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Application of System Dynamics on Shallow Multipurpose Artificial Lakes: A Case Study of Detention Pond at Tainan, Taiwan

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Abstract This study designs a multipurpose urban shallow artificial lake, including water supply, flood detention, and water environment preservation. It is expected to not only preserve a healthy water environment but to also retain water conservation and flood detention. This study adopts system dynamics (SD) to analyze the relationship between different purposes of water resources utilization. Furthermore, different operation strategies effects can be simulated by SD through a proposed urban multipurpose shallow artificial lake system. The results demonstrate the dynamic effects of strategies managers propose such as demand analysis, inflow control, and water quality improvement in this case study for Taiwan. SD aids lake system prediction and understanding temporally in sequential planning for water supply, environmental preservation, and flood detention. The SD model will hopefully serve as a reference to study different features before artificial lakes constructing.

Keywords Water resources planning · System dynamics · Simulation modeling · Strategy analysis · Lake · Eutrophication

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1 Introduction

Taiwan is a country with high-density development in urban areas. Since water demand is continually increasing, water resources management faces a great challenge [18, 27, 33]. To deal with the problem of increasing water demand, the government has decided to construct reservoirs. Unfortunately, reservoir development is gradually becoming scarce due to widespread concerns about adverse impact of such constructions on the environment. In response to this concern, Water Resources Agency of Taiwan has developed a plan to develop small-scale artificial lakes to replace large-scale reservoirs. Detention, ecosystem, and landscape lakes are three examples of such small-scale artificial lakes (referred to as artificial lakes below). However, artificial lakes perform one specific function in detention or landscape, which can be limiting. Artificial detention ponds constructed in France during the last 50 years were not limited to one function. These newly created habitats are rapidly colonized by aquatic flora and fauna. Scher and Thiery [20] evaluated how attractive these ponds can be to aquatic species in order to evaluate their role in regional biodiversity. A pond or lake has the capacity to store floodwater [2]. In a drought, a lake is a habitat in which survival is possible [12]. In normal situations (i.e., no flood or drought), a lake can provide both environmental preservation and required water supply. Therefore, based on these studies of detention ponds, this study develops small-scale, multipurpose artificial lakes. However, designing a multipurpose lake is difficult due to the complexity arising from integrating different perspectives, such as water supply and environment preservation. The system dynamics (SD) approach is beneficial for indicating how different basic elements affect the system and is convenient for exploring how changes in one variable affect others [14, 21, 25].

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Using previous models, a number of models have applied SD to water resources management, including water supply and demand scenarios [27, 32, 33], flood protection [24], and sustainable management [23, 31]. First, various researchers have already applied the SD approach to water resources management. Stave [27] demonstrated building a strategic-level SD model using the case of water management in Las Vegas, Nevada. The proposed model explains the water resource system to illustrate the effects of strategies proposed by the manager and forum participants. The research shows that the SD model increased public understanding of water conservation value in Las Vegas. Compared with the conventional simulation model, SD is an object-oriented program, which easily modifies system structure by manipulating system objects that will change the mathematical description of the system. Moreover, SD is more beneficial for indicating how different changes of basic elements affect future system dynamics [32]. Xu et al. [32] used an SD approach for long-term water resources planning and policy analysis for the Yellow River basin in China. They explored various water supply and demand scenarios and estimated the sustainability index of the water supply system over various periods. Secondly, researchers [5, 30] have also applied SD to evaluate lake system ecology. Achieving both conservation and effective natural resources utilization requires careful system analysis. Güneralp and Barlas [5] utilized a shallow freshwater lake ecosystem model using SD and analyzed policies for potential sustainable management. The study region consisted of a shallow freshwater lake and its surroundings where fishing is a major commercial activity. The research goal was to find a balance between the ecosystem and economic activities in the region. They created a stable water flow cycle to preserve the quality and quantity of the ecosystem. Finally, Ahmad and Simonovic [1] applied SD to describe the Shellmouth Reservoir on the Assiniboine River in Canada. Their study developed a model to minimize flooding in high flood years using alternative operating rules, which they explored by changing reservoir storage allocation and reservoir outflows. Simonovic and Li [25] assessed flood protection performance under climate change and identified the magnitude and probability of floods under climate change using SD. Results indicate that the existing Red River flood protection system has sufficient capacity to accommodate future climate change. Previous studies focus on reaching the target in each objective. However, they fail to combine different aspects such as water supply, environmental preservation, and flood detention using SD and to discuss the topic for planning.

This paper illustrates how to apply SD to designing multipurpose artificial lakes and simulates lake dynamics. SD integrates different aspects with system analysis to aid understanding and prediction. Moreover, the framework proposed by this research is demonstrated to assess the three objectives in the planning stage.

2 Design of Multipurpose Lake Using SD

Figure 1 illustrates the SD procedures [7] applied in this work. The SD procedures include conceptualization, model development, strategy setting, model simulation, and impact analysis and assessment. The details are as follows.

2.1 Step 1: Conceptualization

The proposed artificial lakes will have many functions. This study expects the lake system to be multipurpose at different periods. The achievable system units combine to satisfy different planning purposes, such as water supply,

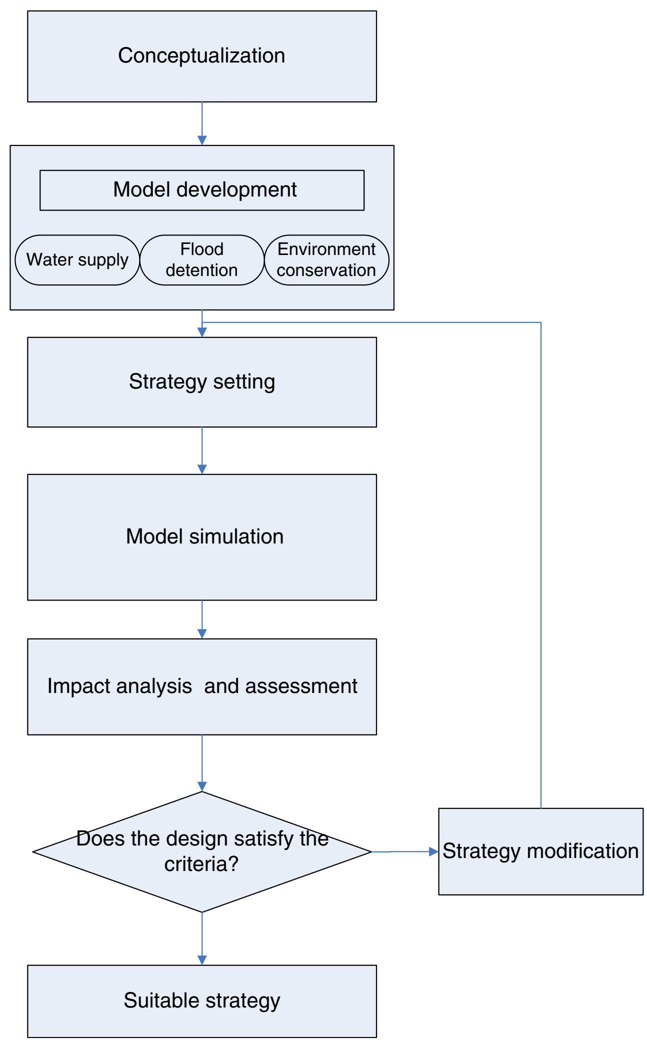


Fig. 1 The SD procedure in this study

flood detention, and environmental conservation. The current work identifies operation purposes at different periods. During a flood, the lake has enough capacity to store excess water. In a drought, the lake has enough stored water to maintain life in the area. At other times, the lake has the capacity to satisfy both water supply and environmental conservation purposes.

2.2 Step 2: Model Development

The multipurpose artificial lake system is composed of both hydrological and eco-hydrological facilities such as storage, infiltration, water quality improvement, and drainage units. In this step, this study models the lake system using the SD approach. The model consists of three sectors (sub-models) as mentioned: water supply, flood detention, and environmental conservation.

1. Water supply: This sector describes the runoff generated by precipitation and stored in the shallow lake system. The water supply meets the demands of sanitation and irrigation.
2. Flood detention: This sector describes feedback relationships between the lake system and rainfall–runoff during flooding. Flooding simulation is a special case in this model. The day before heavy rain, the model activates the flood detention sector.
3. Environmental conservation: Ecosystem health can be measured using an appropriate index, such as a particular species of any life form or physical and biological factors of the system. At the planning stage, it is difficult to predict what flora and fauna the artificial lake area will attract because there are no relevant data [28]. To evaluate ecosystem health, this work proposes water quality as a surrogate index. The vital problem for the shallow lake is eutrophication [17]. This condition causes excessive phytoplankton growth, which contributes to poor water clarity and makes the habitat less suitable for fish. Therefore, effective planning requires a method for long-term eutrophication control.

2.3 Step 3: Strategy Setting

A lake system comprises complex relationships, which could be integrated using SD in the last step. In this step, the planner examines all the existing models and chooses the most promising strategy, then chooses the goal to achieve and make the system operate successfully. Strategy setting includes three points:

1. Supply control: In long-term planning, a planner needs to define the operating rule to achieve system demand requirements. Water release to users in need should be controlled, such as fewer releases in drought.
2. Inflow control: Inflow is controlled so as not to exceed lake capacity and to minimize flooding.
3. Water quality improvement: To improve water quality, wetland management can be adapted to intercept and retain nutrients from incoming water [22, 23].

2.4 Step 4: Model Simulation

The system dynamics model simulates the behavior of complex systems in time. This paper focuses on water quality and quantity. Model simulation allows for a better understanding of the system depending on the existing scenario.

2.5 Step 5: Impact Analysis and Assessment

The lake system allows for adaptive change. Evaluating numerous scenarios which simulate possible future situations based on increased demand or climate change is necessary. The current research develops the proposed model to provide solutions to possible future problems. The model is assessed for each objective using an indicator to make sure the lake system is feasible in the planning stage. Finally, this work determines whether or not the design satisfies the required criteria. If the design does not satisfy, the planner needs to go to step 3 to modify the strategies and variables before continuing.

3 Application and Results

3.1 Definition of the System's Problem

The weather in Tainan of southern Taiwan is characterized by wet–dry cycles. These cycles have significant impact on the hydrological dynamic. On average, 90% of total annual rainfall falls between May and October in the wet season, while November to April of the next year is the dry season, with only 10% of annual rainfall. Heavy flood damage frequently occurs during the wet season due to high intensity cloud bursts by typhoons; drought in the dry season may become a significant problem if there was not enough precipitation the previous year. To mitigate the extreme disturbance caused by wet–dry cycles, this work identifies operational rules controlling the system and develops the lake model to predict temporal variation. The background of this system is described as the following. The detention area of this shallow lake is 5 ha, and maximum water depth is 2 m. Figure 2 illustrates the designed shallow lake system. A wetland needs to be

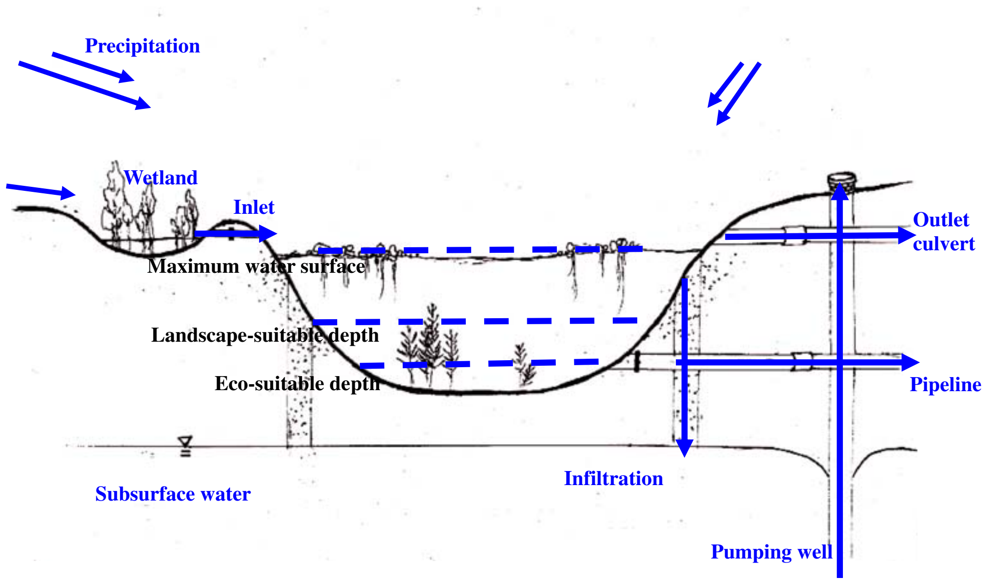


Fig. 2 Schematic diagram of supposed shallow lake system

established upstream from the lake to improve and maintain water quality. This paper defines operation depths as: maximum water surface is at 2 m, landscape-suitable depth is at 1 m, and eco-suitable depth is 0.5 m from the bottom.

This study expands the single functioning lake to multiple purposes, including not only flood prevention but also water supply use and preserving the ecological environment. The operational rules are similar to reservoir operating and control the system. By applying the operational rule, the proposed model can easily incorporate expert experiences into the model. Therefore, besides operating the simulation, the model examines and obtains an appropriated operation rule for the lake system as follows. Rule 1: If the water table is between maximum water depth and landscape-suitable depth, the water supply for public use can function on a daily demand basis and infiltrate into the aquifer. Rule 2: If the water table is between eco-suitable and landscape-suitable depth, the water supply is reduced to 80% of the demand. Rule 3: Whenever the water table drops below eco-suitable depth, it starts pumping groundwater into the lake and stops the water supply. Rule 4: Whenever the lake is full of water, the water spills away into the urban rainfall sewer. In brief, rule 1 and rule 2 are for water supply. Rule 3 is useful for ecological environment preservation. Rule 4 operates for flood detention.

3.2 Developing the Model

This work constructs the three model sectors (sub-models) for water supply, flood detention, and environmental conservation by establishing structural units and strategies linked together using SD. The major model parameters are listed in Appendices 1 and 2.

3.2.1 Water Supply Sub-Model

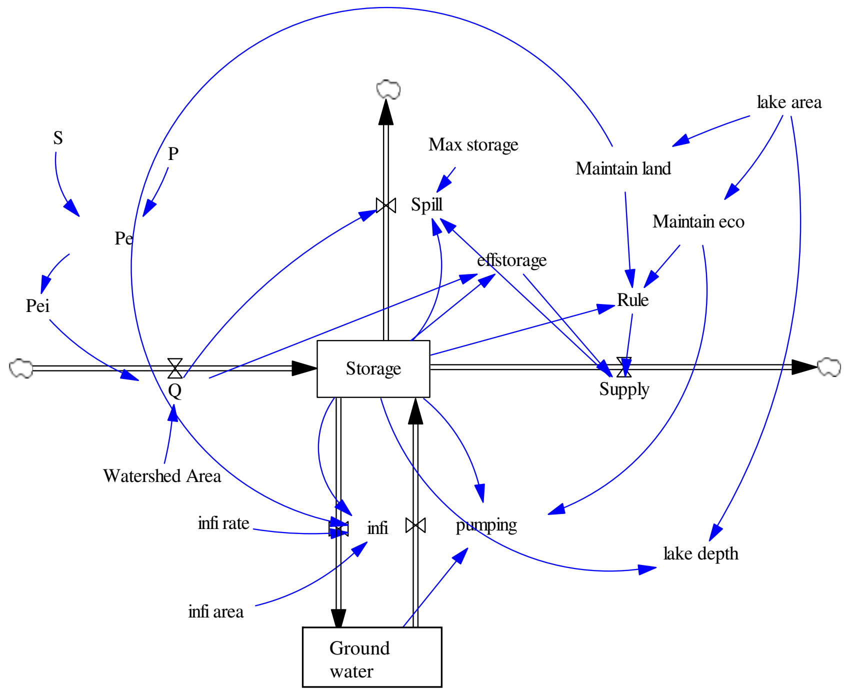
Figure 3 shows the SD lake model for water supply, which includes basic orients graphically, such as stocks (level), flows (rate), connectors and converters (auxiliary) available in the model. Boxes represent stocks, directed arrows are connectors, and double arrows represent material flow, regulated as rate variables. For example, one stock represents lake storage, and flow represents varying inflow and outflow changes in storage over time [1, 27]. Equations used in this sector are illustrated as follows. Lake water storage can be described in terms of the mass balance equation:

$$S_{lake}(t+1) = S_{lake}(t) + (Q(t) - \mathrm{Supply(t)} - \mathrm{Spill(t)} - \mathrm{infi(t)} + \mathrm{pump(t)})\Delta t \tag{1}$$

where $S_{\mathrm{lake}}(t)$ is lake storage during period t; Supply(t) is supply water during period t; Spill(t) represents spill water during flooding period t; infi(t) is infiltration during period t; and pump(t) is pumping rate during period t. Pumping groundwater stabilizes water quantity when the water table is lower than eco-suitable depth. $Q(t)$ denotes inflow with period t, which is overland flow. It generates the discharge hydrograph simultaneously by the excess rainfall hyetograph, calculated using the SCS runoff method. The SCS runoff method is a rainfall–runoff model that was originally developed for predicting flood flow volumes from the watersheds for hydraulic engineering design [16].The general equation for the SCS curve number method is as follows [3]:

$$Q(t) = \frac{(P(t) - 0.2S)^2}{P(t) + 0.8S} \quad \text{where } S = \frac{1,000}{\mathrm{CN}} - 10 \tag{2}$$

Fig. 3 Water supply sub-model



where P is precipitation depth; S is the maximum storage depth; and CN is the runoff curve number based on the hydrologic soil group and land use.

Operating rules for the water resource system specify how water is managed throughout the system. These rules are specified to achieve system demand requirement. Operation rules may be designed to vary with periods and with water storage [13]. The supply strategy is the relationship between supply and storage, illustrated as the following.

$$
\begin{aligned}
&\text{If } S(t) > S_1, \text{then Spill into urban rainfall sewer;}\\
&\text{If } S_1 > S(t) > S_2, \text{ then Supply(t)} = \text{Demand(t);}\\
&\text{If } S_2 > S(t) > S_3, \text{then Supply(t)} = \omega \times \text{Demand(t);}\\
&\text{If } S(t) < S_3, \text{then Supply(t)} = 0, \text{and pump(t)} = \mathrm{S}_3 - \mathrm{S}.
\end{aligned} \tag{3}
$$

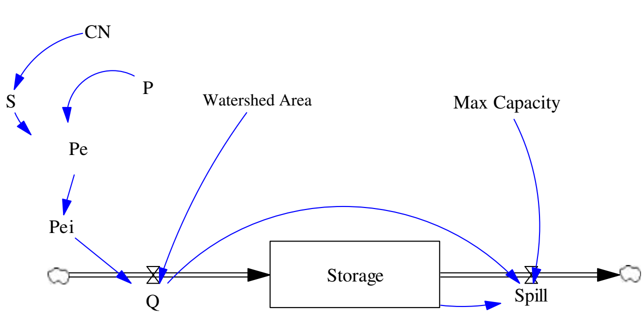


Fig. 4 Flood detention sub-model

where S_1 is maximum storage; S_2 is target storage (below landscape-suitable depth); S_3 is firm storage (below eco - suitable depth); Demand is water demand; and ω is the ration factor.

3.2.2 Flood Detention Sub-Model

Figure 4 shows the lake system model structure for detention. Water storage in flood event could be described in terms of the mass balance equation:

$$S_{lake}(t+1) = S_{lake}(t) + (\mathrm{Qf(t)} - \mathrm{Spill(t)})\Delta t \tag{4}$$

where $S_{\text{lake}}(t)$ is lake storage during period t; Qf(t) denotes available inflow with period t. If $Q(t)$>the threshold, water is allowed to flow into the lake (Qf(t)=$Q(t)$). Else, Qf(t)=0; Spill(t)is spill during flooding during period t. If inflow is greater than the threshold, it is allowed to enter the lake. However, flood detention is the primary work when storms arise in this proposed study case. Thus, the water table drops to eco-suitable depth the day before heavy rain.

3.2.3 Environmental Conservation Sub-Model

Figure 5 shows the lake model for environmental conservation. This study uses a lake eutrophication model based on Jørgensen [11]. The above lake model consists of three state variables, including soluble phosphorus (PS), phytoplankton (Phyt), and phosphorus in detritus (PDet). The

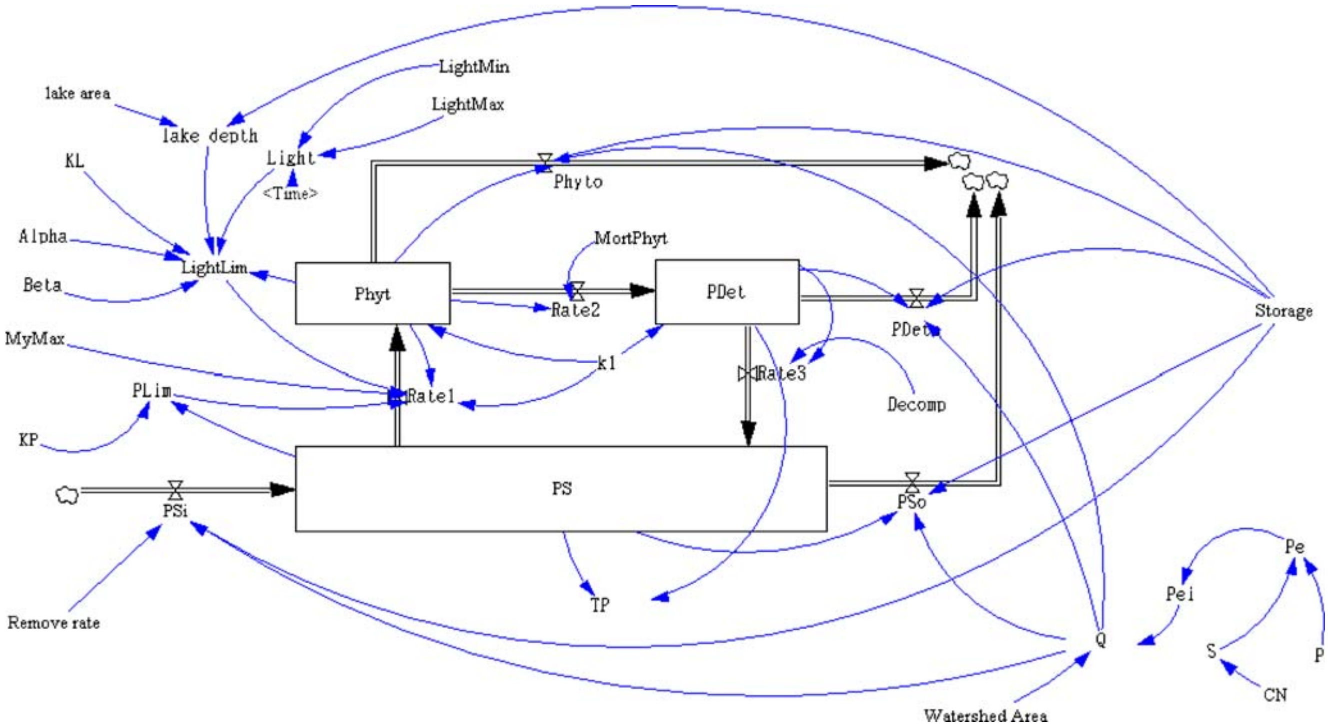


Fig. 5 Environmental conservation sub-model

expressions can be written as the following:

$$\mathrm{PS(t+1)=PS(t)}+\left[\left(\mathrm{PSi\times Q(t)-PS(t)\times\frac{Q'(t)}{S_{lake}(t)}}\right)+\mathrm{Decomp\times PDet(t)}\right.$$
$$\left.-\mathrm{MyMax\times LightLim(t)\times PLim(t)\times k1\times Phyt(t)}\right]\Delta t \tag{5}$$

$$\mathrm{Phyt(t+1)=Phyt(t)}+\left(\mathrm{MyMax\times LightLim(t)\times PLim(t)-MortPhyt-\frac{Q_s(t)}{S_{lake}(t)}}\right)\Delta t \tag{6}$$

$$\mathrm{PDet(t+1)=PDet(t)}+\left(\mathrm{MortPhyt\times k1\times Phyt(t)}-\left(\mathrm{Decomp}+\frac{\mathrm{Q_s(t)}}{\mathrm{S_{lake}(t)}}\right)\times\mathrm{PDet(t)}\right)\Delta t \tag{7}$$

where $Q(t)$ is inflow in each period t; $Q'(t)$ is outflow (Q'=Supply+Spill); $Q_s(t)$ is net flow ($Q_s=Q-Q'$); $S_{lake}(t)$ is storage volume of the lake; PS(t) is soluble phosphorous ; Phyt(t) is phytoplankton; PDet(t) is phosphorous in detritus; $D(t)$ is the depth; Decomp is the detritus decomposition rate; $k1$ is the phosphorus/biomass ratio of phytoplankton; MortPhyt is the mortality rate of phytoplankton; MyMax is the growth rate of phytoplankton; and PSi is the phosphorus concentration of inflow. LightLim is the growth limitation due to light shortage; PLim is the growth limitation due to phosphorus shortage. Phytoplankton growth rate is obtained by combining in a multiplicative way including the maximum growth rate, and the function for light limitation and nutrient limitation are formulated with a Michaelis–Menten expression [11].

1. Light limitation: Radiation during the year is expressed by the equation:

$$\mathrm{Light=LightMin}+\frac{1+\left(\sin\left(2\times\frac{t}{365}-0.5\right)\pi\right)}{2}\mathrm{LightMax} \tag{8}$$

where LightMin is the minimum light intensity and LightMax is the maximum light intensity. The expression for light limitation of phytoplankton growth is the same as the Michaelis–Menten expression for nutrient growth limitation. However, because of light extinction through the water column, the expression must be integrated to depth as the following equation:

$$\mathrm{LightLim}=\frac{\ln\left(\frac{\mathrm{Light+KL}}{\mathrm{Light\times\exp(-(Alpha+Beta\times Phyt)\times D)+KL}}\right)}{\mathrm{(Alpha+Beta\times Phyt)\times D}} \tag{9}$$

where KL is Michaelis–Menten half-saturation constant for light utilization; Alpha is light extinction coefficient of water; and Beta is light extinction coefficient of phytoplankton.

2. Nutrient limitation: Nutrient limitation, PLim, of phytoplankton is formulated with the Michaelis–Menten expression:

$$\mathrm{PLim} = \frac{\mathrm{PS}}{\mathrm{PS} + \mathrm{KP}} \tag{10}$$

where PS is the soluble nutrient and KP is the half-saturation constant.

3.3 Model Analysis for Design Process

This work simulates the design process progressively after implementation using SD. The current research designs the model to satisfy the fundamental requirements, i.e., detention, water supply, and environmental conservation, and identifies the design variables of the system. The strategies are modified based on feedback through model indicators. Then, various scenarios can be further evaluated. This investigation assesses whether the results are feasible or not by the indicators for each purpose. Indicators which are listed in Appendix 3 such as shortage index (SI), trophic category (TC), and detention efficiency (DE) assess performance. This research performs numerical analyses on the multipurpose lake system to verify effectiveness of the proposed methodology. In the study, the SD simulation model includes three sub-models, four state equations (water level, soluble phosphorus, phytoplankton, and phosphorus in detritus), a number of auxiliary equations, and operation rules. The sequential procedure is designed to meet multipurposes in the SD model. The SD model not only deals with the lake system using an integrated approach but also clarifies interactive relationships among the subsystem and identifies embedded links among the components. Moreover, the SD model aids in predicting the lake system temporally in sequential planning for water supply, environment conservation, and flood detention.

3.3.1 Design for Water Supply

Dynamic hydrologic processes in the lake system include precipitation, direct runoff, and others. Direct runoff is the major source of the artificial lakes and varies with wet–dry cycles in Southern Taiwan. Lake inflow, estimated by the SD rainfall–runoff model, varies with time. Figure 6 shows daily variation of the lake inflow in 2003. According to this scenario, the proposed lake system is designed for water supply. Thus, the designed variable in case 1 is water demand. SD simulates lake system dynamics of water supply and can apply to design operation rules based on water levels. Figure 7 shows daily storage variation in the lake under different water demands. The result shows that storage declines before the 73rd day (dry season) and keeps the lake full of water from the 143rd to the 261st day during the wet season. The dramatic decrease in lake water level during the dry season causes several problems of irrigation, macrophyte cover, and fishing [5]. To reduce drought impact, SD considers the water rationing operation rule that conserves more water for future use. The operating rules typically determine artificial lake storage. The operating rules for the lake system specify how water is managed throughout the system, achieving the system demand requirement described in Eq. 3. The current study performs evaluation of the model for different perspectives for a number of cases presented in Tables 1, 2, and 3. For water supply, SD evaluates the shortage index of each case as Table 1 shows and determines feasible cases when SI satisfies the criteria (SI < 1). The suitable demand is under 960 m^3/day in the design through case assessment. SD also explores the relationship between water demand and shortage. The finding indicates that the

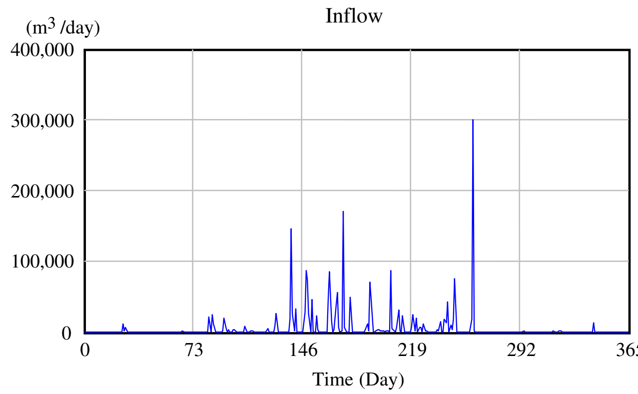


Fig. 6 Inflow of lake throughout SD simulation

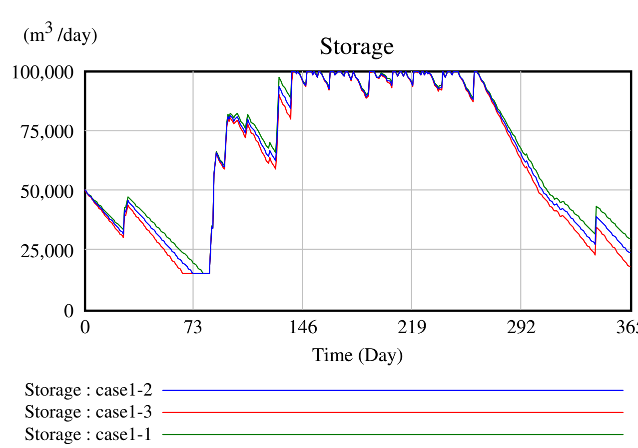


Fig. 7 Storage of lake throughout SD simulation

Table 1 SI Performance of the designed case

	Case1-1	Case1-2	Case1-3
Demand (m^3/day)	800	880	960
SI performance	0.331	0.588	1.201

Table 3 DE performance of the designed case

	Case3-1	Case3-2	Case3-3
Inflow threshold (m^3/h)	0	20	40
DE performance	0	0.291	0.258

shortage correlates with the demand and the risk of shortage increases when demand increases. Figure 8 shows three daily variations of supply in different water demands. Whenever the water table drops below eco-suitable depth around the 70th day, the system stops water supply to retain storage. Results of this case indicate that the SD model can simulate the lake system under an inclusive consideration of water supply reliability.

3.3.2 Design for Environmental Conservation

The SD aims to expand the single functioning existing lake to multiple purposes, which not only include water supply but also preserve the ecological environment. Findings clearly show phosphorous as the important factor varying with time. The designed variable in case 2 is the phosphorous removal rate for environmental management. Considering the objectives of water supply, the designed demand is 880 m^3/day, and the desirable design might be the one that removes phosphorous efficiently to prevent eutrophication. Studies indicate that lake planners control phosphorous content of the lake to prevent poor water quality and excessive phytoplankton growth [4, 19, 26]. Therefore, the lake eutrophication sub-model simulates PS, Phyt, and PDet. The SD model indicates how different the changes of phosphorus elements affecting algal dynamics are in the future. The SD lake model clearly demonstrates the relationship between nutrient loading and algal growth. Table 2 displays SD performance under different phosphorus removal rates to meet the second objective. SD evaluates system performance of TC, exploring the impact caused by removal rate changes. Figure 9 shows the daily variation of total phosphorus treated with different removal rates. Variation of total phosphorus associated with lake storage and inflow may have a dominant influence on in-lake phosphorus distribution [10, 29]. The differences in water levels between wet and dry seasons are caused by the inflow. During the dry season, small storage causes a high concentration of TP. During the beginning of wet season, inflow causes nutrient loading in the lake so that concentration increases sharply. On the 183rd day, inflow during flood events result in rapid flushing and concentration declines. The results agree with this observation that inflow may be a crucial source for the lake. The TP also correlates with removal rate, and eutrophication risk decreases when removal rate increases. An effective planning for the environmental management is desired for sustainable regional development [6]. Phosphorus removal from inflow using the wetland might be one of the most efficient strategies to treat eutrophication. From this viewpoint, a 70% TP removal rate is necessary to meet water quality standards.

Table 2 TC performance of the designed case

	Case2-1	Case2-2	Case2-3
Removal rate	0.3	0.5	0.7
TC performance	Eutrophic	Eutrophic	Mesotrophic

3.3.3 Design for Flood Detention

When the system satisfies the two objectives, this work designs case 3 for the purpose of flood detention. SD displays system performance (the DE) on three thresholds in Table 3. The designed variable is the threshold and the system does not allow low flow discharge to enter. The SD result shows that DE decreases to 29.1% if the threshold is under 20 m^3/h. DE decreases to 25.8% as the threshold increases to 40 m^3/h. These situations obviously demonstrate that the more space there is to save, the more volume is needed to detent the flood. To effectively detain water, the SD model determines the most feasible threshold for

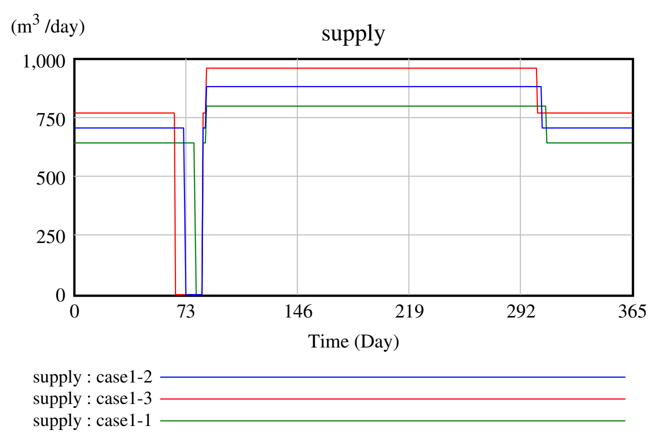


Fig. 8 Water supply throughout SD simulation

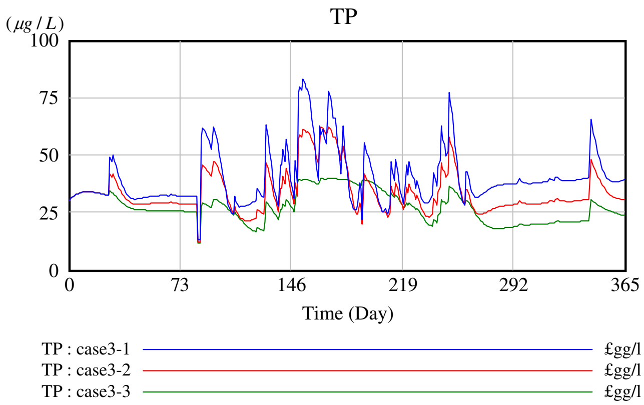


Fig. 9 Total phosphorus in lake throughout SD simulation

inflow, 20 m^3/h. Results illustrate that the flood operating rule may cause changes in flooding start time and peak occurrence. Above all, the proposed design for a multipurpose lake system is accessed by the SD simulation approach. In brief, the SD provides guidelines to design a multipurpose lake system. The results show that SD is a system approach for evaluating the interrelationships of precipitation, hydrologic processes, water quality, and phytoplankton and is also beneficial for exploring different basic elements affecting the system and how changes in one variable affect others [21, 24, 25]. This paper demonstrates one kind of cause and effect relationship: water demand influences water supply, water supply influences water level at next time, and water level further influences soluble phosphorus and phytoplankton. SD quantifies these interactions, provides different estimates of the main designed parameters for the considered region, and finds the appropriate operation rules to satisfy the objectives. Inferring that the scenario analysis using SD suggests the design parameters is appropriate during system planning.

4 Conclusions

The current study provides a basic description of lake function and highlights multi-objectives needing design and operation. Lake design considers three objectives: water supply, flood detention, and environmental conservation. The approach uses SD processes to explore the best way to reach those objectives. The SD model combines with three sub-models including four state equations (water level, soluble phosphorus, phytoplankton, and phosphorus in detritus), a number of auxiliary equations, and operation rules. This study effectively simulates lake status and identifies the relationship between hydrology and nutrient circle.

Using the SD model, the planner can evaluate system performance of each objective and explore the impact when strategy changes. This study clarifies that operating rules affect three objectives and assesses the trade-off between these objectives. The case study confirms that the proposed framework presents a powerful tool for analyzing different strategies and contributes to increased understanding of planning work. The approach is notably more beneficial for the planning stage. Other suggestions follow.

1. The concept this paper uses is suitable for municipality planning. This multipurpose lake concept can be easily implemented in community and urban developments. The lake offers residents another chance to get in touch with nature.
2. An important direction for future studies may include considering economics, such as financial availability and limitations. The present SD model adds to economic considerations, further discussing environmental and financial efficiencies. In other words, an environmental and financially effective lake system will be desirable in the future.
3. The system design may not be reliable enough without considering inflow uncertainty due to inflow variations caused by season and climate alternation. Satisfying increasing demand is difficult in this study. Thus, this work offers further considerations about inflow uncertainty and capacity expansion to overcome these problems.
4. Further studies of wetland water treatment mechanisms and dynamic process modeling by SD may enhance simulating efficiency of the present model.

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Appendix 1. Model Parameter Value in Water Supply and Flood Detention

Symbol	Definition	Value	Unit
CN	Soil conservation service curve number	88	
Lake_area	Lake area	50,000	m^2
Watershed_Area	Watershed area	1,000,000	m^2
Maintain_eco	Eco-suitable depth	0.3	m
Maintain_land	Landscape-suitable depth	1	m
Infi_rate	Infiltration rate	0.15	m/day
Infi_area	Infiltration area	2,000	m^2

Max_S	Maximum storage	100,000	m^3
Max_Capacity	Maximum detention capacity	100,000	m^3
ω	Ration factor	0.8	

Appendix 2. Model Parameter Value in Environmental Conservation

Symbol	Definition	Value	Unit
Alpha	Light extinction coefficient of water	0.25	
Beta	Light extinction coefficient of phytoplankton	0.18	
LightMin	The minimum light intensity	500	$kcal/m^2$
LightMax	The maximum light intensity	4500	$kcal/m^2$
MyMax	Maximum growth rate of phytoplankton	1.5	
KP	Monod constant of phosphorous uptake	0.2	

Appendix 3. Model Indicators

1. The water supply indicator is represented by the shortage index (SI) proposed by the US Army Corps of Engineers as [8, 9]:

$$\mathrm{SI} = \frac{100}{\mathrm{N}} \times \sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\frac{\mathrm{Sh_i}}{\mathrm{T_i}}\right)^2 \qquad (\mathrm{C}-1)$$

where N is number of periods; Sh_i is volume shortage during period i; and T_i is target demand during the period i.

Table 4 OECD management limits for TP

Trophic category (TC)	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
TP (μg/L)	<10	10–35	35–100	>100

2. The environmental conservation index adopts trophic category (TC). Table 4 lists the trophic category with total phosphorus (TP), defined by the Organization for Economic Co-operation and Development [15].

3. The detention efficiency (DE) indicator in flood event is represented as:

$$\mathrm{DE} = \frac{\mathrm{Q_p} - \mathrm{Q_{pb}}}{\mathrm{Q_p}} \times 100\% \qquad (\mathrm{C}-2)$$

where Q_p is peak flow without building the lake and Q_pb is peak flow with building the lake.

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