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Modeling of Complex Egyptian Water Networks' Performance Using System Dynamics

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Abstract:
Water utilities are increasingly facing daily challenges related to managing complex water networks. Decisions should be taken to solve water networks' problems. However, solving these problems need decision supporting tool to simulate and analyze all possible scenarios and get the optimum solution. System dynamics (SD) model can help in solving such dilemma by modeling the complex and dynamic water networks and simulating different scenarios to get the optimum solution. This paper proposes SD model to help water sector managers in Egypt simulating their strategies of repair. The proposed model will use system dynamics to simplify the analysis of complex water networks. The proposed model will stimulate the effect of important variables on the overall network performance. Theoretical case study is used to demonstrate the model formulation and to discuss its result. This paper is useful for practitioners and researchers to help water sector's decision makers to improve their decisions.

Keywords: *System dynamics, water networks, water utilities, modeling, public utilities, causal loops*

1. Introduction

Even though in many developing countries water supply and sanitation services have been provided by state-owned public water utilities (Ndokosho et al., 2007), these public water utilities have failed to provide consumers with adequate water supplies due to high water losses in their distribution systems (Baietti et al., 2006). Non-revenue water loss (NRW) is a worldwide problem that every water utility has (Kingdom et al., 2006). In water distribution systems, the main reasons for losses are physical such as leakages as well as apparent losses in the form of illegal connection and non-sustainable billing systems. This resulted in some water utilities losing more than 50 percent of their treated water. NRW in the distribution system worldwide ranges from 15 percent to 60 percent of the total water produced (Balkaran and Wyke, 2002).Water Networks management is not technically difficult, but it is complex. Simple explanation fails to consider the fact that implementing the NRW reduction program is inherently complex. It requires addressing, ina comprehensive manner, the various problems that lie at the root of the poor performance of a water utility. This represents a challenge that goes beyond just NRW performance (Kingdom et al., 2006). **Error! Reference source not found.** presents the International Water Association (IWA) standard water balance.

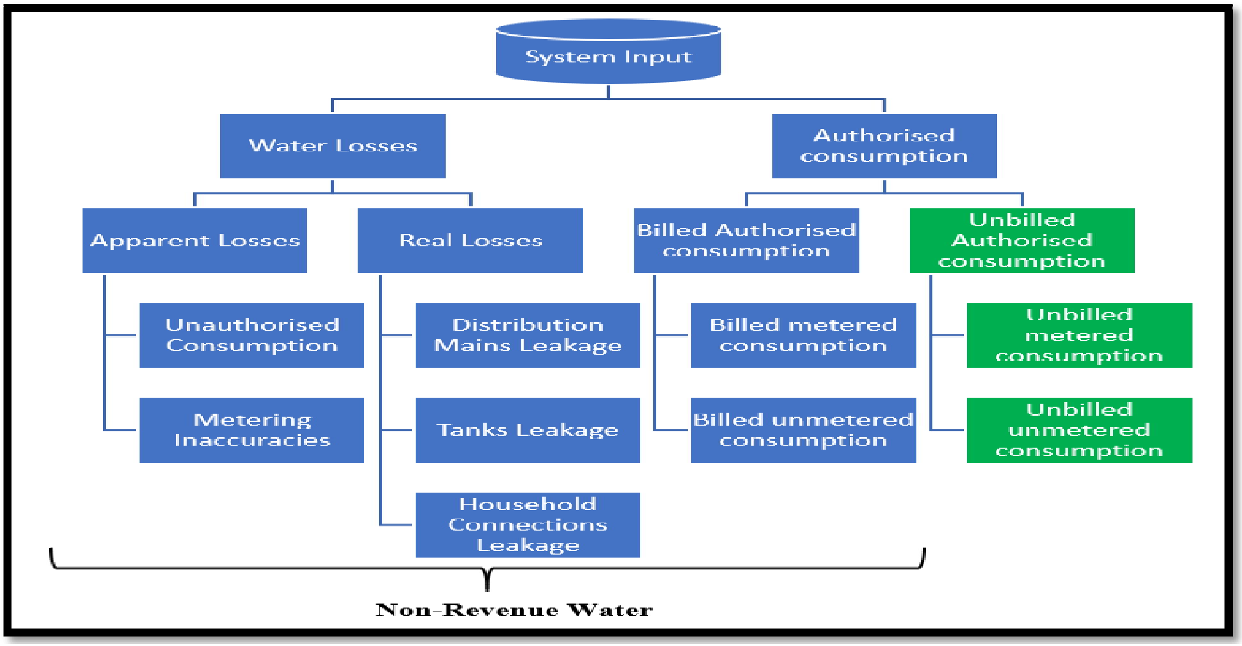


Figure 1: Standard International Water Balance (Iwa)

2. Literature Review

System Dynamics (SD) is a modeling tool that provides an understanding of strategic problems in complex dynamic systems. SD models provide users with insight into the feedback processes and dynamic behavior of a system. SD models have been used by several researchers within the domain of infrastructure and construction systems. (Hong et al 2011) developed a model to capture the complex relationships between public policy decisions and sustainability performance of highway projects. Applications of SD in project management include project change management (Motawa et al 2007) and corrective managerial actions (Pena Mora et al 2008). Other applications include modeling complexities in real estate market (Huang and Wang 2005), public policy and nuclear power plant construction (Taylor et al 2011), highway maintenance optimization (Fallah-Fini et al 2010) and financial viability of water utilities (Rehan et al 2011).

This model is made up of feedback loops and their variables, which are known as causal loop diagrams or influence diagrams. In system dynamics, several diagramming tools are used, including Causal loop diagrams (CLD), and Stock and Flow maps (SFM).The following sections provide an overview of these techniques.

2.1. Causal Loop Diagram (CLD)

CLDs are an easy to understand diagram that represents the feedback structure of a system. They consist of variables, causal links, and important causal loops which are also identified in the diagram (Sterman 2000),

Figure ***2*** represents the important notations of CLD. In CLD different loops will be generated based on various assumptions and different relation among variables. Each CLD contains different notations, reinforcing or balancing loops, and other links, as shown Figure 2. A positive link means that all dependent variables are directly proportional to the originate cause, so that when the cause increase/decrease the depending variables increase/decrease above/below their current state. A negative link indicates that the dependent variable is inversely proportional to the cause, so that when the cause increases (decrease) the depending variable decrease (increase) below (above) what would have been.

Feedback loop is indicated that a loop of interconnected variables, when any variable of this loop is changed, the originating variable will be changed based on the propagation of changes through the loop. When the change in the originating variable causes a change in other variables that strengthens the original process, the feedback loop is calleda reinforcing or positive feedback loop. While,if the change counteracts the original process, the feedback loop is called balancing or negative feedback loop (Hesham 2012).

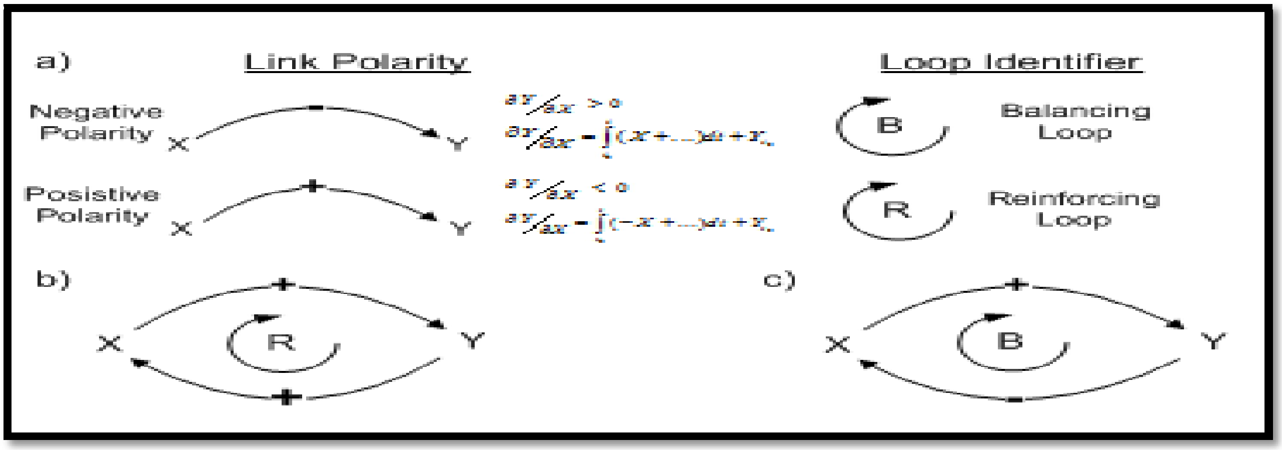


Figure 2: Causal Loop Diagram Notation (Hesham 2012)

2.2. Stock and Flow Diagrams

CLD are very useful at the beginning of the modeling process, as they can capture feedback loops of the analyzed system. However, they suffer from the inability of capturing the Stock and Flow behavior of the system's variables. Stock and flow, along with feedback loops are two central concepts of system dynamics (Sterman 2000).

Stocks represent variables with an accumulating nature, while flows represent the variables that cause the accumulations (rates of accumulation). In Stock and Flow Diagrams, stocks are represented by rectangles and flows are represented by arrows. The value of a stock variable is changed during simulation only when its flow variables are changed (inflows or outflows). Flows can originate/terminate from/at a stock or a cloud (thin air). Clouds represent unlimited stocks outside the boundary of the modeled system, such that they never get dry or full.

This research proposes using system dynamics to help understanding the complexity of water networks. System dynamics can give insights to decision makers to evaluate different policies and strategies to improve the overall network performance. This paper will focus on how factors like (Network pressure, water consumption, and Infrastructure level index (ILI)) can affect the performance of the network. Thus, will help decision makers to consider the effect of these factors on their final decisions regarding repairing or improving network performance.

In this paper, a causal loop diagram will be developed to efficiently represent the complex relations and feedback loops between various sectors (Apparent losses "Also known as: Commercial losses", Real Losses "Also known as: Physical losses", and Consumption). A System Dynamics model with illustrative example will be developed for the water network, using Vensim PLE, to demonstrate the proposed model and its relationships.

3. Proposed Model

The proposed Causal Loop Diagram (CLD) is shown in **Error! Reference source not found.**.CLD of the proposed system dynamic model shows the relation between several variables as shown in **Error! Reference source not found.**.

#	Variable	Unit
1	Commercial losses %	%
2	ILI (Infrastructure Leakage Index) *	Dimensionless
3	L/C/D (Water Requirement) *	Liter/Capita/Day
4	Max WTP Capacity	Cubic meter
5	Network pressure	m
6	Person/HH *	Person
7	Population	Person
8	Network Length	Km
9	Current Annual Physical losses (CAPL)	Cubic meter
10	Unavoidable Physical losses (UAPL)	Cubic meter
11	Physical Losses	Cubic meter
12	Commercial Losses	Cubic meter
13	Losses	Cubic meter
14	Consumption (COSP)	Cubic meter
15	Water in Networks	Cubic meter
16	NRW Indicator	%

Table 1: List of Variables Used in the Proposed SD Model
** These Variables Will Have Different Values during Model Simulation*

The CLD consists of two types of causal relations, The Feedback loops and non-looping. An example on the feedback; the reinforcing feedback loop R1 (in bold) accompanied with thick arrow to represent the direction of causation.R1 represents the relation between losses and production. It includes three variables:1) the amount of produced water (Pro); 2) the amount of water in networks (W Blnc); and 3) The amount of water losses(Losses). All three variables are measured in cubic meter per month. The causality of the loop indicates that: 1) as the water production increase, the amount of water in the networks increases; 2) the increase of water amount in networks is accompanied with an increase in the amount of water losses.

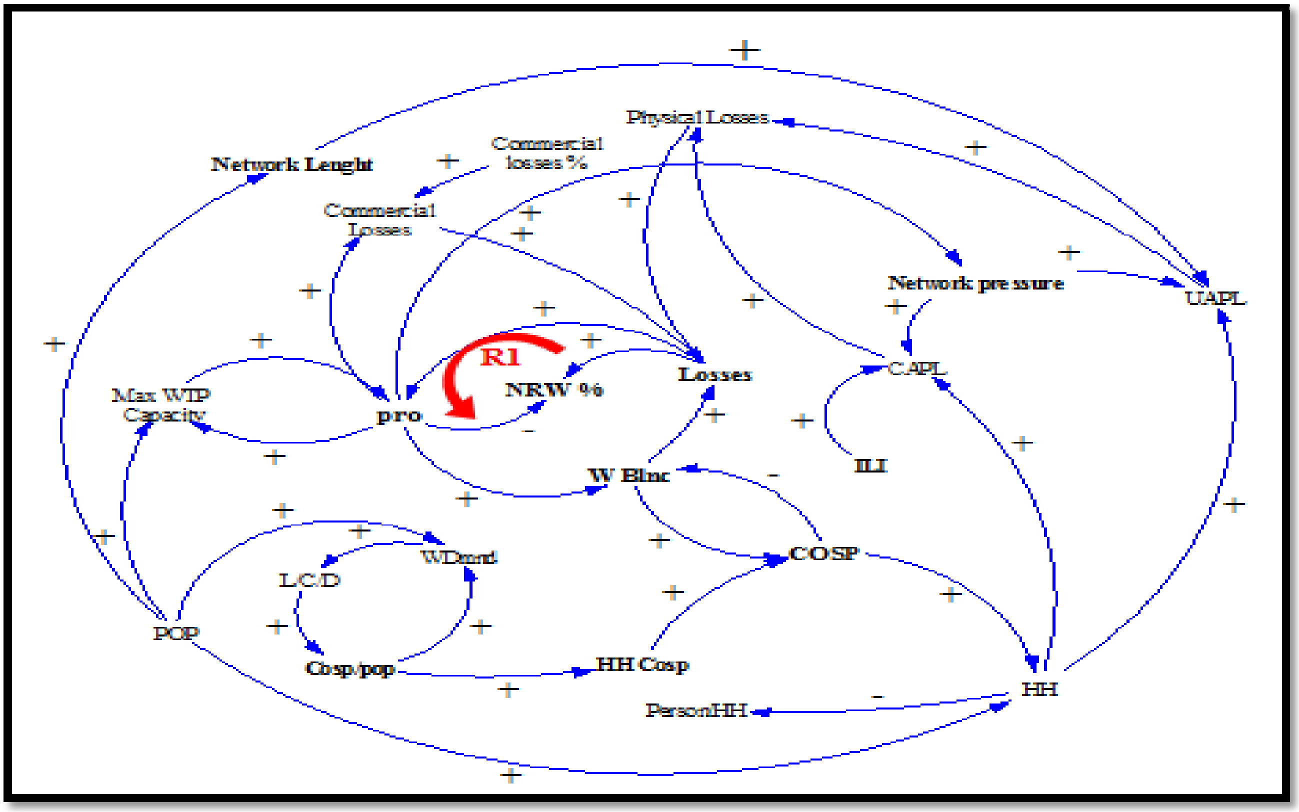
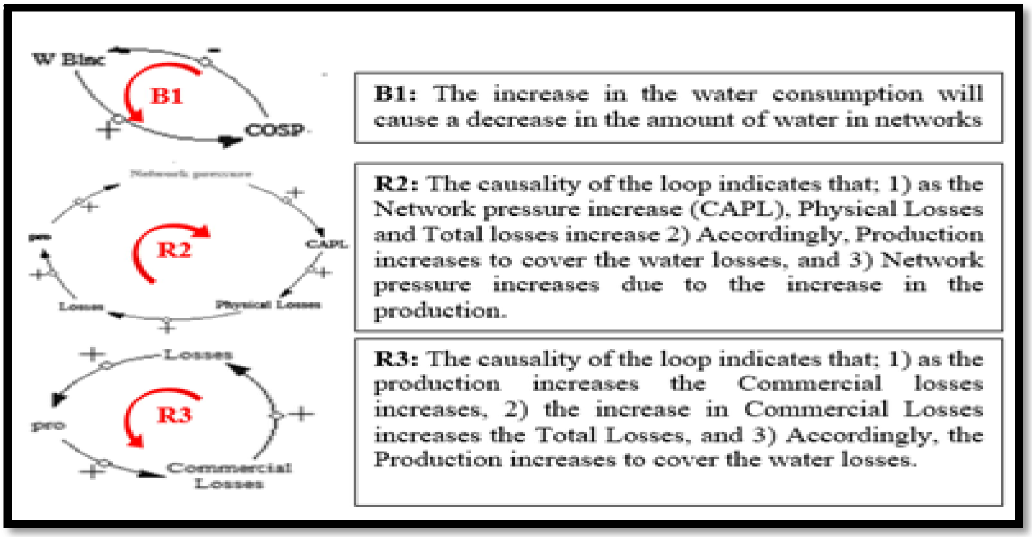


Figure 3: Proposed Causal Loop Diagram

Some variables are connected through a non-looping causal relationship in the SD model, for example, between the ILI (infrastructure leakage index) and the CAP indicates that the ILI directly affects the CAPL. Also, this type of relations could be shown in the relation from the Water requirement (L/C/D) to the Consumption (Cosp). Additional Feedback loops are shown inFigure 4 with a brief description of relation type.



B1: The increase in the water consumption will cause a decrease in the amount of water in networks

R2: The causality of the loop indicates that; 1) as the Network pressure increase (CAPL), Physical Losses and Total losses increase 2) Accordingly, Production increases to cover the water losses, and 3) Network pressure increases due to the increase in the production.

R3: The causality of the loop indicates that; 1) as the production increases the Commercial losses increases, 2) the increase in Commercial Losses increases the Total Losses, and 3) Accordingly, the Production increases to cover the water losses.

Figure 4: Feedback Loops

A SD model as shown in Figure 5*: Proposed System Dynamics Model*

is developed using Vensim PLE, which captures the relationships between the different variables shown in **Error! Reference source not found.**. The numerical data that are assumed in the illustrative example to highlight the model's components and to illustrate the model capabilities.The model components' description and other related information arepresented in the following sections. Each equation represents the relation among different variables. The proposed system dynamics model has six major key performance indicators (KPI), which can be affected by changing the values of several variables as shown in Table 2 *: Initial Values of Models Variables*

** Variables Used In This Study to Test the Proposed System Dynamics Model*

. This paper focuses only on analyzing the six major factors by changing only three variables (L/c/d, Person/HH, ILI). Later, more analysis and other case studies can be done to deeply analyze the effect of all variables on the whole water network condition and other KPIs.

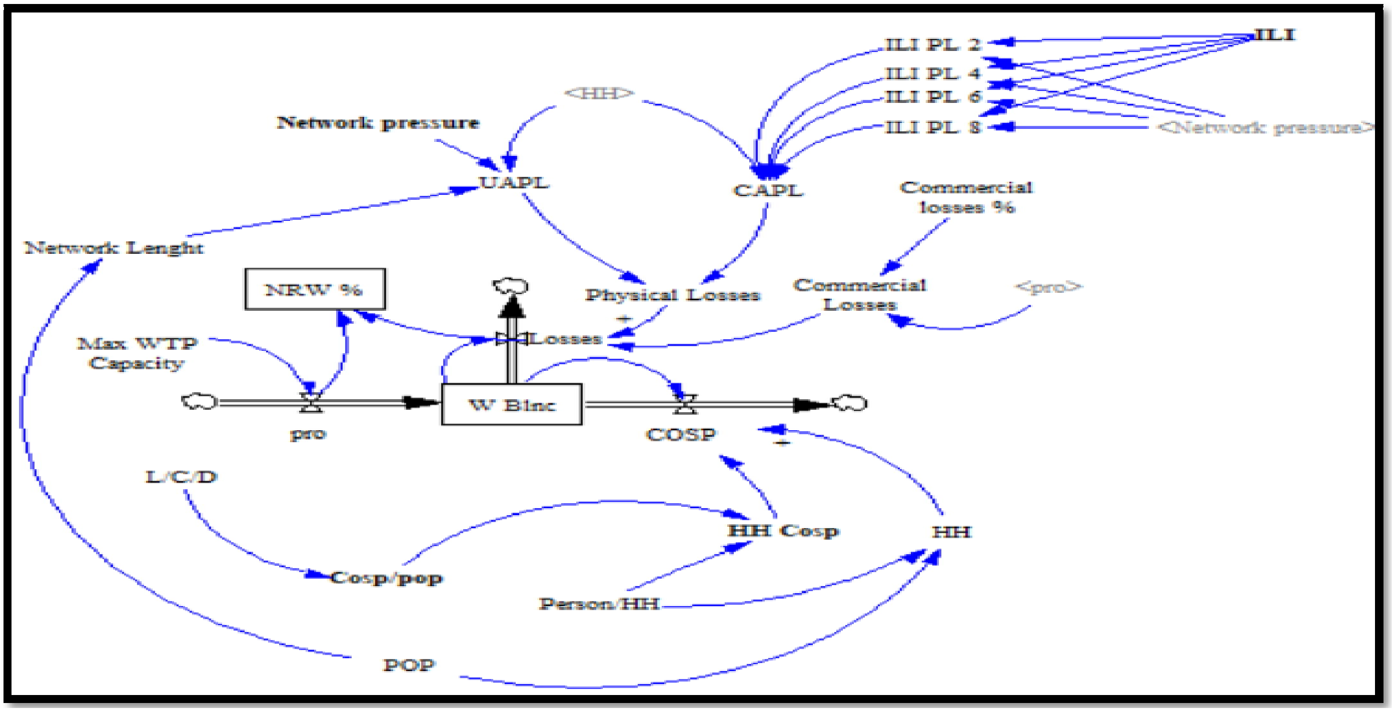


Figure 5: Proposed System Dynamics Model

3.1. Simulation Assumptions

Simulation assumptions consist of two parts; the model properties and the variables' constant values. Before building the model, the properties of the model which define the model boundaries and behavior were assigned; the following are the main model properties:

INITIAL TIME = 0 Units: Month
FINAL TIME = 240 Units: Month (Analysis horizon 20 years)
SAVEPER = TIME STEP Units: Month the frequency which output is stored.
TIME STEP = 1 Units: Month the time step for the simulation.

A Variable (indicated as Text only without rectangular Shape) can be an equation that depends on other Variables, or it can be a constant value. Table 2 *: Initial Values of Models Variables*

** Variables Used In This Study to Test the Proposed System Dynamics Model*

shows the initial values of the model variables. The numbers are based on actual data collected from several water utilities (EWRA, AIR-2013, 2014, 2015) in Egypt. Variables with asterisk sign (*) will be used in this study to test the proposed system dynamics model.

Variable	**Value**	**Unit**
Commercial losses %	30	%
ILI (Infrastructure Leakage Index) *	5 (Poor)	Dmnl
L/C/D (Water Requirement) *	250	Liter/Capita/Day
Max WTP Capacity	67000000	Cubic meter
Network pressure	20	m

Person/HH *	10	Person
Population	4771330 "+ 12000 each 40 years"	Person

Table 2 : Initial Values of Models Variables
** Variables Used In This Study to Test the Proposed System Dynamics Model*

3.2. Network Length

Network length depends on the total population served. An equation willbe formulated to calculate the total network lengthto consider the overallpopulation on the total network length). Currently there is no anyliterature found to formulate this equation, soto obtain such equationseveral data were collected from different water utilities in Egypt to establish a best fit curve between the two variables (EWRA, AIR – 2013,2014,2015). The chart in Figure 6shows the best fit curve for the collected data, the (In) equation, and the R-squared value for the equation. Accordingly, the equation used to simulate the relation between the population and the total network length is

Network Length= 5141.5*LN (POP) – 70219 Equation 1

Where:
POP: Total population served

Based on the data collected from 9 different water utilities, the average population served for all companies has been used to verifytheaccuracy and to validate the proposed equation. The results show high convergence between actual data and the proposed equation.Based on this verification the assumed equation seems to be valid and can be used in the model.

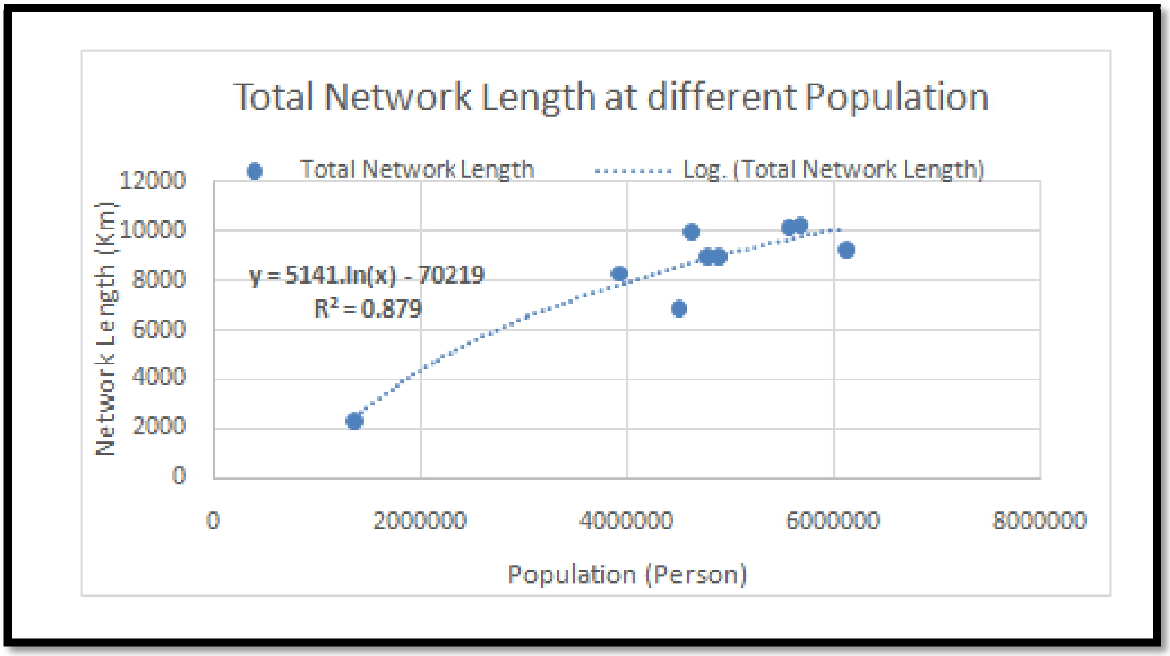


Figure 6: Network Length at Different Population

3.3. Current Annual Physical Losses (CAPL)

The CAPLcan be calculated based on ILI (infrastructure leakage index), Network pressure and HH (Number of Households "Connections"). Infrastructure Leakage Index (ILI) indicates the level of management efficiency of a water utility. Also, itcan bebest indicator for physical water losses. The ILI represents the ratio of total leakage losses to the background leakage (McKenzie and Wegelin, 2009; and Farley et al., 2008). Table 3 shows the anticipated ILI levels and physical losses at different pressure levels.

Technical Performance category		ILI	Physical Losses[litres/connection/day] (When the system is pressured) at an average of				
			10m	20m	30m	40m	50m
Developed countries	A	1-2		<50	<75	<100	<125
	B	2-4		50-100	75-150	100-200	125-250
	C	4-8		100-200	150-300	200-400	250-500
	D	>8		>200	>300	>400	>500
Developing countries	A	1-2	<50	<100	<150	<200	<250
	B	2-4	50-100	100-200	150-300	200-400	250-500
	C	4-8	100-200	200-400	300-600	400-800	500-1000
	D	>8	>200	>400	>600	>800	>1000

Table 3: Physical Losses Target Matrix (Winarni, 2009)

Table 3 can guide decision makers to calculate ILI then classify the network category to propose optimum solutions and repair options:

- Category a — Good. Further loss reduction may be uneconomic and careful analysis is needed to identify cost-effective improvements.
- Category b — Potential for marked improvements. Consider pressure management, better active leakage control and better maintenance.
- Category c — Poor. Tolerable only if water is plentiful and cheap, and even then, intensifies NRW reduction efforts.
- Category d — Bad. The utility is using resources inefficiently and NRW reduction programs are imperative."

To integrate ILI with the proposed SD model, linear relations were developed for each ILI value to obtain the physical losses value at different pressures. Figure 7 shows the linear relation equation and the R-squared Value for each equation. (Winarni, 2009)

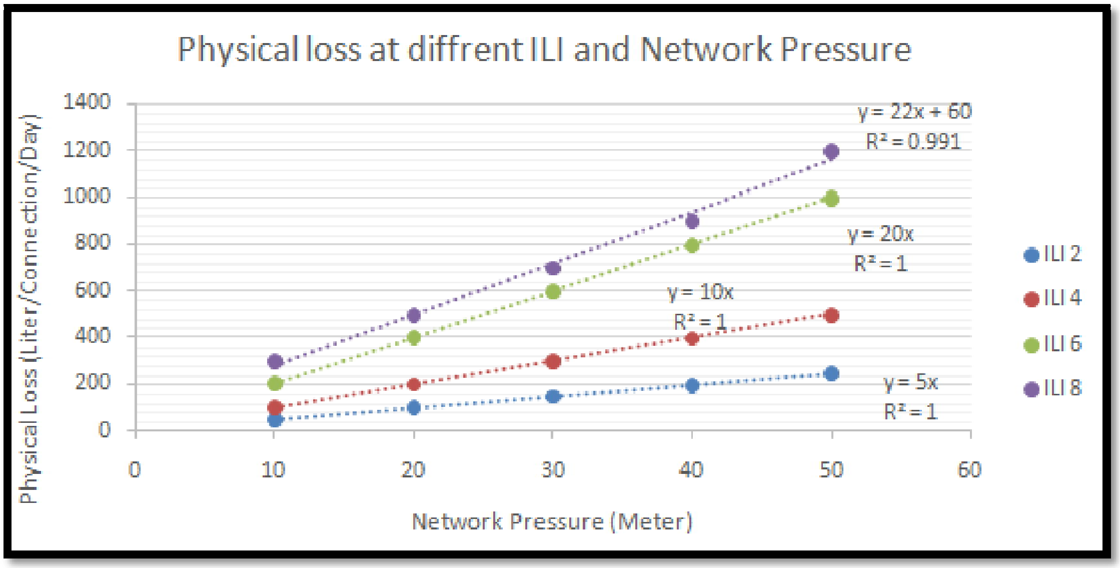


Figure 7: Physical Losses at Different ILI and Network Pressure

Based on Figure 7, the initial equation to calculate the CAPL would be:

CAPL= ILI * 30* HH / 1000 Equation 2

Where:

CAPL: Current annual physical losses

HH: Household (Connections)

However, to make it possible for the simulation software to simulate the change in the ILI and the network pressure at the same time; four variables were created to represent the different levels of ILIPL based on the input ILI (ILI PL 2, ILI PL 4, ILI PL 6, and ILI PL 8). Changing the ILI through the range from 1 to 8 will trigger the respective ILI PL level and the rest will be at value of (Zero). The ILI PL levels equation are as follows:

ILI PL 2= 5* Network pressure Equation 3

IF (ILI <= 2) AND: (ILI >= 1), else = 0

ILI PL 4= 10* Network pressureEquation 4

IF (ILI <= 4):AND: (ILI > 2), else = 0
ILI PL 6= 20* Network pressureEquation 5
IF (ILI <= 6):AND: (ILI > 4), else = 0
ILI PL 8= 22* Network pressure+60Equation 6
IF (ILI <= 8): AND: (ILI > 6), else = 0

As shown in the equations above, “If Condition” was used to identify the ILI and chose the correct equation accordingly. During the simulation one variable only from the ILIPL would have a positive value and others will have a value of Zero. The final equation to calculate the CAPL will be;

CAPL= (ILI PL 2+ILI PL 4+ILI PL 6+ILI PL 8) * 30* HH / 1000
Equation 7

3.4. Unavoidable Physical Losses (UAPL)

The lowest technically reachable annual volume of real losses for well-maintained and well-managed network is identified as unavoidable annual physical losses (UAPL) (Radivojevic et al., 2007). UAPL also can be defined as a percentage of underground system leakage that is too hard to locate and repair or too small to detect using current technology (Çakmakci et al., 2007). UAPL can be measured using a formula developed by IWA Water Losses Task Force (Lambert et al., 2000). UAPL value depends on the number of household connections (Nc), the length of networks mains (Lm in km) and the length of household private pipes (Lp in km) between the streets, property boundary and customer meters, and the average operating pressure (P in metres). According to Lambert and Lalonde(2005) the general equation for UAPL calculations is:

UAPL = (18 x Lm + 0.8 x Nc + 25 x Lp) x P Equation 8

Where:
UAPL = Unavoidable Annual Physical Losses (L/d)
Lm = Length of mains (km)
Nc = Number of service connections (main to meter)
Lp = Length of unmetered underground pipe from street edge to customer meters (km)
P = Average operating pressure at average zone point in meters

Equation 8 was then modified to be usedinto model assumptions. Divided by 1000 to convert into cubic meter instead of liter. Then, multiplied by 30 to convert to month instead of day. The Lp (Length of unmetered underground pipe from street edge to customer meters (km) isassumed to be 10 meters (0.01 Km). The Lm (length of mains) substituted by the variable “Network Length”. The Nc (Number of service connections (main to meter)) substituted by the variable “HH” (Households). The P (Average operating pressure at average zone point in meters) substituted by the variable “Network Pressure”. The final equation to be used by the proposed model will be:

UAPL = ((18* Network Length+ 0.8* HH+ 25* 0.01) * Network pressure) * 30 / 1000
Equation 9

3.5. Physical Losses

Physical losses includeleakage from all parts of the system and overflows at theutility’s storage tanks. They are caused by poor operations and maintenance, the lackof active leakage control, and poor quality of underground assets. The equation used in the model to simulate the physical losses (in cubic meter) is:

Physical Losses= (CAPL+ UAPL) Equation 10

Where:
UAPL = Unavoidable Annual Physical Losses
CAPL = Current annual volume of physical losses

3.6. Commercial Losses

Commercial losses are also known as apparent Losses (AL). Such losses represent those losses that are a result of faulty meter reading, meter inaccuracies, unauthorized water usage, and data mishandling (AWWA, 2009).The commercial losses were calculated using the following equation

Commercial Losses = "Commercial losses %" * pro / 100Equation 11

Where:
Commercial losses % = constant variable set to 30 %
Pro = amount of water produced (Cubic meter)

3.7. Total Losses

Water losses are two types of losses: apparent or commercial losses, and real or physical losses. Apparent lossesthat is not physically lost, but apparently lost include water supplied through illegal connections; water stolen for resale; water consumption undercounted by inaccurate meters; and water sales that cannot be invoiced because meter numbers cannot be accurately correlated with customer names and addresses (Lambert, 2003). Physical losses include leaks from reticulation systems (especially households' connections), leaks from transmission or distribution mains and overflow and leaks from storage and balance tanks. The equation used to simulate water losses (in Cubic Meter) in the model is:

Losses= Commercial Losses + Physical Losses) Equation 12
IF (W Blnc=<0), else = 0
Where:
W Blnc = amount of Water in network (Cubic meter)

If condition was used in Equation 12 to simulate the case where the water in network is equal to zero (water networks are empty) or > Zero (not empty). In case of W Blnc was set to zero then Losses will equal 0, otherwise the value of losses will be the summation of the Commercial losses and the Physical losses.

3.8. Consumption (COSP)

To define the simulation equation of the water consumption, the following variables need to be determined: 1) number of customers which also reflect the number of connections, number of meters, and Households number; 2) The monthly consumption of Households. The typical equation for monthly consumption as shown in Equation 13:

COSP= IF THEN ELSE (W Blnc<0, 0, (HH Cosp)* HH) Equation 13
Where:
W Blnc = amount of Water in network (Cubic meter)
HH Cosp= monthly consumption per Household (Cubic meter)
HH = Number of households (Connections)

If there is no water in the networks the value of consumption will be zero. The "HH Cosp" can be calculated using "L/C/D" (Water Requirement) variable in cubic meter. And "HH" can be calculated using "POP" divided by "Person/HH" variables. Equations used to calculate both variables as shown from Equation 14 to 16.

"Cosp/pop"= "L/C/D"/1000*30 Equation 14
HH= POP/"Person/HH" Equation 15
HH Cosp= "Cosp/pop"*"Person/HH" Equation 16

3.9. Water in Networks

The variable "W Blnc" represents the amount of water in the networks. This variable was simulated into a stock. This stock increase by the flow "Pro" which affected by the "Max WTP Capacity" and decrease by two flows "Cosp" and "Losses". The "W Blnc" (in Cubic meters) is simulated using the following Integration equation;

W Blnc= INTEG (pro-Losses-COSP,0) Equation 17

3.10. NRW Indicator

Non-Revenue Water (NRW) is an indicator of operational efficiency of water networks. The standard method to calculate NRW according to IWA(2008) is a percentage by dividing total amount of water lost by total amount of water produced as shown in Equation 18.

"NRW %" = Losses/ pro* 100 Equation 18

4. Model Verification and Validation

Prior to use, the model was tested using three methods 'model debugging', 'model verification' and 'model validation'. The first method, 'model debugging', is to indicate and correct errors preventing the model from running properly (or at all).

Following Pruyt (2013), verification Targets errors that are obviously present. Those errors were fixed, and verification was done again until it is safe to proceed to the next method. Validation processes used in this study included direct structural tests and extreme condition tests. Direct structural tests assess the "validity of the model structure by directly comparing the simulated reference mode with knowledge about the real system" (Barlas, 1996). The second validation test – extreme condition testing – examined the degree to which themodel "responded plausibly when subjected to extreme policies, shocks, and parameters" (Sterman, 2000: 860).

5. Results and Discussion

The results of the model are summarized in this section with their out puts from SD model, with supplementary explanations necessary. The emphasis is on simulating a situation based on the assumptions, constraints, and constants stated earlier in model explanation. Four scenarios will be discussed and analyzed to show the applicability and effectiveness of the proposed model in analyzing complexity of water network performance. First scenario called 'Base' scenario which provide the reference mode against which different scenarios can be assessed. It's worth mentioning that all the scenarios that will be tested haveimpacton cost of the water service and will influence the utility financial situation however financial calculation is not included in this model.

Some variables have been selected to change their values in different scenarios to assess the effect of their change in the overall network performance and their effect on other variables as well. These changes are simulating the decisions that might be taken by the utility mangers to solve some of the current network problems. The variables and their values that will be changed during model analysis for different scenarios are shown in Table 4:

Variable	**Scenario (Base)**	**Scenario (1)**	**Scenario (2)**	**Scenario (3)**
L/C/D	250	200	250	250
Person/HH*	3	3	6	3
ILI	5	5	5	4

Table 4: The Variables and Their Values for Different Four Scenarios
**Average Person per Family Assumed To Be 3 Persons*

5.1. (Base) Scenario

Figure 11below shows the set of variables that will be used to assess the water network performance. Namely, First row; W Blnc (amount of water in networks), Cosp (water consumption) and NRW (No-revenue water), and in the second row; Physical losses, commercial losses and the total losses.

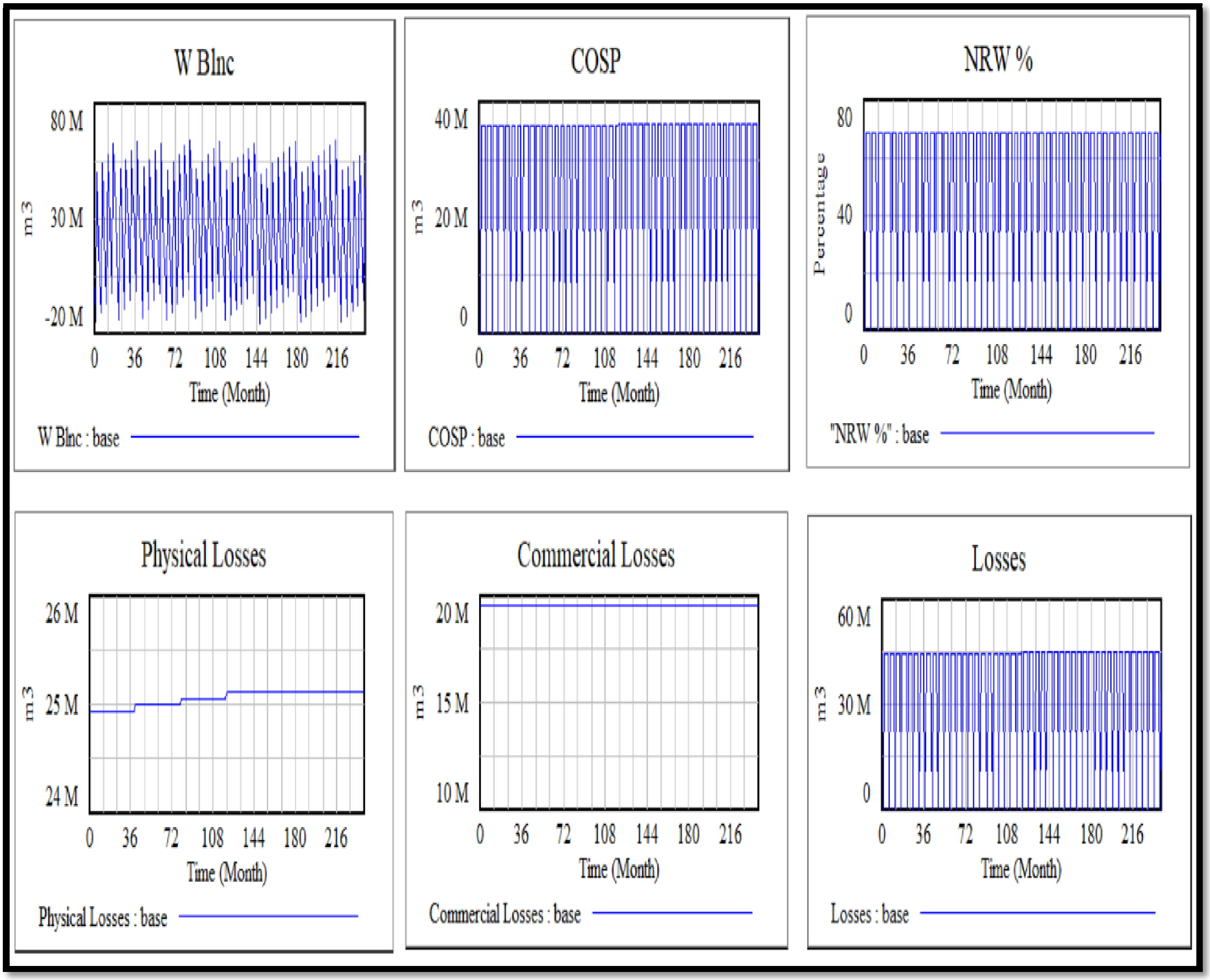


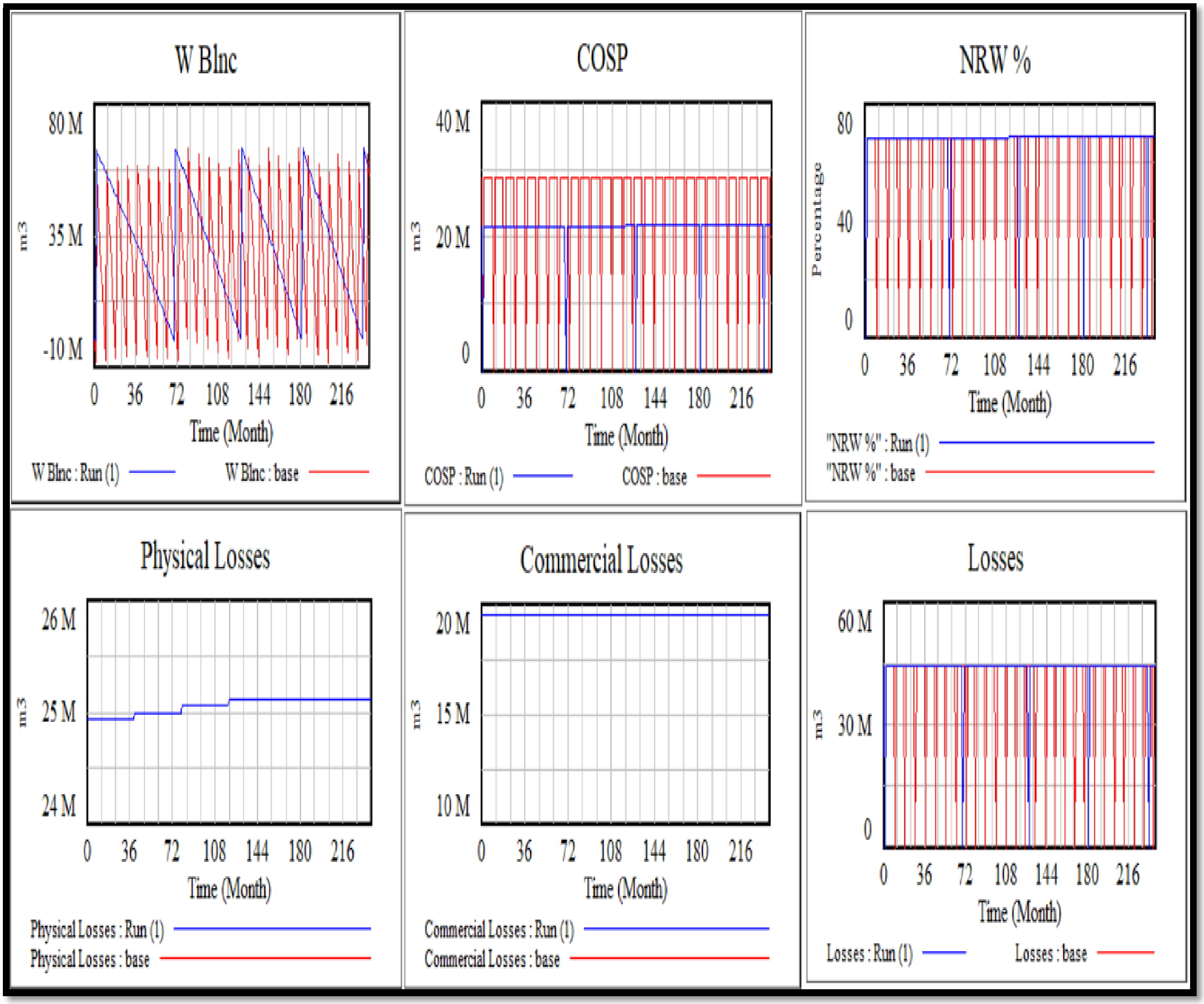
Figure 8: Set of Variables Used for Base Scenario

According to the graphs, the "NRW%", "Cosp" and "Losses" values clearly and rapidly fluctuate. All of them reach the value of zero and come back to positive value. This is due to the fluctuation in the "W Blnc" value throughout the simulation. This indicate that the water amount in the water networks vanished and no more water to be consumed or lost. The intervals between these drops represent the "service disconnection", which mean that the more drops occur the more water service is unstable and unsustainable.

By focusing on the positive values for each variable it can be concluded that the network performance is very poor. The "NRW%" is around 70%, which mean that the Physical losses are around 25 million cubic meter each month and the commercial losses around 20 million cubic meter each month.

5.2. Scenario (1)

In this scenario the water requirement for users' water consumption (Liter/Capita/day) is reduced from 250 L/C/D to 150 L/C/D. This could be done in real world by water conservation strategy.



W Blnc

COSP

NRW %

Physical Losses

Commercial Losses

Losses

Figure 9 shows the result of this scenario.

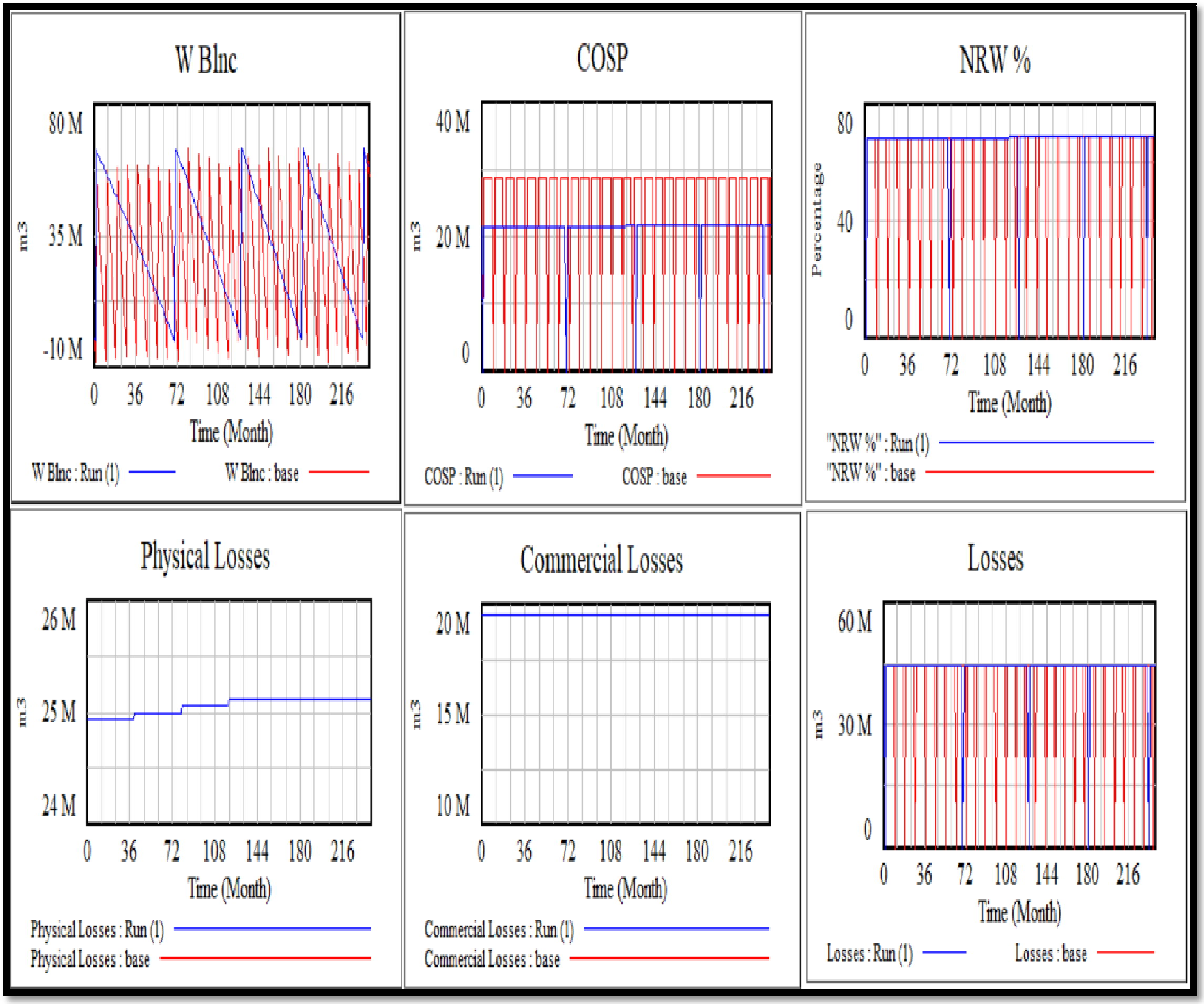


Figure 9: Model Set of Variables (Scenario 1)

As shown in Figure 9, the Base Scenario is represented in red while the Scenario (1) is represented in blue. Two behaviors can be observed, values range, and intervals. The variables values are almost the same except for the “Cosp”. This is due to the direct relation between the water requirement and water consumption. According to the simulation results, a decrease in the water requirement by 40% resulted in a decrease in the consumption by only 25 %.

The second behavior that can be observed is the drop intervals of service disconnection, the duration of the service sustainability increased. It can be concluded that 40% decrease in water requirement resulted in drop every 70 months instead of 9 months. By comparing these durations compared to the total duration of the simulation (240 months), it can be concluded that the sustainability increases from 3.75 % to 29 % which can be considered as a great enhancement for network performance. Accordingly, the reduction in water requirement had a great impact on the service sustainability problem, but it fails to solve or even affect the amount of water lost and accordingly failed to improve the NRW%.

5.3. Scenario (2)

In this scenario the Person/HH variable changed from 3 persons to 6 persons. This variable simulates the number of customers’ connections (no. of water meters). In the Base Scenario, the Person/HH equals3 means that each family (apartment) is connected to one meter. While this Scenario suppose that each 2 apartments are connected to one meter. This could be done in real world by meters rehabilitation strategy. Figure 10 shows the results of this scenario.

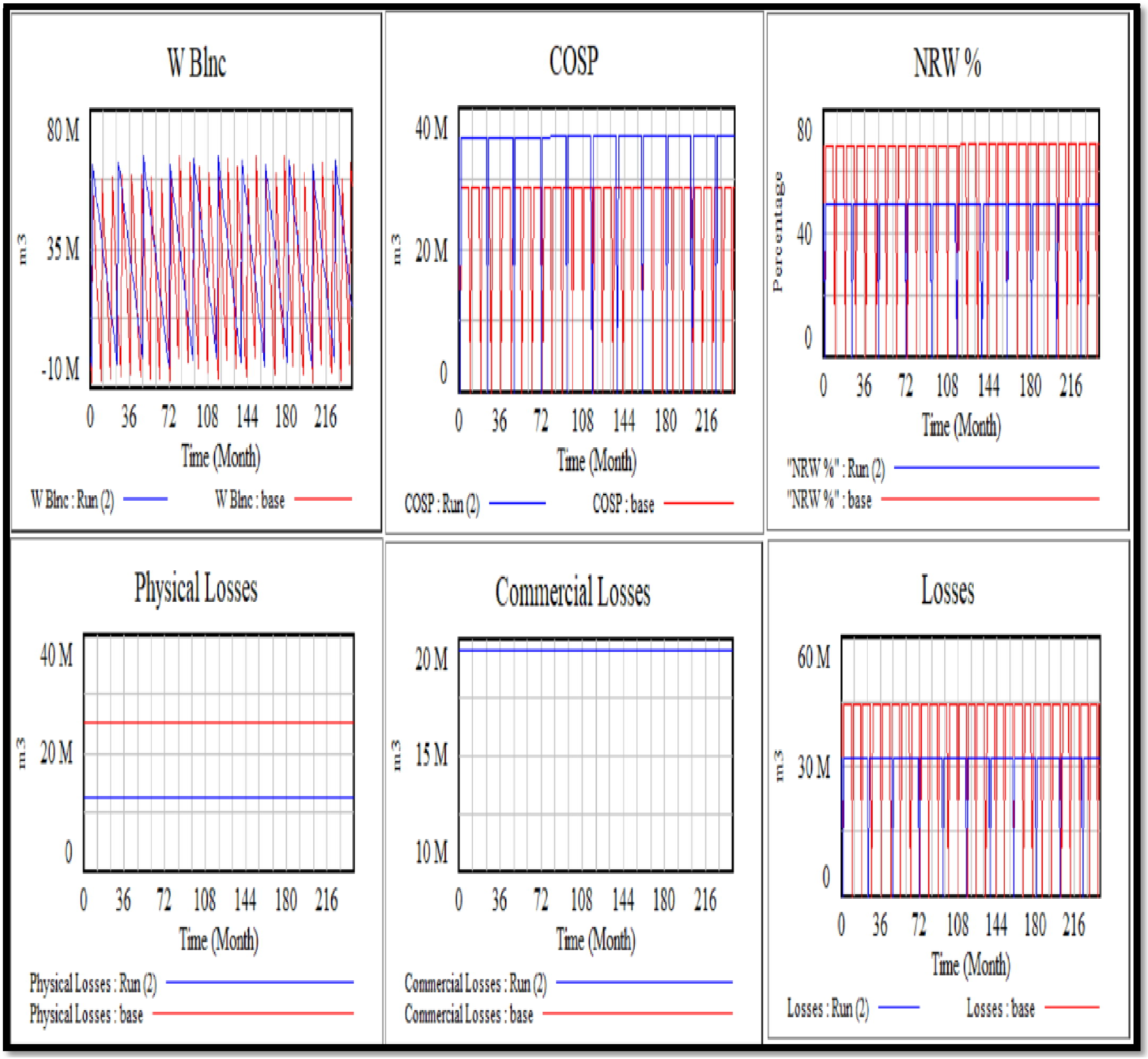


Figure 10: Model Set of Variables (Scenario 2)

As shown in Figure 10, the Scenario (Base) is represented in red while the Scenario (2) is represented in blue. The values greatly changed in the “Cosp”, “NRW%”, “Physical losses” and “Losses”, while the “W Blnc” change is moderate. The 50% decrease in the number of meters resulted in nearly 30% decrease in NRW and Losses, while about 20% increase in consumption. The reason behind the decrease in the losses is the reduction in number of household connections (meters) which are well knownas leakage spots. Accordingly, will result in more water available in network that will directly be used by users “Cosp”.

The intervals of the drop off (service disconnection), the duration of the service sustainability increased. The 50% decrease in the number of meters resulted in drop off every 25 months instead of 9 months. By comparing those durations to the total duration of the simulation (240 months), we will find that the sustainability increases from 3.75 % to 10 %.

5.4. Scenario (3)

In this scenario the ILI (infrastructure leakage index) variable changed from 5 to 4. This variable simulates the water networks condition. As explained earlier, ILI ranges are as follows (1-2 good 2-4 moderate 4-8 poor, and>8 bad). By changing the ILI from 5 to 4 the water networks condition changed from (poor) to (moderate). This could be done in the real world by water networks rehabilitation strategy. Figure 11 shows the results of this scenario.

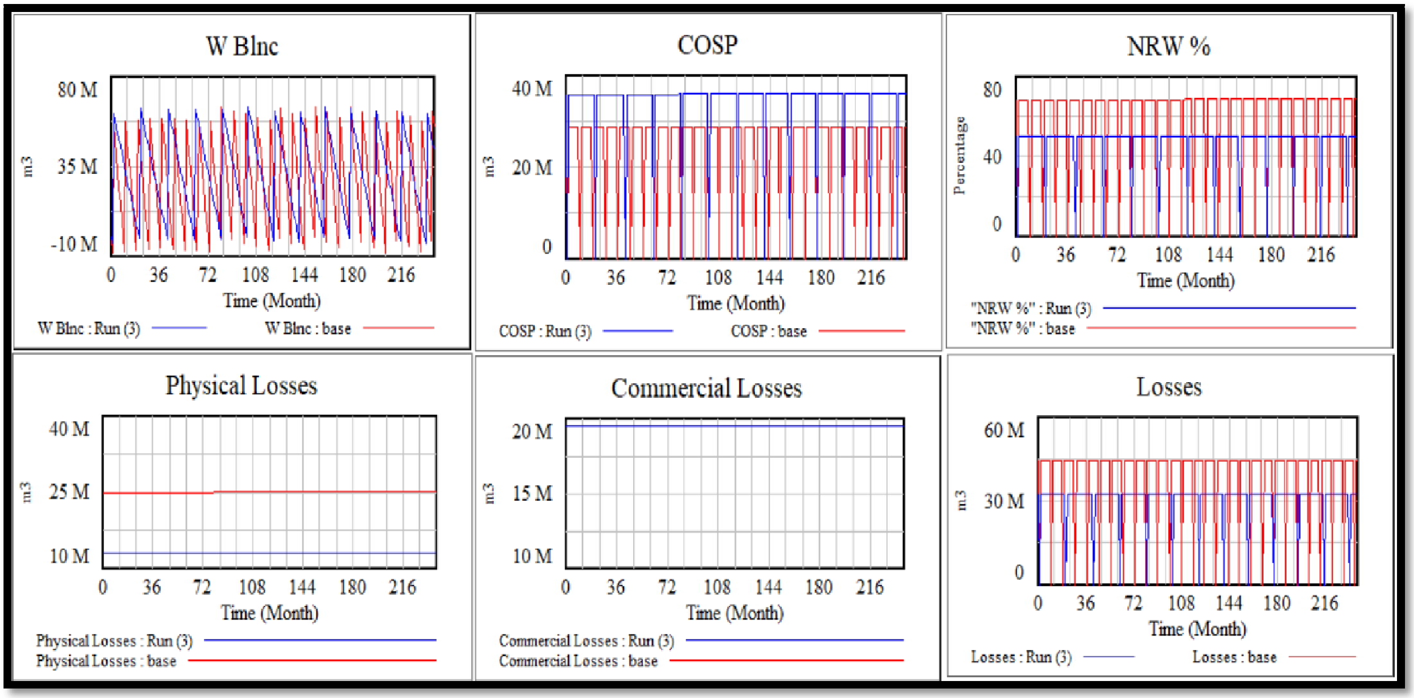


Figure 11: Model Set of Variables (Scenario 3)

As shown in Figure 11, the Base Scenario is represented in red while the Scenario (3) is represented in blue. The values behavior greatly changed in the “Cosp”, “NRW%”, “Physical losses” and “Losses”, while the “W Blnc” change is very moderate. This behavior looks very close to results of scenario (2).The investment in water networks rehabilitation to improve the ILI from 5 to 4 resulted in nearly 30 % decrease in NRW and Losses, while a nearly 25% increase in consumption. The reason behind the decrease in the losses is the reduction in network leakage. Accordingly, that will result in more water available in network that will directly be used by the users “Cosp”.

As the intervals of water drop (service disconnection) decreased, the duration of the service sustainability increased. The 50% decrease in the number of meters resulted in water drop every 25 months instead of 9 months. By aggregating these durations through the total duration of the simulation (240 months), the sustainability increases from 3.75 % to 8.75 %.

6. Conclusions

This paper presented a preliminary system dynamics model for modeling water network performance. The model used a specific set of variables to simulate the effect of the change in these variables on the network performance. This model focused on how utility managers may take decisions related to “water requirements”, “number of meters” and the “infrastructure leakage index” to improve the overall performance of the water network and reflect the effect of these changes on the “Users consumption” and “Losses”. An illustrative simulation example is presented to highlight how could any change in values of any variable has a propagating effect through the overall system’s variables. Preliminary results show that the developed SD simulation model can be used as a test bed to evaluate the impact of utility managers’ decisions on the overall water network performance and accordingly on utility goals. The developed model shows promising results that can help decision makers to optimize their decisions in order to minimize water losses and maximize actual water consumption, accordingly increase the total profit for the water utility.

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