Urban Development Mission (IUDM). Water supply Distribution System for the newly added areas is one of the priority sectors for infrastructure improvement under these schemes. There has been a significant increase in both the population and the number of households in Madurai city and this has enhanced the need for a more efficient water distribution system to improve the water supply to the prospective consumers and enhance the coverage. At present the total population of the City, according to 2011

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census, for the Madurai city is 14,70,754 persons.
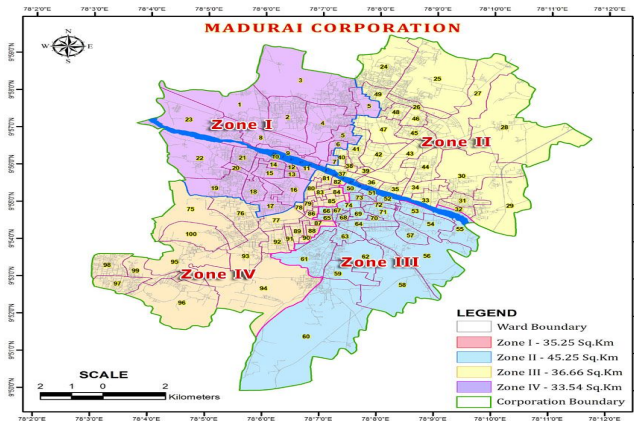

Fig – 2: Madurai Corporation Map (100 Wards)

A. Madurai and its Water resources

The main source for Madurai Water supply is Vaigai Dam. The total storage capacity of Vaigai dam is 6,091mcft. At present, Madurai city has a water supply scheme for 174 MLD, but due to improper monsoon and other factor, the corporation able to supply 105 MLD of water to the system. In that 87 MLD of water drawing Vaigai dam located 65 km away from Madurai city, under Vaigai water supply scheme I and II.

At present, the city supplies at an average of 103 liters per capita by once in 4 days. The estimated Non-Revenue water at present is at 35.58% of total water supply to the system. In that real loss account at major portion i.e. 26.50%. Unauthorized consumption, theft is the second major loss in the water supply system.

At present the demand for Madurai city is 209 MLD, with available existing water resources, the city corporation supply only 115 MLD. Based on the calculation for water demand compared with water supply, at present the city has a shortage of 94 MLD of water. Because of importance in Industries and tourism and population growth the water demand for Madurai will increase gradually on the coming years.

B. Water Resource in Domestic Users

In Madurai, as per Census Reports 2011, the 68% of Households having direction Tap Connection, In North side of the city, and the Tap connection having less connection compares to the south side of the city. In south side most of Tap connections are within the premises. Hand pumps are used by 17% of Households in Madurai. Tube well, having a share of 9% of Households. Compare to the south side, north side of corporation areas is used more percentage of tube wells, because in south side most of the wards ground water tables are depleted. And In all other sources, the Households depend on water supply through tanker Lorries. On the North side, 18% of households depend on tanker water supply for their needs, because there is no water supply infrastructure facility in the newly developed areas.

As per the survey done by Madurai Corporation, 64% of the population are satisfied with the quantity of water supplied, nearly 47% are happy with the quality of water supplied, and 34% not satisfied with the quality of water supply, remaining are neither satisfied nor dissatisfied with the quality of water supply.

C. Factors Impacting Water Demand
The following are the major factors affecting water demand in Madurai,

Climate	Socio- Economic elements
Weather	Population growth.
Climate change	Population density – death and birth rate, Emigration, Immigration.
Rainfall pattern	Household size, Habit of people and their Economic status, Occupancy rate, Size of the city.

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Evapo - transpiration rate	Income, Unemployment rate,.
Maximum daily temperature	Cost of water, Tariffs.
Wind speed	Tourism .
Precipitation	Water consumption, policy and management.
Water supply system	Source substitution and Water usage practices
Water distribution pressure and equality	Effluent reuse
Non revenue water	Rainwater storage tank
Leakages	Waste water generation rate.
Water storage infrastructures and capacity.	Industrial reuse.
Availability of resources – ground water and surface water	
Unauthorized use of water.	

Table -1: Factors impacting Water Demand

IV. SYSTEM DYNAMICS SIMULATION MODELS

A. Basic Concepts

System dynamics modeling is a well-developed systematic tool often used to describe system behaviors with feedback loops for accurate projections. System dynamics, designed similarly to system thinking, is a well-established methodology to quantify complex feedbacks in system interactions (Forrester, 1961, 1968).

A Stock is a collection of stuff, an aggregate. For example, a Stock can represent a population of sheep, the water in a lake, or the number of widgets in a factory.

A Flow brings things into, or out of a Stock. Flows look like pipes with a faucet because the faucet controls how much stuff passes through the pipe.

A Variable is a value used in the diagram. It can be an equation that depends on other Variables, or it can be a constant.

A Link makes a value from one part of the diagram available to another. A link transmits a number from a Variable or a Stock into a Stock or a Flow.

It requires a construction of the 'causal loop diagrams' or 'stock and Flow diagrams' to form a system dynamics context for applications. Within this context, stocks represent the accounting of a system component, either spatially or temporally (i.e., population); flows are the rate at which the component flows in or out of the stock, and converters modify rates of change and unit conversions. All may be intuitively assembled to simulate the dynamic processes of a system.

Most computer simulation applications using system dynamics models rely on the use of software packages, such as Vensim and Stella, in which the mechanisms of system dynamics can be handled by a user-friendly interface. These model development procedures are designed using a visualization process that allows model builders to conceptualize, document, simulate, and analyze models of dynamic systems. They offer a flexible way for building a variety of simulation models from causal loops or stock and flow. The dynamic relationships between the elements (including variables, parameters, and their linkages) can be created onto the interface using user-friendly visual tools. The feedback loops associated with these employed variables can be visualized at every step throughout the modeling process. Such applications can be found for business systems, ecological systems, social-economic systems, agricultural systems, political decision-making systems, and environmental systems. Such a system dynamics modeling approach for water demand estimation and forecasting has not been explored elsewhere; however, we propose a unique water demand estimation method by using a system dynamics model in which Vensim, iconographic software using basic building blocks such as stocks, flows was employed to build up the essential modeling framework in our study.

Population sub-model

This sub-model represents the population of the Madurai City. It is a simplified one consisting of one stock 'population' (*P*), which is

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increased by births (r_b) and decreased by deaths (r_d) (refer Figure). The population at time *t* is mathematically represented as:

$P(t) = P(0) + \int [r_b - r_d] dt$

Households sub-model:

The households sub-model consists of two stocks, namely, households with basic supply (*HBS*) and connected households (*CH*) (refer Figure 3). These two stocks are connected using an 'aging chain' model structure. The first stock (*HBS*) is influenced by the net growth of households with basic supply (r_{gbs}) and the household connection rate (r_c):

$HBS(t) = HBS(0) + \int [r_{gbs} - r_c] dt$

$TIH = TH - (HBS + CH)$

$CH(t) = CH(0) + \int [rc] dt$

$r_c = HBS * NMC * EWSR$

$WSR = AWCH / BAWCH$

Total number of informal households (*TIH*)

Growth rate of households with basic supply (*GRBS*).

Total number of households (*TH*)

Households with basic supply (*HBS*)

Connected households (*CH*).

Connection Rate (r_c)

Effect of water savings on municipal connections (*EWSR*)

Potable water supply sub-model:

Given that potable water supply system in Kirkwood has been the subject of previous modeling endeavors.

The raw water stock (*RW*) is influenced by three flows,

raw water purchases (r_{rwp}), rainfall into raw water reservoirs (r_{rf}) and water treatment rate (r_{tm}).

The mathematical representation of this is:

$RW(t) = RW(0) + \int [(r_{rwp} + r_{rf}) - r_{tm}] dt$

The potable water (*PW*) stock is influenced by water treatment rate (r_{tm}), potable water losses (r_{lo}) and potable water consumption (r_{pwc}), represented as:

$PW(t) = PW(0) + \int [(rtm - r_{lo} - r_{pwc})] dt$

$r_{pwc} = min (MPW, (THD * PW/TAS))$

$r_{rwp} = MRW - (RW/t_{rw})$

$PR = IF\ THEN\ ELSE\ (RW < (WTC*TPR),\ RW,\ (WTC*TPR))$

$r_{tm} = min (MPW, PR)$

$r_{rs} = min ((THStR - RWT), RFA)$

$r_{rwc} = min (RWT, (THD* RWT/TAS))$

$THStR = TNT * ACR$

$RFA = RF* THCR$

The rate of potable water consumption (r_{pwc})

The total household demand (*THD*),

The amount of potable water (*PW*),

Maximum capacity of the potable water reservoirs (*MPW*),

Total available supply of water (*TAS*)

Raw water purchases (r_{rwp})

Rainfall into raw water reservoirs (r_{rf})

Maximum capacity of the raw water reservoirs (*MRW*)

Amount of raw water (*RW*)

water treatment works at its maximum capacity (*WTC*).

The treatment process rate (*TPR*)

The available raw water (*RW*)

Production (*PR*)

Treatment rate (r_{tm})

Rainwater volume in storage tanks (*RWT*)

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Reduced by rain water consumption (r_{rwc}).

The rainwater storage rate (r_{rs})

Amount of rainfall in ML (*RFA*)

The total household storage capacity for rainwater harvesting (THStR)

Number of tanks (*TNT*)

 Average capacity of rainwater tanks (*ACR*)

Product of rainfall (*RF*) and the

Total household catchment for rainwater (*THCR).*

V. RESULT AND DISCUSSION

As per analysis of existing water supply system in Madurai Corporation, the augmentation of new water resource is a very urgent concern to meet the public water supply requirement and demand creates in Madurai city, for bringing completely new water resources to the city is very difficult, The existing water resources are completely depend on Vaigai River and Vaigai Dam, but Vaigai is not Perennial River, the flow in river is only in monsoon season.

The study discussed about the municipal water demand of Madurai city (100 wards). The total demand considers here as bulk losses and Household demand of municipal areas. Whereas , the water supply also projected with the factors of total no of Households, HH with basic supply, Connected HH and average use of water in HH. The total supply in each decade does not meet the required demand. It seems to be deficit of water is more. Losses also increase in each decade. The main causes for this deficiency are increase in population, Tourism rate and insufficient rainfall, climate change etc., System Dynamics modeling forecasted the water demand for Madurai city with the help of Socio-Economic factors and some other common factors.

The results of Water demand are predominantly summarized in this section by using the outputs from the model, with supplementary explanations supplied where necessary. The emphasis is on simulating the problem situation know to, and experienced by, the Madurai city.

Fig -3: Stock and Flow Diagram For Water Demand Forecasting of Madurai City
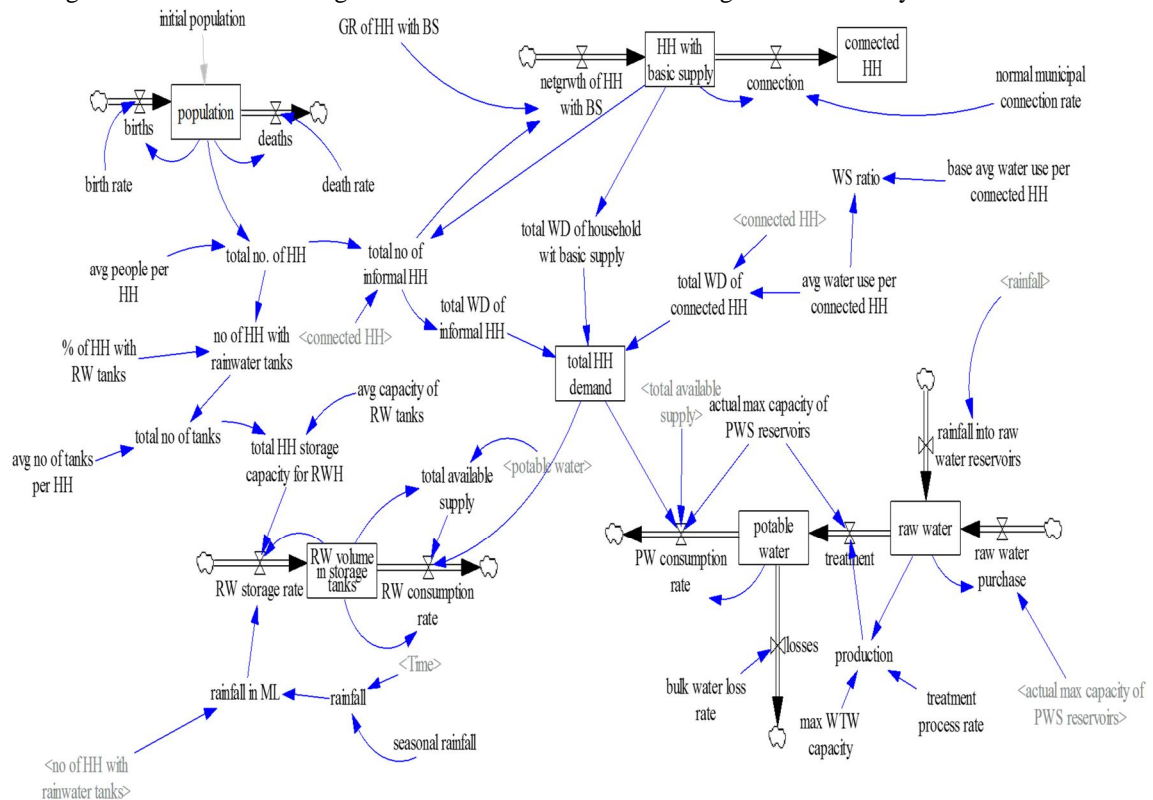
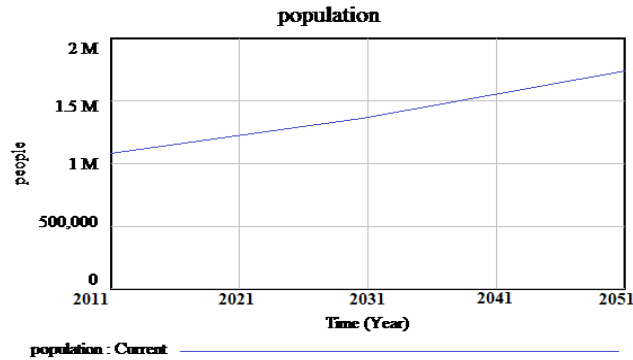# International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Fig -4: Population

S. No	Year	People (in lakhs)
1.	2011	11.4
2.	2021	12.5
3.	2031	14.2
4.	2041	16.2
5.	2051	17.5

Table -2: Population Forecasting

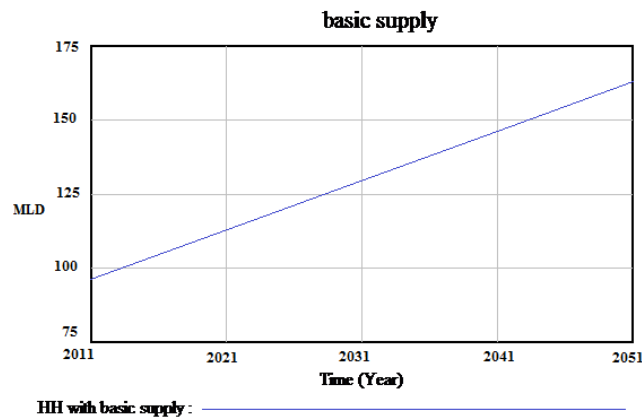Household with Basic Supply by 2041 for 100 wards of Madurai city:

Fig -5: Basic Supply

S.No	Year	Supply(in MLD)
1.	2011	98
2.	2021	111
3.	2031	128
4.	2041	147
5.	2051	166

Table-3: Basic Household Supply

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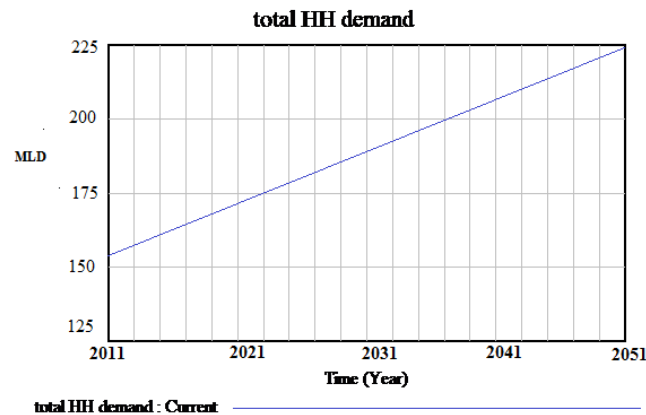
Household Demand by 2041 for 100 wards of Madurai city:

Fig -6: Total HH Demand

S.No	Year	Demand (in MLD)
1.	2011	154
2.	2021	172
3.	2031	188
4.	2041	210
5.	2051	225

Table -4: Total HH Demand
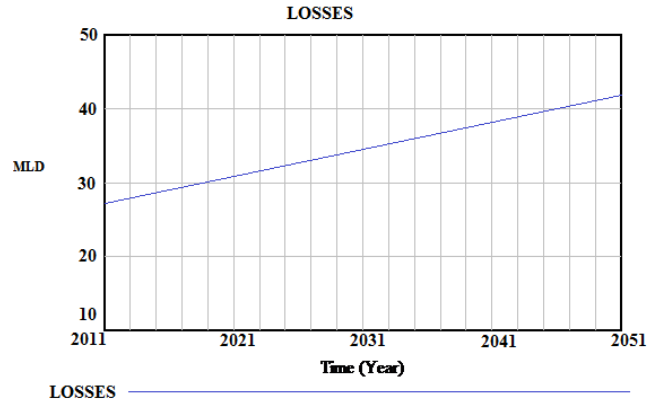
Losses by 2041 for 100 wards of Madurai city:

Fig -6: Losses

S.No	Year	Losses (in MLD)
1.	2011	27
2.	2021	31
3.	2031	35
4.	2041	38
5.	2051	42

Table -5: Losses

Total Demand (HH and Losses) by 2041 for 100 wards of Madurai city:

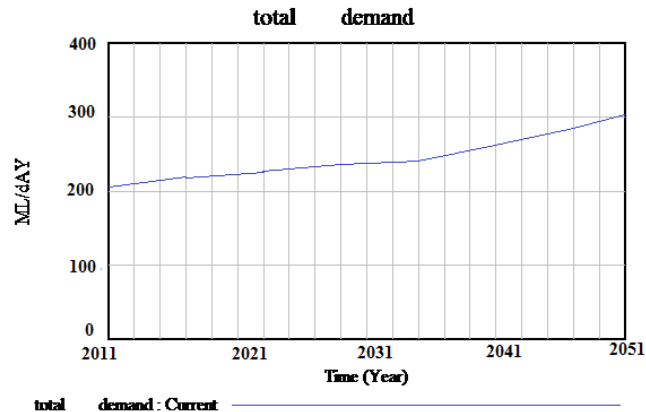# International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Fig -6: Total Demand

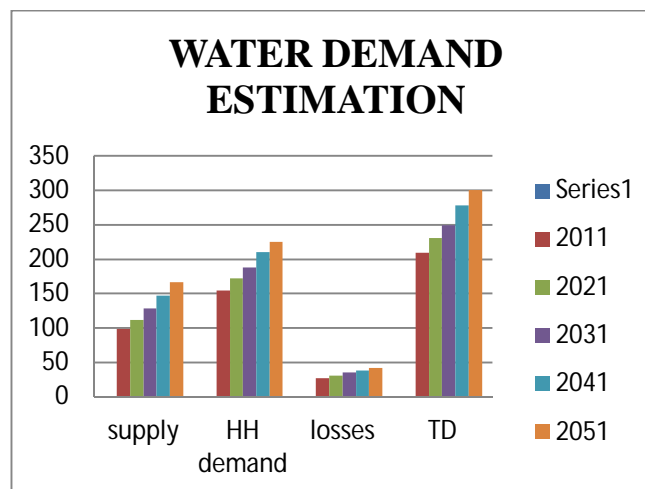| S.No	Year	Losses (in MLD)
1.	2011	209
2.	2021	230
3.	2031	249
4.	2041	278
5.	2051	300

Fig -7: Total Demand

Chart -1: Consolidated Water Demand Estimation For Madurai City

VI. CONCLUSION

A detailed literature review was carried out to study the different water demand estimation models and to identify the factors influencing water demand estimation. It has been identified that sustainable and accurately predictable water demand estimation model is System Dynamics Model. The System Dynamics model has been formulated using the software called Vensim PLE for the study area. The water demand has been projected by 2040 for the study area.

System Dynamics model has been simulated to find the water demand. It has taken the several runs to estimate the appropriate water demand. The forecasted water demand increases in each decade. Water supply doesn't able to satisfy the required demand of water and simultaneously losses also increases. Identified future water demand for the study area has been validated by using the historical demand data and projected demand data using simple mathematical calculations. It has been suggested that the rainwater harvesting policy must be followed strictly. The losses due to Physical failure, improper maintenance, unauthorized connection etc., It has to strictly monitored to reduce the loss rate and manage the required demand.

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