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A Preliminary Model of Lake Toba's Water Level Using System Dynamics

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ABSTRACT

This study develops a preliminary System Dynamics (SD) model to characterize the hydrological behavior of Lake Toba by integrating natural and anthropogenic water-balance components into a unified stock–flow framework. The model incorporates precipitation, runoff, baseflow, groundwater exchange, evaporation, regulated outflow, and sectoral water withdrawals to represent the dominant processes controlling lake-storage dynamics. Using monthly data from 2000 to 2020, the model simulates variations in lake volume and water-level elevation, reproducing the seasonal rise during wet periods and decline during dry periods, as well as revealing a gradual long-term downward trend. Sensitivity analysis identifies precipitation as the most influential driver of lake-level change, while evaporation and outflow function as stabilizing mechanisms that regulate storage. Anthropogenic withdrawals show relatively minor effects under current conditions but may become increasingly important under higher-demand scenarios. Overall, this preliminary model provides a transparent analytical foundation for understanding the feedback structure governing Lake Toba's water balance and offers a basis for future policy-oriented simulations aimed at supporting sustainable lake-water management.

Keywords: *lake level fluctuation, Lake Toba, simulation, System Dynamics, water balance*

1. Introduction

1.1 General Background

Freshwater lakes are critical components of the global hydrological system, functioning as natural reservoirs that regulate water availability, buffer climatic variations, and support ecological and socio-economic activities. In recent decades, however, many lakes around the world have experienced declining water levels due to a combination of climatic variability and increasing human pressure. Notable examples include the Aral Sea and Lake Urmia, where reductions in inflow, coupled with rising evaporation and intensive water withdrawals, have caused substantial long-term shrinkage.

A similar concern has emerged in Indonesia, particularly in Lake Toba, the largest volcanic lake in Southeast Asia and one of the most significant freshwater resources in the region. The lake supports multiple functions, including raw water supply, fisheries, agriculture, tourism, and energy production through the Asahan Hydropower Plant. These diverse uses make the lake highly sensitive to changes in hydrological balance.

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Long-term observations indicate that Lake Toba has undergone a progressive decline in water level, driven by both climatic and anthropogenic factors. Rosid et al. (2025) reported a decline of approximately 0.8 meters between 1957 and 2020, largely attributed to increased evaporation, watershed microclimatic changes, and growing water demands in surrounding communities [1]. Additionally, Irwandi et al. (2019) showed that major climate anomalies such as the El Niño–Southern Oscillation (ENSO) can significantly reduce rainfall across the catchment, causing short-term drops in lake level by more than 1.5–2.5 meters during strong events [2].

These trends highlight that Lake Toba behaves as a dynamic hydrological system influenced by multiple interacting components such asprecipitation, runoff, groundwater exchange, evaporation, river outflow, and human water use. Understanding the lake's behavior requires an analytical framework that can account for such interactions, including feedback mechanisms and time delays, which are not adequately captured by static or linear models.

Given the hydrological, ecological, and socio-economic importance of Lake Toba, a more comprehensive understanding of its water-level dynamics is urgently needed to support sustainable management and policy-making.

1.2 Research Background and Related Studies

The System Dynamics (SD) approach has evolved rapidly in the field of water resources since it was first introduced by Forrester (1961) and systematized by Sterman (2000) [3,4]. SD enables researchers to model complex systems through the representation of stocks and flows and their causal feedback relationships. In hydrology, SD models have been widely used to analyze water balance and to investigate the behavior of lake and reservoir systems influenced by climatic variability and human intervention.

The hydrological behavior of lakes is fundamentally governed by the principle of water-mass conservation, which states that changes in storage result from the net balance between inflows and outflows. This principle was formalized by Winter (1981), who expressed the general lake water-balance equation as [5]:

$$P \pm e_P - E \pm e_E + SI \pm e_{SI} - SO \pm e_{SO} = \pm G \pm e_G \qquad .(1)$$

Equation (1) identifies the primary hydrological components—precipitation (P), evaporation (E), surface inflow (SI), surface outflow (SO), and groundwater exchange (G)—including associated uncertainty terms.

Building upon this conceptual formulation, Ahmad and Simonovic (2000) introduced a dynamic representation in a discrete stock–flow structure suitable for System Dynamics modeling [6]:

$$Storage(t) = Storage(t - \Delta t) + (Qin - Qout)\Delta t \qquad (2)$$

Equation (2) forms the basis of dynamic lake-storage simulation, allowing volume to accumulate as the integral of net inflow.

To incorporate anthropogenic pressures, Hassanzadeh et al. (2012) extended the water-balance formulation for Lake Urmia by explicitly including agricultural and domestic withdrawals [7]:

$$V(t) = V(t_0) + \int_{t_0}^{t} \left[GW(t) + SW(t) + P(t) - E(t) - W_{ag}(t) - W_{dom}(t)\right] dtV(t)\ \Delta t \qquad (3)$$

This Equation (3) demonstrates how human water use (W_{ag}, W_{dom}) alters net inflow and accelerates lake-level decline.

Further enhancements were introduced by Lari et al. (2020), who modeled evaporation as a function of salinity and meteorological conditions [8]:

$$E(t) = \text{Pan Coeff} \times \text{Salt Coeff} \times\ F(t) \times\ G(t) \qquad (4)$$

and proposed the total dynamic water-balance form:

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$$A(t) = A(t_0) + \int_{t_0}^{t} [B(t) + C(t) + D(t) - E(t)] \, dtA(t) \quad (5)$$

Equations (4)-(5) illustrate non-linear evaporation behavior and its impact on lake storage.

In a more natural lake setting, Falconi et al. (2020) formulated a hydrological relationship linking water balance to lake-level elevation [9]:

$$LL = P_l + R + B_f - E_b - R_i - A \pm G_f \quad (6)$$

Equation (6) provides an explicit mapping between hydrological components and lake elevation, offering a useful reference for converting modelled volume into observable lake-level data.

Similarly, Alifujiang et al. (2017) applied SD modeling to Lake Issyk-Kul, incorporating both groundwater exchange and human withdrawals [10]:

$$V(t) = V(t_0) + \int_{t_0}^{t} \left[GW(t) + \left(SW(t) - W(t)\right) + P(t) - E(t)\right] dt \quad (7)$$

Equation (7) highlights the contribution of subsurface inflow and anthropogenic water use to the lake's dynamic balance.

In urban hydrological systems, Ahmad and Prashar (2010) distinguished between surface and groundwater storage components [11]:

$$SW(t) = SW(t - \Delta t) + Q_{in} - (ET + W_d + ILO) \quad (8)$$

$$GW(t) = GW(t - \Delta t) + R - (W_d + GWL) \quad (9)$$

Equations (8)–(9) illustrate how domestic demand (W_d) and recharge influence multiple storage layers.

For Lake Toba specifically, Sihotang (2016) proposed an empirical relationship linking hydrological variables to water-level change [12]:

$$\Delta H = \frac{(P - E) + (Q_{in} - Q_{out})}{A} \quad (10)$$

This Equation (10) emphasizes the importance of precipitation, evaporation, and inflow–outflow balance in controlling short-term dynamics. Complementing this, Rosid et al. (2025) identified long-term climatic trends, an increase in annual precipitation of 8.9 mm/year and evaporation of 1.4 mm/year as key contributors to Lake Toba's declining water level [1].

These formulations (Eq. 1–10) collectively demonstrate the evolution of lake hydrological modeling and provide the theoretical basis for synthesizing a dynamic water-balance model for Lake Toba that integrates natural and anthropogenic components within a System Dynamics framework.

1.3 Research Gap and Problem Statement

Although numerous studies have applied SD to water-resource systems and lake hydrology (Winter 1981; Ahmad & Simonovic 2000; Hassanzadeh et al. 2012; Falconi et al. 2020; Alifujiang et al. 2017), most of these models were developed for arid or temperate lakes, where hydrological behavior is strongly driven by limited precipitation, high evaporation, and severe water withdrawals [5,6,7,9,10]. These characteristics differ substantially from those of Lake Toba, a large tropical volcanic lake with high rainfall, strong seasonal variability, and relatively stable groundwater conditions.

Existing SD-based lake models typically emphasize individual components such as evaporative loss, groundwater exchange, or human water use but do not integrate all natural and anthropogenic processes into a unified stock–flow structure appropriate for a tropical system. Moreover, many past models employ assumptions or parameterizations (e.g., salinity-driven evaporation, linear runoff coefficients) that are not directly transferable to a humid equatorial watershed.

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In Indonesia, studies on Lake Toba remain static, deterministic, or correlation-based, focusing mainly on the relationship between precipitation, evaporation, and water level (Sihotang 2016) or on long-term declining trends [1]. These approaches do not capture the feedback mechanisms, time delays, or dynamic interactions among hydrological and human-driven components that fundamentally shape lake behavior.

Thus, a clear research gap exists:

1. No existing dynamic model represents Lake Toba's water balance using a holistic System Dynamics framework.
2. No prior study integrates precipitation, runoff, baseflow, groundwater exchange, evaporation, regulated outflow, and multiple categories of water use into a single stock–flow model.
3. The dynamic consequences of feedback loops—such as increased evaporation with rising lake surface area or changing outflow due to fluctuating lake volume—remain unexamined.

Given the absence of a comprehensive SD-based representation of Lake Toba, there is a need to develop a preliminary dynamic model capable of:

1. capturing seasonal and long-term water-level fluctuations,
2. representing interactions among natural hydrological processes and anthropogenic water withdrawals, and
3. identifying dominant factors that regulate lake behavior over time.

This study addresses this gap by synthesizing prior hydrological formulations into an integrated System Dynamics model tailored to the physical and socio-hydrological characteristics of Lake Toba.

1.4 Aim *and Purpose of the Study*

The purpose of this study is to develop a preliminary SD model that represents the hydrological behavior of Lake Toba through a synthesized dynamic water-balance formulation. The model integrates natural hydrological processes and anthropogenic water withdrawals into a unified structure expressed mathematically in Equation (11) and Equation (12).

The specific aims of the study are:

1. To identify key hydrological and anthropogenic variables influencing the water balance of Lake Toba, including precipitation, runoff, baseflow, groundwater fluxes, evaporation, regulated outflow, and multiple categories of water use.
2. To construct a conceptual SD framework comprising a Causal Loop Diagram (CLD) and a Stock–Flow Diagram (SFD) that captures feedback mechanisms and time delays within the lake system.
3. To synthesize a dynamic water-balance equation, derived from the fundamental principles established in previous hydrological research, as shown in Equation (11):

$$\frac{dV}{dt} = (P_{lake} \cdot A_{lake}) + \left(R + B_f + GW_{in}\right) - \left(E \cdot A_{lake} + Q_{out} + W_{ag} + W_{dom} + W_{ind} + GW_{out}\right) \quad (11)$$

4. To formulate the functional relationship between lake volume and elevation using an effective surface-area method expressed in Equation (12):

$$LL(t) = LL_0 + \frac{V(t) - V_0}{A_{eff}} \quad (12)$$

5. To evaluate the seasonal and long-term behavior of lake-level fluctuations through simulation using Vensim DSS.

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To ensure that each component of the synthesized water-balance model is grounded in established hydrological theory and previous SD-based lake studies, all variables included in Equations (11) and (12) were traced to foundational literature sources. The summary of these components, their functional roles, and supporting references is presented in Table 1.

Table 1. Summary of variables used in the synthesized dynamic water-balance model and literature sources.

No	Model Component	Symbol	Functional Representation	Key Source(s)	Main Contribution
1	Precipitation input	(P_{lake})	$(P_{lake} \cdot A_{lake})$	Winter (1981); Falconi et al. (2020); Sihotang (2016)	Defines direct rainfall as the main input contributing to the lake volume.
2	Lake surface area	(A_{lake})	Constant value or function of elevation	Rosid et al. (2025); Falconi et al. (2020)	Used to convert precipitation and evaporation into water volume.
3	Surface runoff	(R)	Runoff discharge from the surrounding watershed	Alifujiang et al. (2017); Sihotang (2016)	Provides the primary external inflow component originating from catchment rainfall.
4	Baseflow	(B_f)	Stable subsurface flow	Falconi et al. (2020); Alifujiang et al. (2017)	Adds the contribution of saturated subsurface flow to total inflow.
5	Groundwater inflow	(GW_{in})	Infiltration from surrounding aquifers	Winter (1981); Alifujang et al. (2017)	Represents positive subsurface exchange toward the lake.
6	Evaporation loss	(E)	$(E \cdot A_{lake})$ or seasonal function	Lari et al. (2020); Rosid et al. (2025)	Quantifies water loss to the atmosphere, affected by temperature and humidity.
7	Surface outflow	(Q_{out})	Discharge through the Asahan River	Ahmad & Simonovic (2000); Sihotang (2016)	Controls volume balance and relates to the operation of the Asahan Hydropower Plant.
8	Agricultural water use	(W_{ag})	Water use for agricultural irrigation	Ahmad & Prashar (2010); Lari et al. (2020)	Indicates anthropogenic pressure from the agricultural sector on lake water resources.
9	Domestic water use	(W_{dom})	Water use for household needs	Ahmad & Prashar (2010); Lari et al. (2020)	Adds the socio-economic component influencing water-deficit conditions.
10	Industrial / hydropower use	(W_{ind})	Water use for industrial and hydropower activities	Rosid et al. (2025)	Represents the major anthropogenic component affecting lake-volume loss.
11	Groundwater outflow	(GW_{out})	Infiltration from the lake bottom	Winter (1981)	Describes groundwater loss exiting the lake system.
12	Volume storage	(V)	$\left(\frac{dV}{dt} = \text{Inflow} - \text{Outflow}\right)$	Ahmad & Simonovic (2000); Alifujiang et al. (2017)	Serves as the main stock in the dynamic system, integrating all inflow–outflow changes.
13	Lake level (elevation)	(LL)	$\left(LL(t) = LL_0 + \frac{V(t) - V_0}{A_{eff}}\right)$	Falconi et al. (2020); Rosid et al. (2025)	Links volume change to water-level elevation and is used for model calibration.

Table 1 demonstrates that the synthesized SD model incorporates all major physical and anthropogenic drivers identified across previous lake-balance studies [1,5,7,8,9]. By unifying these components within the dynamic expressions in Eq. (11) and Eq. (12), the model provides a comprehensive representation of Lake Toba's hydrological system. This integrated structure serves as the foundation for simulating seasonal fluctuations, long-term trends, and system responses to changes in climatic or anthropogenic forcing.

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2. Method

2.1 *Conceptual Framework*

The conceptual framework of this study is based on the principles of SD, which represent complex hydrological systems through interconnected feedback structures, stock–flow relationships, and time-dependent interactions. In the context of Lake Toba, the lake water volume is treated as the central stock, while hydrological inputs and outputs including precipitation, runoff, baseflow, groundwater exchange, evaporation, regulated outflow, and anthropogenic withdrawals, form the flows governing its change over time.

The development of the conceptual model follows three sequential steps. First, the major hydrological and anthropogenic components were identified based on previous lake-balance and SD studies [5,6,7,9,10]. These variables were then organized into a causal structure, illustrating how changes in climatic drivers and human water demand influence the lake's storage, and how lake-level variations may in turn affect evaporation and outflow. Table 1 summarizes the variables included in the synthesized model together with their conceptual roles and literature foundations.

Second, the causal structure was translated into a CLD to capture the reinforcing and balancing feedback mechanisms within the system. Reinforcing feedback occurs when increased precipitation and runoff raise the lake volume, potentially expanding the surface area and elevating evaporative losses. In contrast, balancing feedback emerges when higher lake volume increases regulated outflow or when water withdrawals reduce storage, stabilizing the system under new conditions. The CLD provides a qualitative representation of these interdependencies and serves as the conceptual basis for constructing the quantitative model.

Third, the causal relationships were formalized into a SFD, establishing the quantitative pathways through which hydrological processes alter the lake volume. In the SFD, lake volume (V) is modeled as the stock, while all inflows and outflows listed in Table 1 constitute the rate variables. This structure is mathematically expressed in the synthesized dynamic water-balance equation (Eq. (11)), which aggregates all physical and anthropogenic flows into a single expression for the rate of change of lake storage. The linkage between lake volume and lake-level elevation is subsequently defined through the effective area relationship (Eq. (12)), enabling the model to translate simulated volumetric changes into observable water-level fluctuations.

Together, the CLD and SFD provide a coherent conceptual framework that integrates hydrological theory, empirical understanding, and dynamic modeling principles. This framework forms the foundation for implementing the Lake Toba water-balance model in Vensim DSS and for evaluating system behavior under varying hydrometeorological conditions.

2.2 Model Structure: Causal Loop Diagram (CLD) and Stock–Flow Diagram (SFD)

The model structure used in this study consists of two fundamental System Dynamics representations: the CLD, which captures the qualitative feedback relationships within the Lake Toba hydrological system, and the SFD, which formalizes these relationships into a computational structure for dynamic simulation. These diagrams guide the translation of hydrological concepts into the mathematical formulation presented in Section 2.3.

2.2.1 Causal Loop Diagram (CLD)

The CLD describes the directional influences among hydrometeorological variables, groundwater interactions, and anthropogenic water uses. It clarifies how these components create reinforcing and balancing mechanisms that regulate lake storage over time.

As illustrated in Fig. 2, the lake system is shaped by interacting feedback loops. A reinforcing feedback loop arises from the positive influence of precipitation (P_{lake}) on total hydrological inflow. Higher precipitation increases surface runoff R, baseflow B_f, and groundwater inflow GW_{in}, all of which raise lake volume V. This reinforcing mechanism tends to amplify storage during wet periods.

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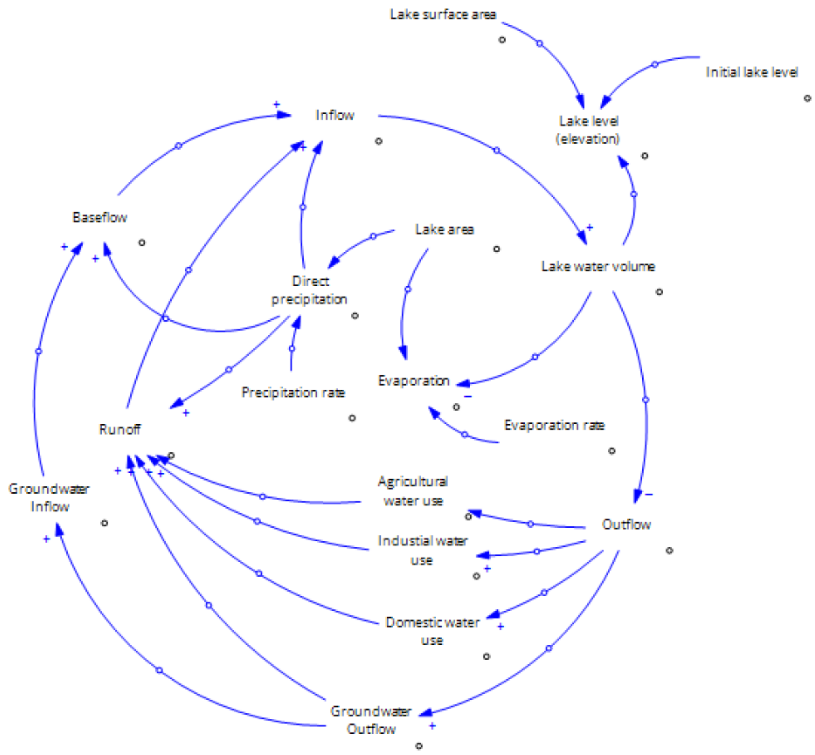

Figure 2. Causal Loop Diagram (CLD).

A balancing feedback loop emerges when rising lake volume increases the regulated outflow Q_{out} and enhances evaporative losses E due to the larger effective lake surface area. Anthropogenic withdrawals—agricultural water use W_{ag}, domestic consumption W_{dom}, and industrial/hydropower use W_{ind}—further contribute to this balancing effect by reducing lake volume, especially during dry seasons.

Subsurface exchanges also introduce slower responses: groundwater inflow GW_{in} and groundwater outflow GW_{out} moderate long-term fluctuations and create time delays that shape system stability.

Together, these loops explain the oscillatory yet self-regulating nature of Lake Toba's hydrological behavior and form the conceptual basis of the quantitative model.

2.2.2 Stock–Flow Diagram (SFD)

The SFD provides a structural representation of the dynamic water-balance system by identifying the single stock—Lake Volume V—and the inflows and outflows that modify this storage over time. The diagram formalizes how physical and anthropogenic variables interact and evolve throughout the simulation.

Fig. 3 displays the SFD used in this study. This shows that lake volume V is influenced by several inflow pathways, each feeding water into the system. Direct precipitation P_{lake} contributes immediately to the lake's storage, while rainfall over the watershed generates surface runoff R. Subsurface pathways, such as baseflow B_f and groundwater inflow GW_{in}, provide additional contributions that may respond more slowly to climatic changes. These inflows operate concurrently and vary seasonally, forming the primary drivers of volume increase.

Water leaves the lake through multiple outflow processes. Evaporation E removes water from the lake surface, and regulated discharge through the Asahan River Q_{out} represents the operational management component of the system. Groundwater outflow GW_{out} accounts for seepage, while anthropogenic withdrawals—agricultural demand W_{ag}, domestic use W_{dom}, and industrial or hydropower extraction W_{ind}—remove water from the lake according to human needs and economic activities.

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The interaction among these components produces the characteristic seasonal and interannual dynamics observed in Lake Toba. Increases in lake volume can intensify evaporation or promote higher discharge, providing a balancing effect, while decreases in storage can reduce these losses and partially stabilize the system. The SFD thus captures the full structure of hydrological, environmental, and socio-economic interactions that will be mathematically formalized in Section 2.3.

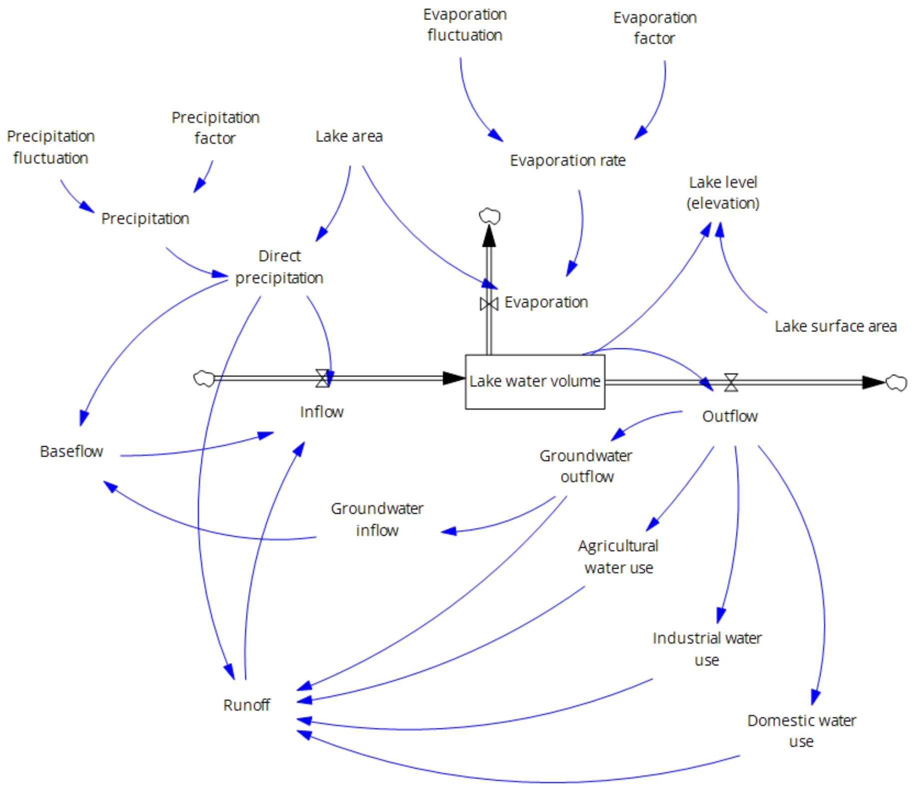

Figure 3. Stock Flow Diagram (SFD).

2.3 Mathematical Formulation

The mathematical formulation of the model is based on the water-mass conservation principle, which states that changes in lake storage arise from the difference between all incoming and outgoing water fluxes. The qualitative relationships shown in the CLD (Fig. 2) and the flow structure in the SFD (Fig. 3) are translated into a continuous-time stock–flow equation suitable for implementation in Vensim DSS.

2.3.1 Dynamic Water-Balance Equation

The rate of change in lake volume is governed by the following general expression:

$$\frac{dV}{dt} = \text{Total Inflow} - \text{Total Outflow} \tag{13}$$

This formulation evaluates the combined influences of hydrometeorological drivers, subsurface flows, and anthropogenic withdrawals on lake storage.

2.3.2 Inflow Components

All inflow processes contributing to lake storage are aggregated as:

$$\text{Total Inflow} = P_{\text{lake}} \cdot A_{\text{lake}} + R + B_f + GW_{in} \tag{13a}$$

where P_{lake} defines precipitation over the lake surface, A_{lake} the lake surface area, R the surface runoff from the watershed, B_f the baseflow and GW_{in} denotes the groundwater inflow. These terms represent the principal hydrological inputs identified in Table 1.

2.3.3 Outflow Components

Water losses from the lake are aggregated as:

$$\text{Total Outflow} = E \cdot A_{\text{lake}} + Q_{out} + GW_{out} + W_{ag} + W_{dom} + W_{ind} \tag{13b}$$

where E defines the evaporation rate, Q_{out} the regulated outflow through the Asahan River, GW_{out} the groundwater seepage loss, W_{ag}, W_{dom}, W_{ind} denotes the agricultural, domestic, and industrial water withdrawals, respectively. These terms in Eq.(13b) represent natural and anthropogenic pressures acting to reduce lake storage.

2.3.4 Numerical Integration in Vensim DSS

The dynamic water balance in (11) is implemented in Vensim using the INTEG function:

$$V = \text{INTEG}(\text{Total Inflow} - \text{Total Outflow}, V_0) \tag{13c}$$

where V_0 is the initial lake volume corresponding to the reference lake level.

The model is simulated with a monthly time step, matching the temporal resolution of the meteorological (BMKG) and hydrological (BWS Sumatera II) datasets. At each time interval, Vensim recalculates all inflow and outflow components, enabling the model to reproduce dynamic interactions, delays, and seasonal behavior.

2.3.5 Volume–Elevation Conversion

To express storage changes in terms of observed lake-level elevation, a linearized relationship between lake volume and effective surface area is used:

$$LL(t) = LL_0 + \frac{V(t) - V_0}{A_{eff}} \tag{14}$$

where $LL(t)$ refers to the lake-level elevation, LL_0 the reference elevation, A_{eff} the effective lake surface area and V_0 defines the reference storage volume. This formulation enables direct comparison between simulated and observed lake-level fluctuations.

2.3.6 Model Integration and Behavioral Implications

The mathematical system formed by Eqs. (11)–(12) integrates physical hydrology with anthropogenic influences into a single dynamic structure. Seasonal precipitation and runoff drive increases in storage, while evaporation, regulated discharge, and water withdrawals reduce it. Groundwater exchanges introduce delayed responses that moderate long-term trends. The resulting dynamics capture the oscillatory and stabilizing behaviors observed in Lake Toba's historical lake-level records.

3. Results and Discussion

3.1 Model Behavior and Simulation Results

The model was implemented in Vensim DSS using monthly hydrometeorological data from BMKG Parapat and hydrological records from BWS Sumatera II for the period 2000–2020. The simulation produces time-series outputs of lake volume V(t) and lake-level elevation LL(t), which are subsequently compared with observed lake-level measurements to assess model performance.

Figure 4 shows the simulated lake-level trajectory alongside the observed elevation data. The model reproduces the overall direction and magnitude of lake-level variations over the 20-year period, demonstrating its ability to capture the dominant hydrological processes governing Lake Toba. Although some discrepancies are present, particularly during periods of rapid short-term change, the simulated trend aligns with the long-

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term behavior identified in previous empirical analyses. Notably, the model indicates a gradual decline in lake level over the study horizon, consistent with the long-term reduction reported by Rosid et al. (2025) [1].

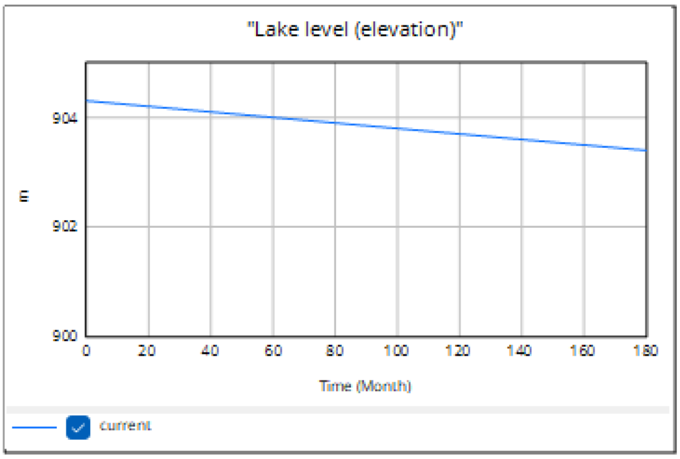

Figure 4. Simulated lake-level graph.

The deviation between simulated and observed elevation in certain intervals may reflect uncertainties in several components: (1) the operational discharge Q_{out}, which is influenced by hydropower management rules not fully represented in the model; (2) the representation of groundwater exchange, which may exhibit nonlinear responses to long-term hydroclimatic variability; and (3) possible underestimation of anthropogenic withdrawals due to limited high-resolution water-use data. Even with these uncertainties, the model successfully produces a coherent macrodynamic pattern that reflects the structural feedbacks outlined in the CLD and SFD.

A key feature of the model behavior is its demonstration of how changes in lake storage are governed by the balance between hydrometeorological inflows and outflow drivers. When inflows remain relatively stable while evaporative demand and discharge intensity increase, the storage responds through a persistent downward drift in elevation. This emergent trend suggests that the lake's long-term trajectory is sensitive to incremental changes in outflow-related processes. The consistency of this behavior across simulation runs indicates that the model structure adequately captures the system's dominant feedbacks.

The overall agreement between simulated and observed lake-level dynamics supports the validity of the synthesized water-balance formulation. The model demonstrates that a simplified System Dynamics representation—focused on key hydrological drivers and major anthropogenic withdrawals—can replicate the macroscopic behavior of a large and complex lake system such as Lake Toba. These results provide a useful foundation for subsequent sensitivity analysis and scenario-based evaluations of management interventions.

3.2 Sensitivity and Dominant Factors

Sensitivity analysis was performed by varying three key variables which are precipitation, evaporation rate, and regulated outflow by ±10% from their baseline values. These variables were selected because they represent the principal hydrological drivers governing the inflow–outflow balance of Lake Toba.

The results show markedly different magnitudes of influence across the three components. A 10% increase in precipitation produces the strongest response, raising the mean simulated lake-water elevation by approximately +0.7 m per year. This substantial increase reflects the direct role of precipitation in enhancing multiple inflow pathways, including direct rainfall on the lake surface, surface runoff, baseflow , and groundwater inflow .

In contrast, loss-side variables exhibit more moderate but directionally consistent effects. A 10% increase in the evaporation rate reduces lake elevation by approximately −0.10 m per year, illustrating the sensitivity of the system to atmospheric water demand. Similarly, increasing regulated discharge by 10% results in an elevation decline of roughly −0.11 m per year, highlighting the significant influence of hydropower-related outflow regulation on long-term lake storage.

These results align with the feedback structure presented in the CLD: precipitation-driven inflows contribute to a reinforcing loop that expands lake volume, whereas evaporation and outflow are part of the balancing loop that suppresses increases in storage. Although outflow and evaporation exert smaller numerical impacts compared to precipitation, their cumulative effects shape the long-term trajectory of lake-level decline.

Anthropogenic withdrawals, agricultural, domestic and industrial/hydropower were also tested, but their sensitivity responses remained minor, generally below 0.05 m per year for ±10% perturbations. While these components currently exert limited influence, their importance may grow under scenarios of increased irrigation demand, population growth, or industrial expansion.

Overall, the sensitivity analysis demonstrates that Lake Toba is most responsive to changes in precipitation, with evaporation and regulated discharge exerting secondary but stabilizing influences. These findings reinforce the importance of managing loss-side processes, particularly outflow regulation, as key leverage points for sustaining the lake's hydrological balance.

3.3 Interpretation and Implications

The simulation and sensitivity results reveal how Lake Toba's hydrological behavior is shaped by the reinforcing and balancing feedback mechanisms embedded in its water-balance structure. The model shows that lake storage responds strongly to changes in precipitation, where a 10% increase produces an annual elevation rise of approximately +0.7 m. This result is consistent with earlier lake-balance studies such as Winter (1981), Falconi et al. (2020), and Alifujiang et al. (2017) which similarly identified precipitation as the principal driver of volumetric change in natural lake systems [5,9,10].

Conversely, the model demonstrates that loss-side processes exert stabilizing yet significant influence. A 10% increase in evaporation reduces lake elevation by roughly −0.10 m per year, consistent with findings by Lari et al. (2020) and Rosid et al. (2025), who emphasized the importance of atmospheric water loss in long-term lake decline [1,8]. Similarly, the effect of a 10% increase in regulated outflow (−0.11 m per year) aligns with hydropower-driven discharge dynamics reported in Ahmad & Simonovic (2000) and Hassanzadeh et al. (2012), both of which showed that operational outflow regimes can substantially shape lake-level trends [6,7].

Anthropogenic withdrawals, agricultural, domestic, and industrial produce comparatively small deviations (typically <0.05 m per year). This aligns with earlier System Dynamics applications to water-use systems (Ahmad & Prashar 2010; Lari et al. 2020), which found that when natural hydrological fluxes dominate, human withdrawals tend to act as slow-moving pressures rather than immediate drivers of system behavior. However, these components can become critical under scenarios of expanding irrigation or industrial activity, underscoring the importance of monitoring demand-side growth [8,11].

The behavior reproduced by the model reflects the feedback structure outlined in the CLD: precipitation-driven inflows feed the reinforcing loop that elevates lake volume, while evaporation and regulated discharge form the balancing loop that constrains growth. This interplay of feedbacks is central to System Dynamics theory as articulated by Forrester (1961) and Sterman (2000), which posits that long-term system behavior arises not from individual variables but from the structure of interacting loops [2,3].

Methodologically, the agreement between simulated and observed lake-level trends illustrates that the simplified stock–flow representation captures the essential hydrological processes of Lake Toba. Similar to findings by Madani (2009) in water-resources policy modeling and by Hassanzadeh et al. (2012) in their study of Lake Urmia, the use of System Dynamics enables transparent interpretation of causal mechanisms and provides a robust platform for scenario exploration [7,13].

These insights carry clear implications for lake management. The strong sensitivity to precipitation highlights the potential impacts of climate variability on basin-scale water availability. The significant influence of outflow regulation suggests that hydropower operational policies could be leveraged to counter long-term declines. Meanwhile, the steady but currently modest anthropogenic withdrawals indicate that early governance of water-use growth will be essential to prevent future stress on the system. Collectively, the results position the model as a practical analytical tool for anticipating hydrological trajectories and supporting sustainable lake-management strategies.

4. Conclusion

This study developed a preliminary System Dynamics model to characterize the hydrological behavior of Lake Toba by representing key natural and anthropogenic fluxes within a simplified stock–flow framework. The model is able to reproduce the general direction of lake-level changes over the 2000–2020 period, indicating that the dominant hydrological interactions, precipitation inputs, evaporative losses, discharge regulation, and groundwater exchange are reasonably captured at a macroscopic level. However, discrepancies between simulated and observed lake levels remain, particularly during periods of rapid short-term change, suggesting that several processes (such as operational discharge rules or nonlinear groundwater responses) may not yet be fully represented.

The sensitivity analysis shows that the system responds most strongly to variations in precipitation, where a 10% increase raises lake level by approximately +0.7 m per year. Evaporation and regulated discharge also exert measurable influence, with 10% increases reducing lake elevation by −0.10 m and −0.11 m per year, respectively. Anthropogenic withdrawals currently produce relatively small effects, though their influence may increase if water demand grows. These results reinforce the structural interpretation that the lake's long-term evolution is shaped primarily by the balance between climatic inflows and loss-driven feedbacks.

Overall, the model provides a conceptual starting point for understanding the broader mechanisms governing Lake Toba's hydrological behavior. Given its preliminary nature, the model should be interpreted with caution. It is not intended to provide precise forecasts but rather to outline the major interactions that influence storage trends. Further refinement particularly through improved representation of discharge operations, higher-resolution water-use data, and enhanced groundwater characterization will be required to increase the model's explanatory and predictive capacity. Nevertheless, the present formulation offers a basis for more detailed future modeling efforts and for examining how changes in hydrological drivers could affect lake-level trajectories over time.

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6. Conflict of Interest

The authors declare that there are no conflicts of interest related to the research, analysis, or publication of this article. All results and interpretations presented in this paper are the outcome of independent and objective scientific investigation.

References

[1] M. S. Rosid, H. Irwandi, and T. Mart, "Evaluation of Lake Toba's water level decline in Indonesia over the past six decades," *Environmental Earth Sciences*, vol. 84, no. 6, pp. 1–14, 2025.

[2] H. Irwandi, M. S. Rosid, and T. Mart, "Identification of the El Niño effect on Lake Toba's water-level variation," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 406, p. 012022, 2019.

[3] J. W. Forrester, *Industrial Dynamics*. Cambridge, MA, USA: MIT Press, 1961.

[4] J. D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston, MA, USA: McGraw-Hill, 2000.

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[5] T. C. Winter, "Uncertainty in estimating the water balance of lakes," *Water Resources Research*, vol. 17, no. 1, pp. 82–115, 1981.

[6] S. Ahmad and S. P. Simonovic, "System dynamics modeling of reservoir operations for flood management," *Journal of Computing in Civil Engineering*, vol. 14, no. 3, pp. 190–198, 2000.

[7] H. Hassanzadeh, A. Zarghami, A. Hassanzadeh, S. M. Nazemi, and S. Madani, "Determining the main factors in declining the Urmia Lake level using system dynamics modeling," *Water Resources Management*, vol. 26, no. 1, pp. 129–145, 2012.

[8] A. Lari, A. Madani, and H. Hassanzadeh, "A system dynamics approach to basin policy design: Urmia Lake case study," *Water*, vol. 12, no. 1, p. 223, 2020.

[9] L. M. Falconi, R. Boccaletti, and F. C. Falconi, "A system dynamics model for the water balance of Lake Bracciano (Lazio, Italy)," ENEA Casaccia Research Centre, 2020.

[10] N. Alifujiang, G. Abuduwaili, and Z. G. Zhang, "System dynamics modeling of water level variations of Lake Issyk-Kul, Kyrgyzstan," *Water*, vol. 9, no. 11, p. 861, 2017.

[11] S. Ahmad and S. Prashar, "Evaluating municipal water conservation policies using a dynamics simulation model," *Water Resources Management*, vol. 24, no. 13, pp. 3373–3395, 2010.

[12] H. Sihotang, "Kajian dinamika hidrologi dan fluktuasi air Danau Toba," *Jurnal Teknik Sipil Universitas Sumatera Utara*, vol. 5, no. 2, pp. 101–112, 2016.

[13] A. Madani, "System dynamics analysis of water resources management in Iran," *Environmental Modelling & Software*, vol. 24, no. 2, pp. 183–197, 2009.