System Dynamics Model for Estimating Water Pollution

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***Abstract*—Water resources are essential for all living organisms. They are used for domestic consumption, agriculture, transportation, recreation, etc. Thus, water quality degradation is a global challenge, according to the United Nations (UN). This paper provides a system dynamics model that helps us see the interrelationships among water quality and the factors that affect it. The following are factors that influence the water quality in this model: national water policy, water and wastewater management, industrial growth, agricultural growth, population growth, and people's awareness of health. These factors are grouped the three main sectors: household, industrial, and agricultural. This system dynamics model helps to generate an overview of the problem and see how each factor affects each other. Thus, this model contributes to improving the quality of water.**

***Index Terms*—System dynamics, Water pollution, Water quality, Water and wastewater management**

I. Introduction

The world in the 21st century has been facing many problems as a result of population growth [1, 2]. One of the major problems is the water quality problem, which continues to intensify. Approximately one-third of global biodiversity has been reduced as a consequence of intensifying water pollution problems [3-5]. In addition, water quality degradation has a direct impact on social, economic, and environmental quality [6, 7]. The problem of water pollution is worse in developing countries. Ninety percent of sewage in developing countries is directly discharged without treatment [8-10].

Water pollution is caused by many factors and comes from many sources. Sources of water pollution come from both point sources and non-point sources [5, 11, 12]. Most point sources' pollution is generated in the industrial sector [13]. UNESCO reports that industrial effluents are discharged into water bodies (approximately 300-400 megatonnes/year) around the world [5, 14]. Industrial wastewater has high hazardous chemical contamination, especially in metal finishing, electroplating, battery manufacturing, and chemical manufacturing industries [15-17]. For non-point sources, water pollution comes from agricultural and household sectors [7, 18]. For example, fertilizers and insecticides in the agricultural sector and household cleaning supplies in the household sector are products that can cause water pollution if discharged directly into water bodies [19]. Without proper wastewater and sewage treatments, these hazardous chemicals cause severe water pollution. Both point sources and non-point sources usually have a large amount of wastewater to release into water resources at a higher rate than a source's self-recovery capacity. This leads to persistently low water quality in water resources [20]. Due to the many factors that are involved in the deterioration of water quality, the need to understand an effective water quality system for water resources is important and desirable.

Recently, in order to reduce water pollution, water quality models, such as the Hydrological Simulation Program–FORTRAN (HSPF) [21], Watershed Analysis Risk Management Framework (WARMF) [22], and Soil and Water Assessment Tool (SWAT) [23], are widely used more than empirical methods [24-28] (e.g. differential analysis techniques, Fourier amplitude sensitivity test (FAST) [29]). The empirical models are constructed based on direct observations, measurements, and extensive data records [30]. They allow users to assess a variety of water resource allocation and management strategies. The empirical methods may not work properly on the deterioration of water quality problems because of nonlinearity, discontinuousness, intractability, and interaction of model parameters [31]. Some models, such as Morris Screening [32, 33] and General Sensitivity Analysis (GSA) [34, 35], are used to forecast water quality. However, these models can only provide qualitative predictions. Due to their mathematical complexity with a large number of parameters, these models often involve many uncertainties [36], especially when modeling water resource systems that have a lack of sufficient data for simulation and validation.

System Dynamics (SD), Discrete Event Simulation (DES), and Agent-Based Simulation (ABS) are methods that model complex systems. These methods have both advantages and disadvantages and are applicable in different situations. SD modeling is capable of analyzing complex systems, which have high abstraction, whereas DES modeling is used to analyze complex systems at low to medium abstraction [37]. ABS modeling is used for all levels of abstraction [37]. SD is able to model both continuous and discrete systems while DES and ABS are used in modeling discrete systems. An SD model is deterministic, but a DES model is stochastic in nature. An ABS model can be expanded from an SD model since all SD models have an equivalent formulation in an ABS model [38] . The outputs of ABS models show the complex behavior arising from individual decision-making [37, 39], while the SD models simplify an individual's decision making by aggregated entities in systems.

In this study, System Dynamics is used to describe the interrelationships of factors that influence the water quality in water resources. Many systems related to water resources are constructed using SD, such as water management systems, irrigation systems, and water quality systems [40-42]. Previous research on water quality systems was studied to improve water resource management. For instance, a water quality system was influenced by contaminated wastewater from wastewater treatment plants [42], and the Watershed System Dynamics model (WSD model) was developed to simulate population, land use, and runoff in the Nishi-Imbanuma basin, Chiba, Japan. The WSD model contained three sectors: agricultural sector, urban sector, and nature sector. These factors have interrelationships with water quality [43]. These studies did not directly study three social sectors: household, industrial, and agricultural sectors. Thus, this study differs from the previous studies as it applies the social interactions that have an influence on water quality. A Causal Loop Diagram (CLD) and a Stock and flow Diagram in SD are developed by using Vensim software, to show the interrelationships among different factors. This helps us to gain an understanding of the accumulation of water pollution.

II. Methods

System Dynamics models are used to model a water quality system in water resources. Since the main sources of water pollution in water resources are from household, industrial, and agricultural sectors, the SD model of a water quality system is composed of three subsystems, which include household, industrial, and agricultural subsystems [7, 44-46].

A causal loop diagram (CLD) is developed to show the interrelationships among causes and effects of factors that influence the water quality. A CLD consists of two components: variables and influences [47]. An influence has a direction represented by an arrow and an indicator that indicates a change of two variables. If two variables change in the same direction, then the indicator is represented by +. If two variables change in the opposite direction, then the indicator is represented by -. Another important notation is used to represent feedback loops. There are two main types of feedback loops. A balancing feedback loop (B loop) preserves the level of variables. For example, an increase in death rate reduces the population number, while an increase in population number increases the death rate, as shown in Fig. 1. The second type of feedback loop is a reinforcement loop (R loop) which is a loop that continuously increases or decreases the level of variables. As shown in Fig. 1, the population number increases (decreases) as the birth rate increases (decreases) since an increase (decrease) in population leads to an increase (decrease) in the birth rate. The population number depends on the types of feedback loops. Types of feedback loops usually determine the main behavior of a system [47].

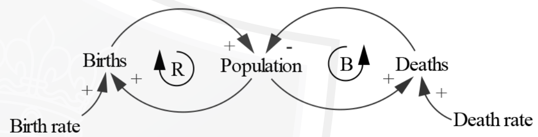

Fig. 1. Simple causal loop diagram of population growth

A stock and flow diagram is another useful model in SD. A fundamental component of a stock and flow diagram is stock, which is the level or condition of a measurable element at a point in time. Stocks are entities that can accumulate or deplete. A level of stock changes with the flows associated with the stock [48-50], as shown in Fig. 2. The population number is regarded as a stock. The population number increases when the inflow of births is higher than the outflow of deaths. However, the stock of population decreases when the inflow of births is less than the outflow of deaths.

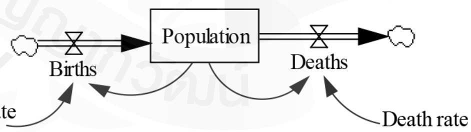

Fig. 2. Simple stock and flow diagram of population growth

III. Result and Discussion

Household Subsystem

Population growth leads to urban expansion and increases in food and water demand [51]. Wastewater and solid waste increase as a result of an increase in food and water demand [52]. Discharging untreated wastewater and solid waste into water resources leads to declining water quality. When water quality is degraded, people who live near water resources are affected by water pollution. As a consequence, these people become aware of water pollution [53, 54]. They are willing to restore water quality to have good water conditions around them for their consumption and other activities. When people have awareness of health, they are willing to follow government policies by reducing the discharge of wastewater and solid waste into water resources. Furthermore, people's awareness of health can influence the government to change policies, to increase wastewater treatment efficiency and improve solid waste disposal management. These policies can help to improve water quality. Fig. 3 shows the interrelationships between water quality and household consumption.

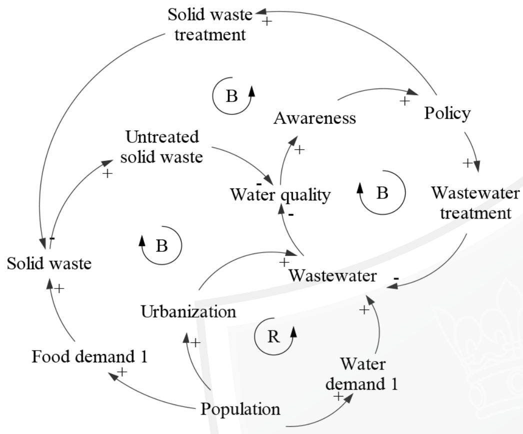

Fig. 3. CLD of water quality affected by household sector

Industrial Subsystem

Interrelationships between industry and water quality are described in Fig. 4. Population growth has resulted in economic expansion and industrial development to respond to human needs [55]. Consequently, higher production is necessary to support these needs. Most production processes use a large amount of water, which also means that they produce a large amount of wastewater. Some untreated wastewater is directly discharged into a water body and degrades water quality [56-59]. For example, aqueous wastes from the semiconductor electronics industry is the main source of chromium, nickel, cadmium, etc. in surface water [60]. As water resources are contaminated, industries and residents near a water resource are affected. They are aware of water pollution. Thus, they are interested in improving water quality [53]. This leads to public and private organizations cooperating to urge the national government to improve water resources.

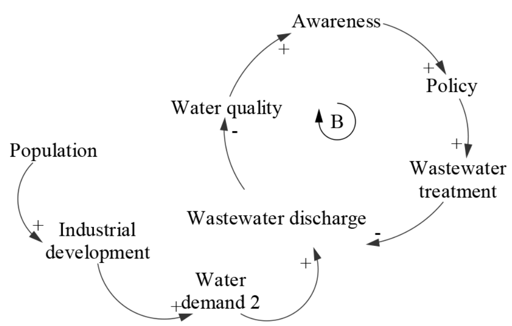

Fig. 4. CLD of water quality affected by industrial sector

Agricultural Subsystem

The increase in population has resulted in higher food consumption. Thus, an agricultural sector is required to fulfill this need [59, 61]. As the rate of cultivation increases, the amount of water used in agricultural processes also increases. As a result, the amount of wastewater from the agricultural sector increases. If untreated wastewater flows into water resources, then water quality degradation occurs. Fertilizers and chemicals that are used in agriculture mainly consist of organic matter [62]. If these components are overused on farms, then the unused amount of nutrients and organic matter are washed into water resources [45]. This leads to eutrophication which causes low water quality in water resources [20, 63]. When water quality is degraded, farmers cannot use water from water resources for their farms. Thus, farmers are aware of the problem and turn their attention to water quality problems [53, 54]. Farmers can be a driving force to require new policies to reduce fertilizers and chemical usage in cultivation. In addition, new policies to reduce wastewater and reuse water in plantations are encouraged. Fig. 5 demonstrates the interrelationships between water quality and agriculture.

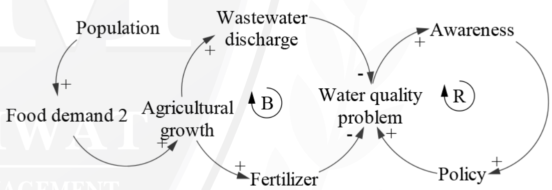

Fig. 5. CLD of water quality affected by agricultural sector

The interrelationships of the three subsystems can be summarized in Fig. 6. An increase in population results in urbanization and an increase in water and food demand, which are followed by an agricultural and economic expansion. In the process of cultivation and production, a large amount of water is used from water resources. As a result, a large amount of wastewater, solid waste, and leftover fertilizer are generated. Subsequently, water quality is degraded. The interrelationships of the three subsystems mentioned above show that those people who are affected by water pollution both directly and indirectly are more interested in and aware of the water pollution problems. When the people's awareness increases, people start to follow the national water policies. Also, they avoid releasing wastewater and dumping solid waste into water resources. These actions can eventually improve water quality.

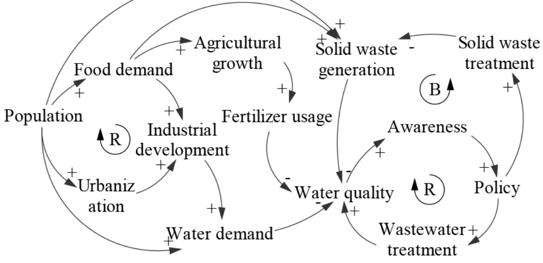

Fig. 6. CLD of water quality in a water resource

After perceiving the interrelationships of the three subsystems in the CLDs, a stock and flow diagram is created. To present the levels and flows of variables that are interrelated to water quality, a stock and flow diagram of a water quality system is presented in Fig. 7. The water pollution problem is intensified due to the influence of the volume of untreated wastewater and untreated solid waste in water resources. A factor that affects the amount of wastewater and solid waste is the population growth. The amount of wastewater discharge is also affected by industrial development and agricultural growth. To reduce the volume of wastewater, the water consumption and solid waste generation rate should be reduced. Increasing the capacity of wastewater treatment and solid waste treatment plants can reduce the amount of untreated wastewater and solid waste, respectively. Moreover, people's awareness of health is another factor that can indirectly reduce wastewater discharge and solid waste generation.

An example of a simulation run of the total water pollution generation for the next ten years in the world is shown in this paper. The equations that are used in the model are linear equations. The parameters in this model are from a literature review and assumptions. Table I shows all of the functions that were used in the model. Water consumption (WC) is calculated from the rate of water consumption (56,575 L/capita/year) [64]. Food demand (FD) is generated from the food consumption rate (334 Kg/capita/year) [65]. Agricultural growth (AG) and industrial development (IN) are generated from the percentage of GDP reported by the world bank [66]. For the functions of wastewater from farms (WF) and from industries (WI), we assume that an increase of 1% of GDP leads to a 50,000 L increase of wastewater. The awareness function is created by assuming that if the water pollution (WP) is lower than 5×10^{14} L, the awareness value is 0 (no awareness). Otherwise, the awareness value is 1 (awareness). The function of wastewater discharge (WD) is correlated with the awareness function. If the awareness value is 1, then people discharge only 80% of the wastewater, which is from the wastewater from consumption (WC), wastewater from farms (WF), and wastewater from industries (WI).

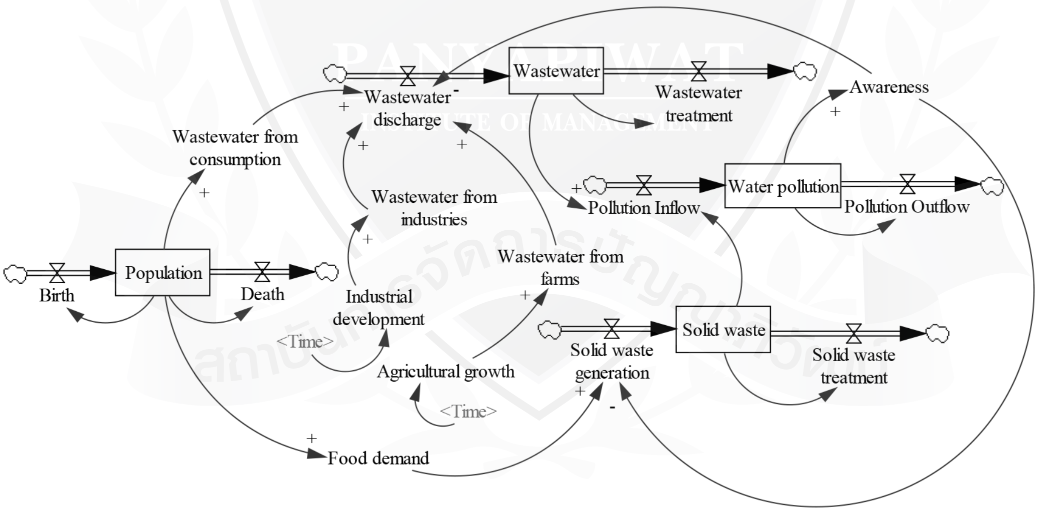

Fig. 7. Stock and flow diagram of water quality in a water resource

Otherwise, people discharge all of the wastewater. Solid waste generation (SG) is also correlated with people's awareness. If the awareness value is 1, then people dispose of 50% of the solid waste generation. However, if people do not have awareness, then they dispose of all of the solid waste generation. Pollution inflow (PI) is a combination of the water pollution occurring from wastewater and solid waste. The pollution of water occurring from solid waste is assumed to be 20% of the untreated solid waste. The population number (Pop), volume of wastewater (WW), volume of solid waste (SW), and total water pollution (WP) are stocks which are created by accumulating the difference between the inflow and the outflow of each stock. Initial values and rates that are used in this simulation are shown in Table II. Two important factors that affect water pollution are the efficiency of solid waste treatment plants (SWT) and the efficiency of wastewater treatment plants (WWT).

TABLE I
DESCRIPTIONS OF
VARIABLES AND UNITS USED IN THE SIMULATION.

Variables	Equations	Units
WC	56,575×Pop	L
FD	334×Pop	Kg
AG	-0.0281×Time + 4.1016	%
IN	-0.1703×Time + 17.97	%
WF	50000×AG	L
WI	50000×IN	L
Awareness	IF THEN ELSE (WP<5×1014, 0, 1)	-
WD	IF THEN ELSE (Awareness=1, 0.5×(WC+WF+WI), (WF + WI + WC))	L
SG	IF THEN ELSE (Awareness=1, 0.5×((FD/334)×533), (FD/334)×533)	Kg
PI	WW+0.2×SW	L
Pop	$\int_0^{10} Births - Deaths \quad dt$	People
WW	$\int_0^{10} WD - WT \quad dt$	L
SW	$\int_0^{10} SG - SWT \quad dt$	Kg
WP	$\int_0^{10} PI - Pollution \quad Outflow \quad dt$	L

TABLE II
Parameters Used in the Simulation: Initial Values, Units, and Sources of Parameters.

Variables	Initial values/Rate	Units	Sources
Pop	7.6×109	People	[68]
Births	18	People/1000	[69]
Deaths	8	People/1000	[69]
WW	4.57×1014	L	Assume
SW	5×1012	Kg	Assume
WWT	20	%	[70]
SWT	77	%	[71]
WP	5×1014	L	Assume

Fig. 8 shows the result from the model, which is a prototype of a system dynamics model. The trend of the amount of WP on the Earth is demonstrated from 2018 to 2028, and the trend is gradually increasing. The result demonstrates the potential of the developed system dynamics model to generate the trend of accumulated pollution in water resources. However, this simulated result cannot provide an accurate forecast of the trend of wastewater in the world due to a lack of data. This model can be used as a guideline to develop a model to forecast the trend of water pollution in the future.

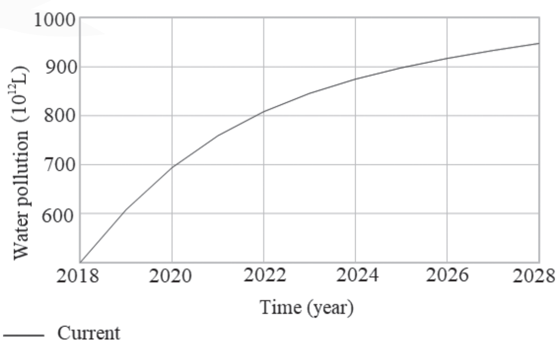

Fig. 8. Result from the simulation that shows the amount of wastewater in the world from 2018 to 2028.

IV. Conclusion

This study explores the interrelationships of factors that influence the water quality in water resources by using a System Dynamics (SD) approach. The SD model is composed of three subsystems, including the household, industrial, and agricultural sectors. In this paper, the result shows that the SD model can track the trend of water pollution in a water resource. Thus, this SD model can be used as a guideline for studying water quality at specific water resources. This model leads to a better comprehension of the interrelationships among the users and the health of a water resource. In the future, the SD model can be applied to track water pollution, such as nitrogen and phosphorus. In addition, alternative public policies, such as improving wastewater treatment, solid waste disposal, and raising people's awareness, can be evaluated in the model, to achieve environmental sustainability in water resources.

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