Equivalent: Jurnal Ilmiah Sosial Teknik
Volume 8, Issue 6, 2501-2520
e_ISSN: 2775-0833
https://jurnalequivalent.id/index.php/jequi/index
DOI: doi.org/10.59261/jequi.v8i6.497

System Dynamics Based Decision Support Model for Assessing Urban Water Availability: A Case Study of Bogor City

Bella Febiolita
Universitas Bina Nusantara, Indonesia

Leo Susy Villianny*
Universitas Bina Nusantara, Indonesia

Monica Audrey
Universitas Bina Nusantara, Indonesia

Rida Zuraida
Universitas Bina Nusantara, Indonesia

***Corresponding author:**
Leo Susy Villianny, Universitas Bina Nusantara, Indonesia.
✉leo.villianny@binus.ac.id*

Article Info:

***Article history*:**
Received: October 12, 2026
Revised: November 12, 2026
Accepted: November 14, 2026
Available Online: November 24, 2026

***Keywords*:**
Decision Support System;
Sensitivity Analysis;
System Dynamics;
Urban Water Availability;
Water Balance;

This is an open access article under the CC BY-SA license.

Copyright © 2026 by Author. Published by Politeknik Siber Cerdika International

Abstract

Background: Urban water availability is increasingly challenged by population growth, land-use changes, and rising water demand, necessitating integrated approaches to sustainable water-resource management.
Objective: This study aims to develop a system dynamics-based decision-support framework for assessing long-term urban water availability in Bogor City, Indonesia.
Methods: System dynamics modeling was conducted using Vensim, incorporating causal loop diagrams (CLDs), stock-and-flow diagrams (SFDs), and sensitivity analysis over a 100-year simulation period. Two scenarios were evaluated: a baseline model representing primary water supply and demand components (Scenario 1) and an expanded model incorporating green open space, rainfall, tourism, nonresident workers, water pricing, and household groundwater consumption (Scenario 2).
Results: Both scenarios demonstrated declining trends in water availability and water balance. At Year 100, the high-case water balance reached approximately −1.40 billion m^3/year in Scenario 1 and −1.01 billion m^3/year in Scenario 2, reflecting structural model differences rather than demonstrable improvements in water availability. Sensitivity analysis identified the new subscriber rate and green open space ratio as the most influential parameters. In Scenario 2, variations in the new subscriber rate generated differences of approximately 33 billion m^3 in available water and 446.33 million m^3/year in water balance. Birth rate, death rate, tourism, and household well expansion exhibited relatively limited sensitivity.
Conclusion: The findings emphasize the importance of integrating urban water-demand dynamics and land-use characteristics into water-resource assessments. The proposed framework supports preliminary decision-making by identifying priority variables for monitoring, further validation, and sustainable urban water-management planning.

To cite this article: Febiolita, B., Villianny, L. S., Audrey, M., & Zuraida, R. (2026). System dynamics based decision support model for assessing urban water availability: A case study of Bogor City. *Equivalent: Jurnal Ilmiah Sosial Teknik*, *8*(6), 2501-2520. https://doi.org/10.59261/jequi.v8i6.497

INTRODUCTION

Urban water availability represents a complex dynamic system influenced by interactions among hydrological processes, engineered water supply, demographic growth, economic development, land-use changes, and water consumption behavior (Gohari et al., 2022; Raza et al., 2026). Assessing urban water security therefore requires an integrated perspective that extends beyond precipitation levels and the capacity of formal water supply infrastructure (Apolinário et

al., 2026; Krueger et al., 2022). Population growth, urban expansion, groundwater abstraction, and changes in consumption patterns simultaneously influence the balance between water supply and demand (Asadollahi et al., 2024). Zheng et al. (2024) demonstrated that System Dynamics modeling provides a comprehensive approach to examining interactions among urban development, water demand, and resource management. Similarly, Bano et al. (2022) emphasized that understanding feedback relationships between formal and informal water supply systems is essential for identifying long-term challenges in urban water management. Consequently, System Dynamics offers an appropriate methodological framework for analyzing feedback mechanisms, stock accumulation, and the long-term behavior of interconnected urban water systems.

Bogor City, Indonesia, provides a relevant context for examining these interactions because its relatively high precipitation occurs alongside substantial population density and diverse urban economic activities. According to statistical information reported by Badan Pusat Statistik Kota Bogor (2026), the city exhibits characteristics of a densely populated urban area with significant development in service-related activities. The data compiled for this study indicate annual rainfall of approximately 3,709.1 mm, a population of 1,083,776 inhabitants in 2024, and a population density of approximately 9,730 persons/km^2. These characteristics demonstrate that abundant rainfall does not automatically ensure adequate usable water resources. Urban water availability is influenced by the relationship among hydrological inputs, effective infiltration, infrastructure capacity, and consumption requirements.

Research by Zheng et al. (2024) further indicates that the relationships among economic activities, population dynamics, and water consumption should be evaluated systematically to understand long-term urban water-resource constraints. The available local evidence is used here to justify an investigation of system dynamics, rather than to assert that Bogor is already experiencing a verified citywide water crisis. In the absence of a complete empirical time series on water production, service coverage, groundwater abstraction, and supply shortages, this study focuses on how water availability may evolve under the model's specified structures and assumptions.

From a hydrological perspective, precipitation cannot be assumed to contribute entirely to available water resources because rainfall is distributed among surface runoff, evapotranspiration, soil infiltration, and groundwater recharge. Siddik et al. (2022) demonstrated that land-use and land-cover changes influence groundwater recharge, particularly in areas experiencing urban expansion and increasing impervious surface coverage. Accordingly, the present study incorporates rainfall, the Green Open Space Ratio (RTH), and the geographical area of Bogor City into a simplified infiltration mechanism representing potential contributions to water inflow. Green open spaces are considered relevant because vegetated land cover can influence infiltration processes and the hydrological response of urban areas. Nevertheless, the proposed formulation is intended for exploratory System Dynamics simulations rather than detailed hydrological forecasting or aquifer characterization. This distinction is important to avoid interpreting simplified model relationships as direct measurements of groundwater recharge.

Urban water demand is similarly multidimensional and cannot be adequately represented by residential consumption alone. Industrial activities, commercial services, agriculture, tourism, and nonresident populations contribute to the overall demand imposed on urban water systems. Zheng et al. (2024) highlighted the importance of integrating socioeconomic development and sectoral water consumption when evaluating urban water-resource management strategies. In Bogor City, accommodation establishments, restaurants, and other service-related businesses contribute to economic activity and may generate additional water requirements beyond those associated with registered residents. Therefore, the expanded model incorporates tourism and nonresident worker demand alongside domestic, industrial, service-sector, and agricultural consumption. These variables provide a broader representation of urban water demand while allowing their relative influences to be examined through scenario-based sensitivity analysis.

Another important consideration is the coexistence of formal piped water services and self-supplied groundwater. In many developing urban contexts, households and businesses rely on multiple water sources when formal distribution networks do not fully satisfy their

consumption requirements.

Bano et al. (2022) identified significant interactions between formal and informal water supply arrangements and demonstrated that their feedback structures influence long-term system reliability and sustainability. These findings indicate that assessments relying exclusively on formal utility consumption records may overlook water abstraction occurring outside established distribution systems. In the present study, household groundwater abstraction not captured in formal utility demand records is represented by the variable Masked Demand. This variable is treated as an additional demand component affecting Water Demand and Available Water, rather than as a new source of water inflow. Its inclusion expands the model boundary and permits examination of the potential effects of household well use on simulated urban water availability.

Water pricing represents an additional behavioral mechanism influencing urban water demand. Economic instruments, including water tariffs, are frequently incorporated into water-resource management to encourage efficient consumption. However, consumer responses to price changes depend on socioeconomic characteristics, existing consumption patterns, and the magnitude of tariff adjustments. Vidal-Lamolla et al. (2024) demonstrated that residential water-demand elasticity can be examined through simulation-based approaches that account for heterogeneous consumer behavior and alternative pricing conditions. Their findings support the importance of evaluating demand responses rather than assuming that tariff adjustments produce uniform reductions in consumption. Accordingly, this study incorporates water pricing and demand elasticity through the Demand After Price Increment mechanism. Because the relationships among tariff changes, household consumption, and alternative water-source use have not been empirically calibrated for Bogor City, this mechanism is treated as an exploratory scenario assumption rather than a verified local behavioral relationship.

Integrated urban water modeling requires explicit representation of the relationships among water inflow, accumulated water availability, and sectoral consumption. System Dynamics provides a useful framework for examining these relationships over time. Zheng et al. (2024) modeled interactions among water supply, demand growth, and management strategies in Shenzhen, while Bano et al. (2022) emphasized feedback relationships between formal and informal water supply arrangements.

Recent applications in Linhai and Padang likewise demonstrate that dynamic models can organize interactions among urban development, water demand, supply, and management scenarios (Arbi et al., 2025; Chen et al., 2023). Sun et al. (2024) further demonstrated the value of combining system-oriented analysis with water-resource carrying-capacity assessment. Together, these studies support the use of dynamic modeling while also demonstrating that model structures are context-dependent. Their environmental conditions, institutional settings, and demand representations differ from those of Bogor, necessitating contextual adaptation rather than direct transfer.

The present study builds upon an existing System Dynamics water-shortage model developed for Rafsanjan City, Iran. The reference model represents Available Water as a stock influenced by water penetration, transferred water supply, and sectoral consumption. However, the hydrological and socioeconomic characteristics of Rafsanjan differ substantially from those of Bogor City. Rafsanjan represents a relatively arid environment with substantial agricultural water demand and groundwater constraints, whereas Bogor is characterized by a tropical climate, relatively high rainfall, intensive urban activities, and diversified water consumption. Consequently, directly applying the reference model without contextual adaptation may inadequately represent the specific mechanisms influencing Bogor's urban water system. To address these differences, the present study expands the model boundary by incorporating the Green Open Space Ratio into the penetration mechanism, together with tourism, nonresident worker demand, price-responsive consumption, and Masked Demand associated with household groundwater abstraction. The adaptation retains the reference model's stock-and-flow logic for available water and aggregate demand while modifying the parameterization for Bogor and expanding the structure to represent rainfall, green open space, tourism, nonresident workers,

water pricing, and household groundwater use. These additions are treated as context-specific extensions supported by urban water theory and available local information. The novelty lies in the adapted decision-support structure and sensitivity analysis rather than in the addition of variables per se. The reference model is documented by (Shahsavari-Pour et al., 2023).

Against this background, a remaining methodological question concerns how alternative model boundaries alter long-term system behavior and parameter sensitivity in a densely populated tropical city. Existing studies have separately examined urban water supply-demand interactions, land-use effects on groundwater recharge, and behavioral responses to water pricing (Zheng et al., 2024). However, these studies do not establish how the combined representation of green open space, nonresident demand, tourism, price responsiveness, and household groundwater use affects Bogor City's simulated Water Balance. The research gap addressed in this study therefore concerns the effects of expanding both inflow and demand boundaries within a single System Dynamics framework. Rather than presuming that Bogor currently faces verified water scarcity, this study examines how alternative model structures and parameter conditions shape simulated Available Water and Water Balance over a 100-year period.

The primary objective of this study is to develop an adaptable System Dynamics-based decision-support framework for assessing long-term urban water availability, using Bogor City as a case study. The framework evaluates the implications of alternative model boundaries and parameter conditions for Available Water and Water Balance while identifying variables that may require closer monitoring, improved empirical data, and further management analysis. The model is implemented using an annual time step over a 100-year simulation horizon and incorporates rainfall, the Green Open Space Ratio, penetration, transferred water supply, demographic factors, industrial and service-sector subscribers, agricultural consumption, tourism, nonresident worker demand, price-responsive consumption, and household groundwater abstraction.

Detailed distribution-network hydraulics, short-term operational dynamics, aquifer physics, groundwater quality, and prescriptive spatial land-use planning remain outside the model boundary. Parameters with insufficient empirical evidence are represented through literature-based proxies or explicit scenario assumptions and assessed through sensitivity analysis. The intended contribution is an exploratory decision-support framework that enables comparisons of alternative urban water-system representations and supports the identification of priority variables for subsequent empirical validation and sustainable water-resource planning.

METHOD

This study developed a System Dynamics model to assess long-term urban water availability, using Bogor City as a case study. The model was designed to examine how alternative model boundaries and parameter conditions influence Available Water and Water Balance over a 100-year simulation period.

Figure 1 illustrates the sequential research stages, including problem identification and objective formulation; identification of key variables and data collection; development of the Causal Loop Diagram (CLD); development of the Stock-and-Flow Diagram (SFD); model formulation using Vensim; model verification and validation; baseline simulation; scenario development; sensitivity analysis; and interpretation of the results for decision-support purposes. The identified variables were linked through causal relationships and represented in a CLD to identify reinforcing and balancing feedback loops. The CLD was subsequently translated into an SFD comprising stocks, flows, auxiliary variables, parameters, and mathematical relationships required for quantitative simulation. The model was formulated in Vensim based on the identified equations, parameters, initial conditions, and available data. Before simulation, the model underwent verification and validation to assess the consistency of its structure, equations, units, and simulated behavior. Scenario-based analysis was then conducted to examine how alternative model structures and parameter conditions affect Available Water and Water Balance, consistent with previous applications of System Dynamics in water resource management. The results were interpreted to identify variables associated with stronger or weaker long-term responses and to support the prioritization of monitoring activities, data improvements, and further management

analyses.

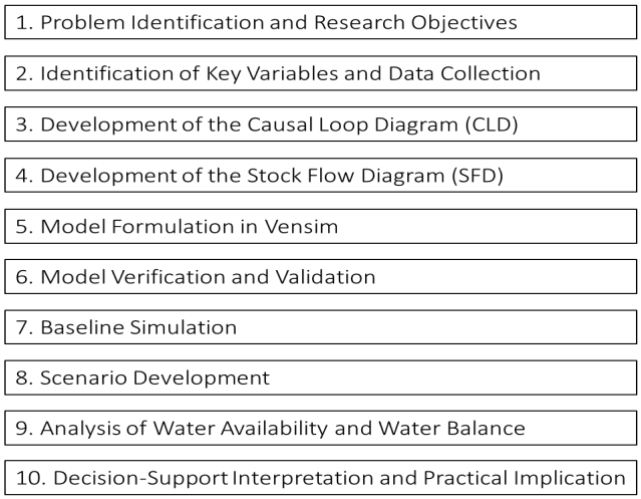


Figure 1. Research Methodology for System Dynamics Modeling using Vensim Software

The data used in this study were collected from various sources, as detailed in Table 1.

Table 1
Data Collection Reference

Variable	Description	Resources
BA	Bogor Area	Jabar.bps.go.id
GOS	Green Open Space	Kotabogor.id
R	Rainfall	Bogorkota.bps.go.id
POP	Population	Bogorkota.bps.go.id
BR	Birth Rate	Disdukcapil.jabarprov.go.id
DR	Death Rate	Disdukcapil.jabarprov.go.id
NWCP	Non-drinking water consumption per person	Bapperida.kotabogor.go.id
ADWCP	Annual drinking water consumption per person	Bapperida.kotabogor.go.id
ATR	Annual Transfer Rate	Tirtapakuan.co.id
SR	Shrinking Rate	Bogorkota.bps.go.id
CA	Cultivated Area	Bogorkota.bps.go.id
AWCPH	Agricultural water consumption per hectare	Bogorkota.bps.go.id
WP	Water Price	Tirtapakuan.co.id
WPO	Well Point	Tirtapakuan.co.id
WC	Well Capacity	Tirtapakuan.co.id
TR	Tourism	Metropolitan.id
NSR	New Subscriber Rate	Klikbogor.id
ISS	Industrial and Services Subscriber	Bogorkota.bps.go.id

RESULTS AND DISCUSSION

Results

The proposed System Dynamics framework was applied to Bogor City, Indonesia, as a case study to demonstrate how the model can be parameterized for a specific urban context. Bogor was selected because it represents a densely populated tropical urban area characterized by relatively high rainfall, diverse urban water demands, and a combination of formal water supply and household groundwater use. These characteristics provide an appropriate case for examining how the general model structure can be adapted by incorporating locally relevant inflow and demand variables.

The Bogor case study model was parameterized using local demographic, hydrological, land-use, agricultural, utility, and urban activity data. The city covers approximately 111.39 km^2

and had a population of 1,083,776, representing a relatively high population density. Rainfall, Green Open Space Ratio, and city area were used to parameterize the penetration mechanism, while population, industrial and service subscribers, agricultural area, tourism, and nonresident worker demand were used to represent different components of urban water demand. Formal water transfers and household groundwater use were also incorporated to represent the coexistence of utility-based and self-supplied water sources.

On the inflow side, rainfall was not assumed to become fully available water. Instead, rainfall, Green Open Space Ratio, and Bogor City area were incorporated through the penetration mechanism. This adaptation reflects the need to represent land-cover-related differences in effective water inflow within the simplified System Dynamics structure. On the demand side, the model includes not only residential and sectoral demand but also tourism, nonresident workers, price-responsive demand, and Masked Demand associated with household well use. These variables represent the context-specific extensions of the core urban water model for the Bogor case study.

Following the case study parameterization, the model structure was developed in Vensim using a Causal Loop Diagram and a Stock-and-Flow Diagram. Two scenarios were subsequently simulated to examine how differences in model boundaries influence long-term system behavior and parameter sensitivity.

This decision-support orientation is consistent with Linggabinangkit & Hermana (2026), who used System Dynamics scenario analysis to translate long-term urban environmental behavior into implications for integrated planning and decision-making.

Development of the Causal Loop Diagram (CLD)

The first step involved developing the causal loop diagram (CLD) of the urban water system. Figure 2 presents the CLD representing the overall system structure for Scenario 1, while Figure 3 presents the CLD for Scenario 2. The diagrams were developed based on dynamic hypotheses derived from the literature review and further refined through expert opinions obtained from semistructured interviews. Each causal relationship is represented by an arrow labeled with either a positive (+) or negative (−) sign. Positive (+) polarity indicates that changes in two variables occur in the same direction, whereas negative (−) polarity indicates that changes occur in opposite directions.

Among all the variables, Available Water represents the central state variable because it directly reflects the sustainability of the urban water system. A continuous decline in Available Water may trigger a water crisis, resulting in significant environmental, social, and economic consequences if appropriate management interventions are not implemented in a timely manner.

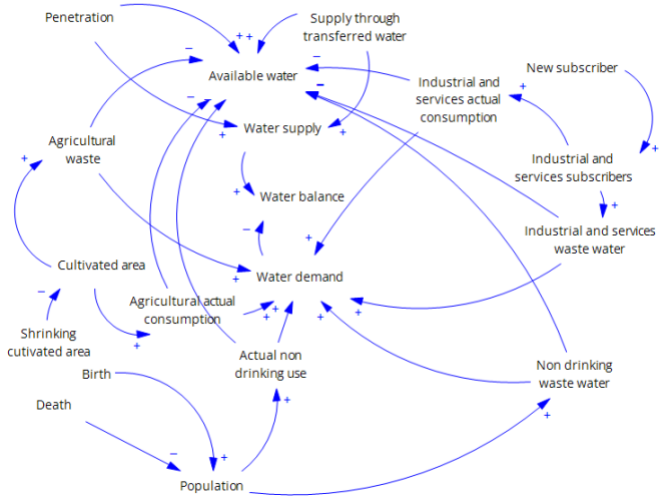


Figure 2. Causal Loop Diagram (Scenario 1)

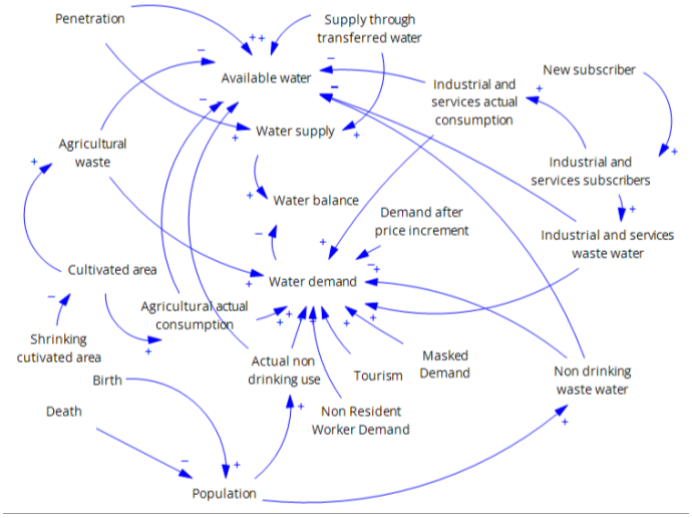


Figure 3. Causal Loop Diagram (Scenario 2)

Development of the Stock and Flow Diagram

The next step involved developing the stock-and-flow diagram and conducting the model simulations. The model variables, together with their descriptions and units, are summarized in Table 2, while the overall stock-and-flow structure is presented in Figure 4 for Scenario 1 and Figure 5 for Scenario 2. For convenience in model formulation, each variable was assigned an abbreviation, which is used consistently in the mathematical equations and simulation model.

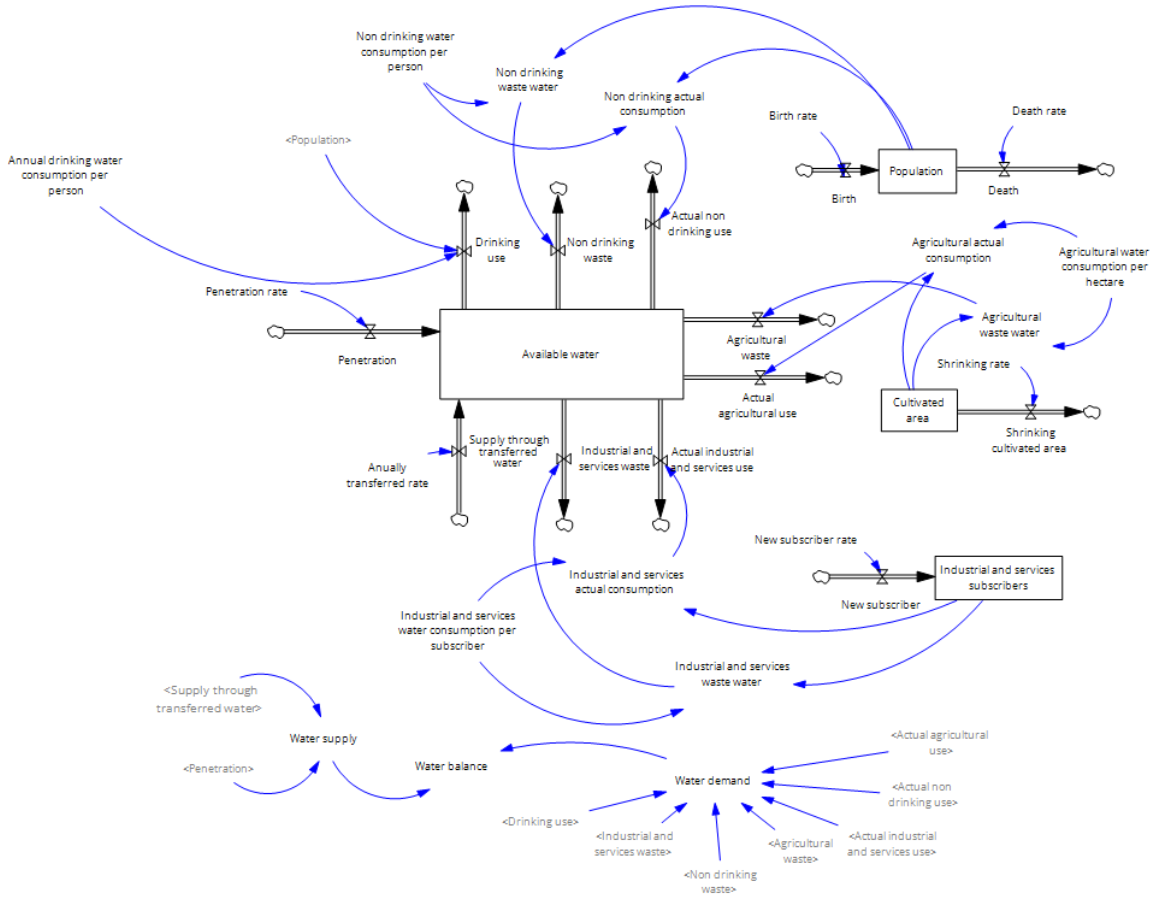


Figure 4. Stock and Flow Diagram (Scenario 1)

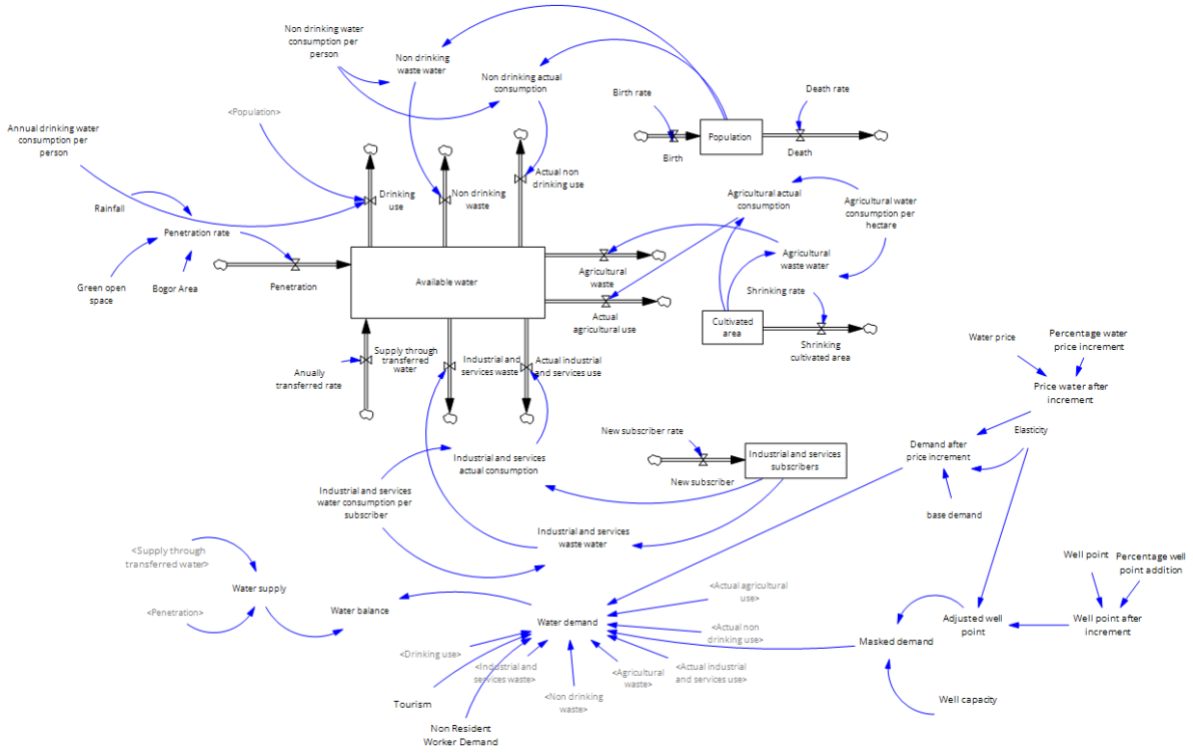


Figure 5. Stock and Flow Diagram (Scenario 2)

Table 2
Description of Stock Flow Diagram Variables

Variable	Description	Unit
PR	Penetration rate	Cubic meter/year
P	Penetration	Cubic meter/year
AW	Available Water	Cubic meter
DU	Drinking use	Cubic meter/year
ADWCP	Annual drinking water consumption per person	(Cubic meter/person)/year
STW	Supply through transferred water	Cubic meter/year
ATR	Annually transfer rate	Cubic meter/year
NDW	Non-drinking waste	Cubic meter/year
ANU	Actual non-drinking use	Cubic meter/year
NWW	Non-drinking wastewater	Cubic meter/year
NAC	Non-drinking actual consumption	Cubic meter/year
NWCP	Non-drinking water consumption per person	(Cubic meter/person)/year
POP	Population	Person
B	Birth	Person/year
BR	Birth rate	Person/year
D	Death	Person/year
DR	Death rate	Person/year
AGW	Agricultural waste	Cubic meter/year
AAU	Actual agricultural use	Cubic meter/year
AAC	Agricultural actual consumption	Cubic meter/year
AWW	Agricultural wastewater	Cubic meter/year
AWCPH	Agricultural water consumption per hectare	(Cubic meter/hectare)/year
CA	Cultivated area	Hectare
SCA	Shrinking cultivated area	Hectare/year
SR	Shrinking rate	Hectare/year
AISU	Actual industrial and services use	Cubic meter/year
ISW	Industrial and service waste	Cubic meter/year
ISAC	Industrial and services actual consumption	Cubic meter/year

ISWW	Industrial and services wastewater	Cubic meter/year
ISWCP	Industrial and services water consumption per subscriber	(Cubic meter/Subscriber)/year
ISS	Industrial and services subscribers	Subscriber
NS	New subscriber	Subscriber/year
NSR	New subscriber rate	Subscriber/year
WS	Water Supply	Cubic meter/year
WD	Water Demand	Cubic meter/year
WB	Water Balance	Cubic meter/year
R	Rainfall	Meter/year
WP	Water Pricing	Rp/cubic meter
HW	Household Well	Cubic meter/year
DAPI	Demand After Price Increment	Cubic meter/year
PWAI	Price Water After Increment	Rp/cubic meter
WPO	Well Point	Ea
AWP	Adjusted Well Point	Ea
WC	Well Capacity	Cubic meter
TR	Tourism	Cubic meter/year
NRWD	Non Resident Worker Demand	Cubic meter/year
GOS	Green Open Space	%
BA	Bogor Area	Square meter
PWI	Percentage Water Price Increment	%
PWP	Percentage well point addition	%
MD	Masked Demand	Cubic meter/year
WPPI	Well Point After Price Increment	Ea
PWPA	Percentage Well Point Addition	%

The model was formulated in Vensim using the mathematical relationships presented below. These equations represent the structure of the System Dynamics model used to assess urban water availability in the Bogor City case study.

Equation (1) shows the total Available Water. The initial value of the Available Water stock variable is 81,678,240 m^3.

AW = INTEG(P+STW-AAU-AISU-ANU-AGW-DU-ISW-NDW, 81,678,240) (1)

Equation (2) indicates the amount of water infiltrating underground aquifers, which is equal to the penetration rate shown in Equation (3).

P = PR (2)

PR = R x GOS x BA (3)

Equation (4) represents the amount of water transferred into the system annually, which is equal to the annual water transfer rate shown in Equation (5).

STW = ATR (4)

ATR = 14,200,000 (5)

Equation (6) represents annual drinking water consumption, which is calculated by multiplying the annual drinking water consumption per person by the population, as defined in Equations (7) and (13).

DU = ADWCP x POP (6)

ADWCP = 1.83 (7)

Equation (8) represents non-drinking waste, which is assumed to be equal to the amount of non-drinking wastewater calculated in Equation (9).

NDW = NWW (8)

NWW = NWCP x POP x 0.3 (9)

Equation (10) represents actual non-drinking water use by the population, which is assumed to be equal to actual non-drinking consumption, as calculated in Equation (11).

ANU = NAC (10)

NAC = NWCP x POP x 0.7 (11)

NWCP = 37.69 (12)

Equation (13) represents the population stock variable, with births as the inflow, as defined in Equation (14), and deaths as the outflow, as defined in Equation (16).

POP = INTEG(B - D, 1,083,776) (13)

Equation (14) indicates the number of births, which is equal to the birth rate specified in Equation (15).

B = BR (14)

BR = 18,468 (15)

Equation (16) indicates the number of deaths, which is equal to the death rate specified in Equation (17).

D = DR (16)

DR = 6,443 (17)

Equation (18) represents agricultural wastewater, which is calculated as the portion of agricultural water consumption allocated to wastewater in Equation (19).

AGW = AWW (18)

AWW = AWCPH x CA x 0.4 (19)

Equation (20) represents actual agricultural water use, which is calculated as the portion of agricultural water consumption allocated to actual consumption in Equation (21).

AAU = AAC (20)

AAC = AWCPH x CA x 0.6 (21)

AWCPH = 8,000 (22)

Equation (23) represents the cultivated area stock variable, which is determined by its initial value and the annual reduction in cultivated area.

CA = INTEG(SCA, 605) (23)

Equation (24) represents the annual reduction in cultivated area, which is equal to the shrinkage rate specified in Equation (25).

SCA = SR (24)

SR = 8 (25)

Equation (26) represents actual water consumption in the industrial and service sectors, which is equal to actual consumption calculated in Equation (27).

AISU = ISAC (26)

ISAC = ISS x ISWCP x 0.8 (27)

Equation (28) represents industrial and service wastewater, which is calculated as the portion of industrial and service water consumption allocated to wastewater in Equation (29).

ISW = ISWW (28)

ISWW = ISS x ISWCP x 0.2 (29)

ISWCP = 4,824 (30)

Equation (31) represents the industrial and service subscriber stock variable. Its inflow is the number of new subscribers, and its initial value is 53,527 subscribers.

ISS = INTEG(NS, 53,527) (31)

Equation (32) represents the number of new subscribers, which is determined by the new subscriber rate specified in Equation (33).

NS = NSR (32)

NSR = 2,239 (33)

Equation (34) represents the total Water Supply to the system.

WS = P + STW (34)

Equation (35) represents Demand After Price Increment, which is determined by Base Demand (Equation (36)) and the Price of Water After Increment (Equation (37)).

DAPI = BD x PWAI ^ (-E) (35)

BD = AAU + ANU + AISU + AGW + NDW + ISW + DU (36)

PWAI = WP x (1 + PWI) (37)

Equation (38) determines Masked Demand based on Well Capacity and Adjusted Well Points, using the Well Points After Price Increment mechanism presented in Equations (39)–(41).

MD = WC x AWP (38)

AWP = WPPI ^ (-E) (39)

WPPI = WP x (1+PWPA) (40)

WC = 4.63 (41)

Equation (42) describes total Water Demand within the system.

WD = AAU + ANU + AISU + AGW + NDW + ISW + NRWD + T + DU + MD + DAPI (42)

Equation (43) defines Water Balance as the difference between Water Supply (Equation (34)) and Water Demand (Equation (42)). A positive value represents a modeled surplus, whereas a negative value represents a modeled annual deficit.

WB = WS – WD (43)

Table 3

Variable Value

Variable	Current	Down	Up
BA	111,390,000		
GOS	0.05	0.05	3
R	7.2	3.19	12.87
POP	1,083,776		
ADWCP	1.83		
ATR	14,200,000		
NWCP	37.69		
BR	18,468	20,158	14,600
DR	6,443	2,859	11,698
ISWCP	4,824		
ISS	53,527		
NSR	2,239	2,580	1,655
AWCPH	8,000		
CA	605		
SR	8		
T	1,895,493	1,890,754	1,800,718
NRWD	956,838	2,733,822	341,728
WP	3,500		
WC	4.63		

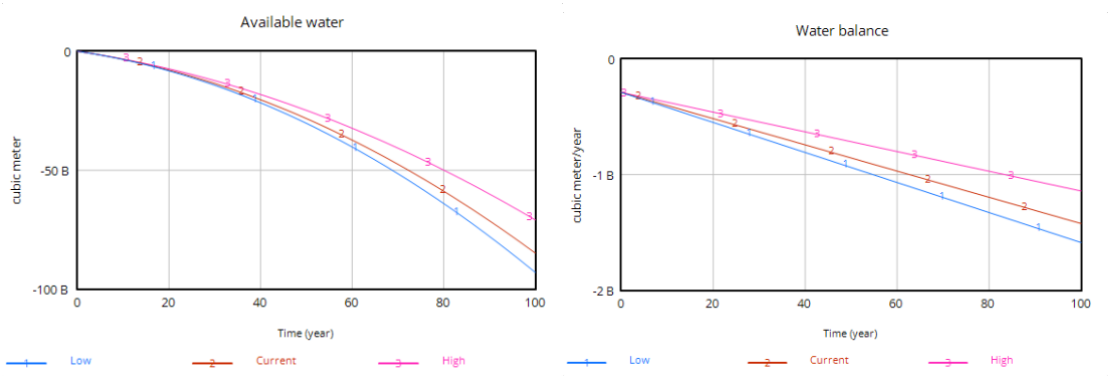
WPO	1,545

Results obtained by first scenario

Scenario 1 represents the baseline model structure using the main formally identifiable water supply and demand components. Sensitivity analysis was conducted for Birth Rate, Death Rate, and New Subscriber Rate to examine how variations in these parameters influence Available Water and Water Balance over the 100-year simulation horizon.

The results show that Birth Rate and Death Rate have relatively limited influences on the simulated system within the tested parameter ranges. For Birth Rate, the Low, Current, and High trajectories remain closely aligned for both Available Water and Water Balance. By Year 100, Available Water reaches approximately −85 billion m^3, while Water Balance declines to approximately −1.4 billion m^3/year. A similar pattern is observed for Death Rate, with Available Water reaching approximately −86, −85, and −84 billion m^3 for the Low, Current, and High cases, respectively. The relatively narrow separation indicates that the model outputs have low sensitivity to changes in these demographic parameters. A negative Water Balance is interpreted as a modeled annual deficit, whereas a negative Available Water stock would be physically problematic if interpreted as stored volume. The stock equations, flow directions, units, and initial conditions were therefore conceptually reexamined. Negative stock values are treated as indications that cumulative modeled demand has exceeded the represented supply within the unconstrained simulation, rather than as literal negative water storage.

In contrast, New Subscriber Rate produces a substantially clearer separation among the simulation trajectories. By Year 100, Available Water reaches approximately −93 billion m^3 in the Low case and −71 billion m^3 in the High case. Water Balance shows a similar divergence. This stronger response occurs because changes in industrial and service subscribers directly affect sectoral water demand and accumulate over the simulation horizon. Therefore, New Subscriber Rate emerges as the most influential parameter tested within Scenario 1.



(a) **(b)**

Figure 6. Sensitivity of Scenario 1 to New Subscriber Rate: (a) Available Water and (b) Water Balance.

In summary, Scenario 1 illustrates that the system does not respond equally to all the parameters tested. For Available Water and Water Balance, the outputs of different simulated trajectories differ relatively little in response to variations in Birth Rate and Death Rate but can differ substantially in response to variations in New Subscriber Rate. Thus, given the model structure and the position of each variable in relation to other variables, its effect on long-term system behavior cannot be determined solely from its numerical value.

Results obtained by second scenario

Scenario 2 expands the baseline model boundary by incorporating additional inflow and demand mechanisms, including rainfall and Green Open Space Ratio in the penetration mechanism, tourism, nonresident worker demand, price-responsive demand, and Masked Demand associated with household groundwater use. Sensitivity analysis was conducted to

examine how variations in these parameters, together with the baseline demographic and subscriber variables, influence Available Water and Water Balance over the 100-year simulation horizon.

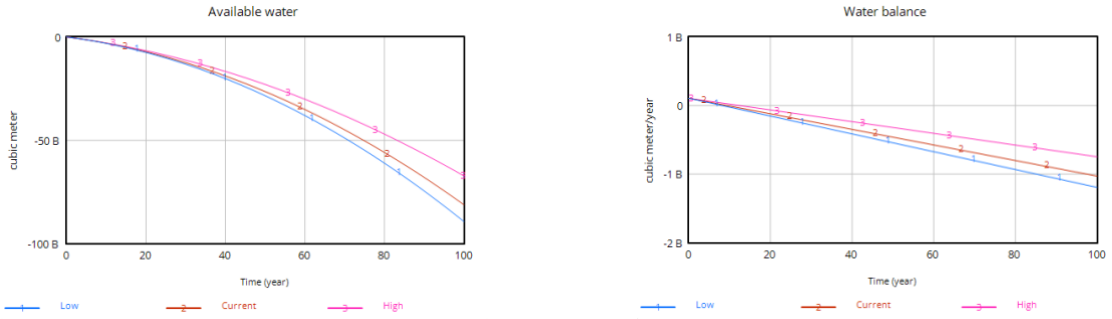
The results show that the tested variables do not influence the system equally. Birth Rate and Death Rate continue to produce relatively small differences among the Low, Current, and High trajectories, indicating limited sensitivity within the tested ranges. Tourism also produces only minor changes in both Available Water and Water Balance. Percentage Well Point Addition, which is used to test the sensitivity of Masked Demand associated with household groundwater use, similarly produces closely aligned trajectories. This limited sensitivity does not imply that household groundwater use is unimportant; rather, it indicates that variations within the tested parameter range have only a small incremental effect on the current model response.

Rainfall, Nonresident Worker Demand, and Percentage Water Price Increment show intermediate or output-specific effects. Higher rainfall increases modeled penetration and partially offsets the decline in Available Water, although its influence on Water Balance is more limited because demand-side pressures continue to operate simultaneously. Nonresident Worker Demand has a relatively limited influence on Available Water but produces a more visible effect on Water Balance, suggesting a more direct influence on annual demand. Similarly, Percentage Water Price Increment produces relatively small differences in Available Water and a modest response in Water Balance. Because the price-response mechanism is based on scenario assumptions, this result should be interpreted as model sensitivity rather than as an empirical estimate of consumer behavior.

Among the tested variables, New Subscriber Rate produces one of the strongest responses. By Year 100, the difference between the Low and High trajectories reaches approximately 33 billion m^3 for Available Water and 446.33 million m^3/year for Water Balance. The stronger separation reflects the cumulative effect of changes in industrial and service subscribers on sectoral water demand over time.

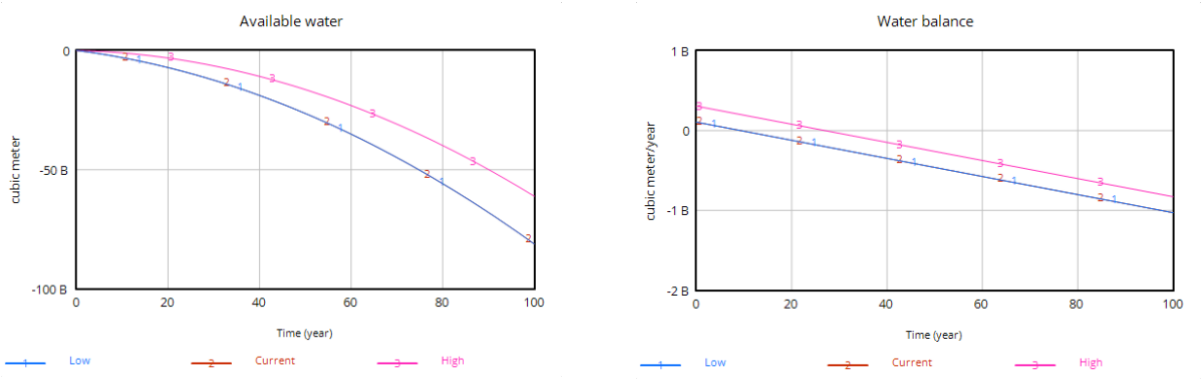
Green Open Space Ratio also generates one of the clearest separations among the Scenario 2 trajectories. In the model, a higher Green Open Space Ratio increases the penetration term and consequently increases inflow to Available Water. This relationship produces visible differences in both Available Water and Water Balance, making Green Open Space Ratio one of the more influential parameters within the expanded model structure.

Overall, Scenario 2 demonstrates that expanding the model boundary changes the sensitivity pattern of the simulated urban water system. Variables that are conceptually relevant do not necessarily become dominant drivers, whereas variables positioned within cumulative stock-and-flow mechanisms may generate substantially stronger responses. These results reinforce the conclusion that parameter influence depends on system structure, interactions, and accumulation over time rather than on input magnitude alone.



(a) **(b)**

Figure 7. Sensitivity of Scenario 2 to New Subscriber Rate: (a) Available Water and (b) Water Balance



(a) (b)

Figure 8. Sensitivity of Scenario 2 to Green Open Space Ratio: (a) Available Water and (b) Water Balance

To summarize the sensitivity analysis while avoiding repetitive graphical outputs, Table 4 presents the relative effects of the tested Scenario 2 parameters on Available Water and Water Balance.

Table 4
Summary of Scenario 2 sensitivity results

Parameter	Model Role	Available Water	Water Balance	Relative Sensitivity	Main Interpretation
Birth Rate	Demographic Demand	Small Separation	Small Separation	Low	Limited sensitivity within tested range
Death Rate	Demographic Demand	Small Separation	Small Separation	Low	Limited sensitivity within tested range
New Subscriber Rate	Industrial & Service Demand	Clear Separation	Clear Separation	High	Cumulative subscriber-driven demand
Rainfall	Penetration/inflow	Visible separation	More Limited Separation	Medium	Higher rainfall increases modeled penetration and inflow
Tourism	Additional Urban Demand	Small Separation	Small Separation	Low	Limited sensitivity within tested range
Non-Resident Worker Demand	Additional Urban Demand	Limited	More Visible	Low-Medium	More direct effect on annual demand
Green Open Space Ratio	Penetration/inflow	Clear Separation	Clear Separation	High	Directly influences modeled penetration
Percentage Water Price Increment	Price-responsive Demand	Limited	Modest Separation	Low-Medium	Exploratory behavioral response
Percentage Well Point Addition	Masked Demand/household groundwater use	Limited	Limited	Low	Expands demand representation but has limited sensitivity within

tested range

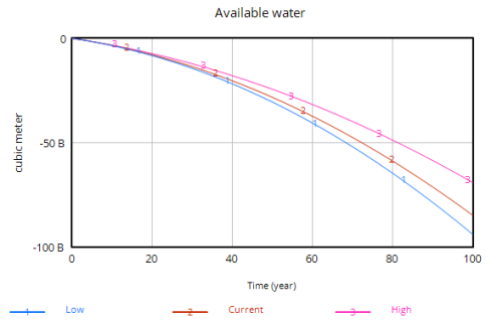
Overall, the summary confirms that New Subscriber Rate and Green Open Space Ratio produce the clearest responses, whereas several additional demand variables show relatively limited sensitivity within the tested ranges.

Comparison Scenario 1 and Scenario 2

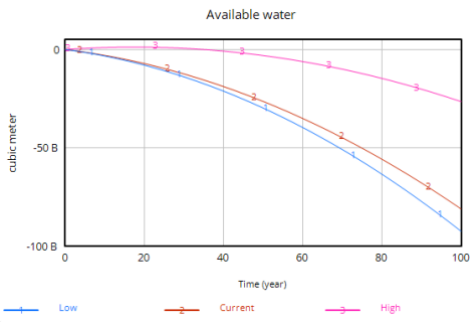
The comparison between Scenario 1 and Scenario 2 illustrates how expanding the model boundary changes the simulated behavior and sensitivity of the urban water system. Scenario 1 represents the baseline model using the main formally identifiable water supply and demand components. Scenario 2 retains the baseline structure while incorporating additional mechanisms relevant to the Bogor case study, including rainfall and Green Open Space Ratio (RTH) in the penetration mechanism, tourism, nonresident worker demand, price-responsive demand, and Masked Demand associated with household groundwater use. Therefore, the comparison is intended to examine the effects of different system representations rather than to determine which scenario produces a better outcome.

Both scenarios show declining trajectories for Available Water and Water Balance over the 100-year simulation horizon. Under the reported simulation conditions, the high-case Water Balance endpoint changes from approximately −1.40 billion m^3/year in Scenario 1 to approximately −1.01 billion m^3/year in Scenario 2. This difference should not be interpreted as an improvement in system performance but rather as a consequence of the expanded model boundary and the additional inflow and demand mechanisms represented in Scenario 2. Because Scenario 2 introduces several mechanisms simultaneously, the difference between the scenarios cannot be attributed to any single added variable. The comparison is therefore interpreted as a structural model contrast. Isolating the marginal contribution of each mechanism requires additional one-at-a-time or factorial scenario experiments and is identified as a priority for subsequent model development.

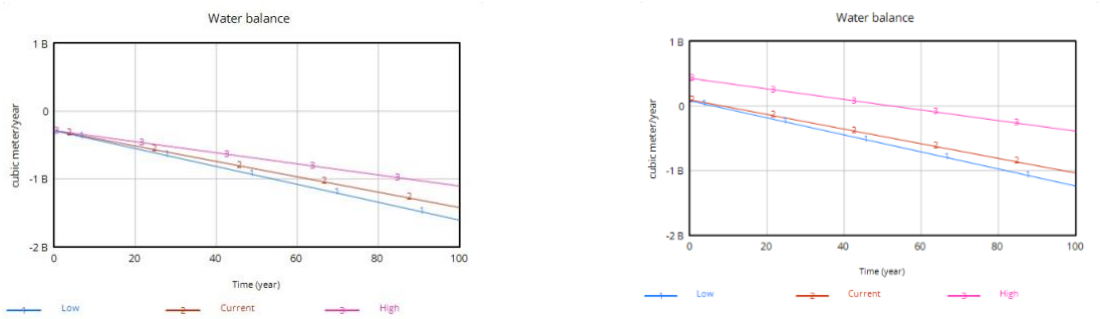
The two scenarios also show different sensitivity patterns. In Scenario 1, Birth Rate and Death Rate produce relatively limited separation among the Low, Current, and High trajectories, whereas New Subscriber Rate generates a clearer response. In Scenario 2, sensitivity to New Subscriber Rate becomes more pronounced, with a Low–High difference at Year 100 of approximately 33 billion m^3 for Available Water and 446.33 million m^3/year for Water Balance. Green Open Space Ratio also produces one of the clearest trajectory separations in Scenario 2 because it directly influences the penetration mechanism. In contrast, several additional demand variables, including Tourism and the parameter associated with household Masked Demand, show relatively limited sensitivity within the tested ranges. Overall, the comparison demonstrates that expanding the model boundary changes not only the simulated trajectories but also the relative sensitivity of the variables represented in the system.



(a)



(b)



(c) (d)

Figure 9. Comparison of Scenario 1 and Scenario 2 over the 100-year simulation horizon: (a) Available Water in Scenario 1 (b) Available Water in Scenario 2; (c) Water Balance in Scenario 1; (d) Water Balance in Scenario 2

The results demonstrate that expanding the model boundary changes both the simulated behavior and the sensitivity pattern of the urban water system. Both scenarios show long-term declines in Available Water and Water Balance, indicating that the modeled growth in water demand continues to place pressure on the urban water system over the simulation horizon. This finding is consistent with the Intergovernmental Panel on Climate Change IPCC (2022), which emphasizes that urban water insecurity results from interacting climatic and nonclimatic drivers, including increasing demand, urbanization, and infrastructure limitations. Similarly, the UNESCO World Water Assessment Programme (2024) highlights the importance of integrated water resource management in addressing the interconnected challenges of water availability, economic development, and environmental sustainability. The difference between Scenario 1 and Scenario 2 should not be interpreted as an improvement in system performance but rather as evidence that incorporating additional inflow and demand mechanisms can materially change how long-term system behavior is represented. This interpretation is also consistent with evidence that urban water risk reflects interacting scarcity, demand, and development pressures rather than a single driver (Ba et al., 2023; Liu et al., 2024).

The sensitivity analysis further shows that the modeled variables do not contribute equally to changes in system behavior. New Subscriber Rate and Green Open Space Ratio generate the clearest responses in Available Water and Water Balance, whereas Birth Rate, Death Rate, Tourism, and Percentage Well Point Addition produce relatively limited changes within the tested parameter ranges. Rainfall, Nonresident Worker Demand, and price-related variables show intermediate or output-specific effects. These differences illustrate that the dynamic influence of a variable depends not only on its numerical magnitude but also on its position within the stock-and-flow structure, its interactions with other variables, and whether its effects accumulate over time. The IPCC (2022) similarly emphasizes the importance of considering interactions among environmental processes, socioeconomic development, and infrastructure when assessing urban water-related risks. Therefore, the sensitivity patterns identified in this study should be understood as outcomes of the specified model structure and parameter assumptions rather than as universal measures of variable importance. The prominence of Green Open Space Ratio is directionally consistent with evidence on green infrastructure and urban hydrological function Huang (2024), while the demand heterogeneity emphasized by Savelli et al. (2023) upports closer scrutiny of subscriber-driven consumption.

This sensitivity mapping is useful not merely for identifying which variables generate the largest numerical responses but also for indicating where further monitoring, data improvement, and management analysis may be most valuable. Variables showing stronger responses may warrant closer examination, whereas variables showing limited sensitivity may require improved empirical data or alternative parameter ranges before their roles can be interpreted further. UN-Water (2023) emphasizes that improved data availability, institutional capacity, innovation, and coordinated governance are essential for strengthening sustainable water resource management. Accordingly, the proposed sensitivity-based assessment provides a preliminary analytical basis for identifying priority monitoring needs and guiding subsequent model refinement.

The proposed framework extends the System Dynamics structure developed by Shahsavari-Pour et al. (2023) for Rafsanjan City, Iran. The Rafsanjan model was developed for a semiarid, groundwater-constrained environment in which agricultural demand represents a major component of water use. The present study retains the fundamental stock-and-flow logic of Available Water, water inflow, and sectoral demand while allowing the model boundary to be adapted to different urban characteristics. For the Bogor case study, the extension includes Green Open Space Ratio in the penetration mechanism, tourism, nonresident worker demand, price-responsive demand, and Masked Demand associated with household groundwater use. This contextual adaptation is consistent with the integrated perspective presented by the IPCC (2022), which recognizes that water resource risks and adaptation requirements vary according to local hydrological, socioeconomic, and urban development conditions. The contribution of the present study is therefore not to replace the reference model but to demonstrate how an existing System Dynamics structure can be contextually extended while preserving its underlying stock-and-flow relationships.

The approach is also consistent with previous applications of System Dynamics in urban water resource management. Rezagama et al. (2025) incorporated water demand, service coverage, infrastructure development, and policy interventions into a System Dynamics model for Semarang City. More broadly, the UNESCO World Water Assessment Programme (2024) emphasizes that sustainable water resource planning requires attention to interactions among water supply, economic activities, environmental conditions, and institutional governance. The IPCC (2022) likewise identifies the importance of integrated approaches that consider both supply-side and demand-side adaptation strategies. Compared with these perspectives, the present framework places greater emphasis on examining how alternative model boundaries influence simulated system behavior and parameter sensitivity. The framework therefore allows additional context-specific variables to be incorporated without requiring the fundamental Available Water–Water Supply–Water Demand–Water Balance structure to be redesigned for each case study.

An additional insight concerns the representation of nonformal household demand. Masked Demand associated with household groundwater use broadens the demand boundary beyond consumption captured through formal utility records. However, the sensitivity analysis shows that Percentage Well Point Addition produces only limited changes in Available Water and Water Balance within the tested range. This distinction is important because improving the completeness of a model does not necessarily mean that every newly introduced variable will become a dominant driver of system behavior.

Jasechko et al. (2024) documented widespread groundwater-level declines across aquifer systems globally, highlighting the importance of groundwater monitoring and sustainable abstraction management. Their findings reinforce the need to consider groundwater use even when its modeled sensitivity appears relatively limited. In the Bogor case study, Masked Demand contributes to a broader representation of urban demand, whereas New Subscriber Rate and Green Open Space Ratio generate substantially stronger sensitivity responses. Nevertheless, the present model does not directly evaluate groundwater-level changes or aquifer depletion.

The primary benefit of the proposed framework is therefore its role as an exploratory decision-support tool rather than a direct policy-prescription model. It allows decision-makers to compare alternative representations of an urban water system, identify variables that generate meaningful changes in long-term system behavior, and determine which factors may require closer monitoring, improved data collection, or further analysis before specific interventions are formulated.

This orientation is consistent with UN-Water (2023), which emphasizes evidence-informed decision-making and stronger institutional coordination as essential components of effective water governance. For the Bogor case study, the relatively strong sensitivity of New Subscriber Rate and Green Open Space Ratio suggests that these variables deserve greater analytical attention than variables showing only limited responses under the tested conditions. The framework is not intended to prescribe a specific policy based on the current simulation

results but rather to support the identification and prioritization of variables relevant to subsequent decision-making.

Practical & Policy Implication

The simulation results provide practical implications across short-, medium-, and long-term decision horizons. In the short term, the framework can guide monitoring priorities and data improvement. Variables with stronger sensitivity, particularly New Subscriber Rate and Green Open Space Ratio, should receive greater attention, whereas variables with lower sensitivity, such as Tourism and Percentage Well Point Addition, require stronger local evidence before firm conclusions can be drawn. For local government and water service institutions, this implies integrating demographic, land-use, utility-consumption, and groundwater-use data more systematically. UN-Water (2023) emphasizes that reliable data and strengthened monitoring are fundamental to evaluating water management performance and improving sustainable water governance. Community and business participation may further improve information on actual water-use patterns, including self-supplied groundwater.

The framework also enables decision-makers to consider interactions among environmental, demographic, and infrastructure processes rather than evaluating them independently. The UNESCO World Water Assessment Programme (2024) highlights the importance of institutional cooperation and cross-sectoral information integration in sustainable water management. Accordingly, exploratory modeling can help organize complex information and identify evidence gaps that should be addressed before specific interventions are implemented.

In the medium term, improved empirical data can support model recalibration and validation and enable combined scenario analyses involving subscriber growth, land-cover change, rainfall, formal supply, and nonformal demand. Such analyses can help government agencies and water service providers examine interactions and trade-offs among alternative management options. The IPCC (2022) notes that effective urban water adaptation commonly requires combinations of infrastructure development, demand management, ecosystem-based measures, and institutional coordination. Therefore, future scenarios should evaluate interactions among demand, land use, and hydrological change rather than examining isolated parameters. Additional hydrological observations are also needed to assess whether the simplified penetration mechanism adequately represents local infiltration.

In the long term, following sufficient calibration and validation, the model may support periodic urban water planning by comparing alternative development and management conditions. Its purpose is not to prescribe a single policy but to strengthen anticipatory and evidence-based decision-making. UN-Water (2023) stresses coordinated action, institutional capacity, and data use in sustainable water resource planning, while the UNESCO World Water Assessment Programme (2024) links integrated water governance with economic resilience, social well-being, and environmental sustainability.

Although demonstrated in Bogor City, the model is designed to be adaptable to other urban areas. The core relationships among Available Water, Water Supply, Water Demand, and Water Balance may be retained, while parameters are adjusted to reflect local hydrological, demographic, land-use, economic, and demand conditions. The IPCC (2022) emphasizes that urban water risks differ across geographical and socioeconomic contexts, supporting the need for locally appropriate adaptation. However, transferability should be verified through additional empirical applications.

Several limitations remain. The model is aggregated and does not represent detailed hydrological, aquifer, or distribution-network processes. Some behavioral and nonformal demand variables rely on literature-based proxies or scenario assumptions. Moreover, the 100-year simulation is intended to examine long-term behavior and sensitivity rather than provide a calibrated forecast. Jasechko et al. (2024) demonstrate the importance of extensive groundwater observations, while the IPCC (2022) highlights uncertainties in long-term water projections. Therefore, the numerical outputs should not yet be treated as direct policy prescriptions. Further calibration, validation, dimensional consistency assessment, and model refinement are required

before predictive or policy-prescriptive applications can be considered.

CONCLUSION

The System Dynamics simulations indicate declining trends in Available Water and Water Balance under both scenarios, with New Subscriber Rate and Green Open Space Ratio identified as the most influential parameters. Differences between scenarios reflect model structures rather than verified improvements or individual mechanisms. Negative Water Balance values indicate modeled deficits, while negative Available Water values highlight limitations in the unconstrained stock formulation requiring further calibration. The framework serves as a preliminary decision-support tool for exploring interactions, identifying sensitive parameters, and prioritizing data collection rather than providing validated forecasts of Bogor's future water conditions. Future research should incorporate observed water production, distribution, service coverage, groundwater, consumption, and shortage data, test additional mechanisms incrementally, and conduct independent validation before applying the model to operational policy decisions.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the institutions and data providers whose publicly available information supported the development of this study. The authors also acknowledge the contributions of individuals who provided valuable insights and expert input during the development and refinement of the System Dynamics model. The authors appreciate all support that contributed to the completion of this research.

AUTHOR CONTRIBUTION STATEMENT

Bella Febiolita: Conceptualization, investigation, data collection, methodology, system dynamics modeling, simulation, formal analysis, and writing–original draft. Leo Susy Villianny: Conceptualization, supervision, methodology, validation, interpretation of results, and writing–review and editing. Monica Audrey: Literature review, data curation, model development, sensitivity analysis, visualization, and writing–review and editing. Rida Zuraida: Supervision, validation, critical analysis, interpretation of findings, and writing–review and editing. All authors contributed to the research development, critically reviewed the manuscript, and approved the final version for publication.

REFERENCES

Apolinário, A., Oliveira Silva, W., Marques, P. C., & Reis, J. (2026). Multidimensional assessment of urban water security under post-disaster and environmental stress conditions. In *Discover Sustainability* (Vol. 7, Number 1). https://doi.org/10.1007/s43621-026-04183-9

Arbi, Y., Ramadhianty, R., Rahayu, S., & Putri, W. (2025). System dynamics modelling of integrated urban clean water management: A case study in Padang City, Indonesia. *Journal of Engineering Researcher and Lecturer*, *4*(2), 66–76. https://doi.org/10.58712/jerel.v4i2.184

Asadollahi, A., Sohrabifar, A., Ghimire, A. B., Poudel, B., & Shin, S. (2024). The Impact of Climate Change and Urbanization on Groundwater Levels: A System Dynamics Model Analysis. *Environmental Protection Research*. https://doi.org/10.37256/epr.4120243531

Ba, W., Wang, D., Gong, B., Dai, Y., Yang, Z., & Liu, Z. (2023). Urban water scarcity in China: A systematic review of research advances and future directions. *Applied Geography*, *159*, 103069. https://doi.org/10.1016/j.apgeog.2023.103069

Badan Pusat Statistik Kota Bogor. (2026). Kota Bogor dalam angka 2026. Publikasi resmi BPS 2026

Bano, R., Khiadani, M., & Nyam, Y. S. (2022). System Archetypes Underlying Formal-Informal Urban Water Supply Dynamics. *Water Resources Management*, *36*(13), 4995–5010. https://doi.org/10.1007/s11269-022-03288-w

Chen, X., Xu, Q., & Cai, J. (2023). Research on the urban water resources carrying capacity by using system dynamics simulation. *Hydrology Research*, *54*(3), 418–434. https://doi.org/10.2166/nh.2023.101

Gohari, A., Savari, P., Eslamian, S., Etemadi, N., & Keilmann-Gondhalekar, D. (2022). Developing a system dynamic plus framework for water-land-society nexus modeling within urban socio-hydrologic systems. *Technological Forecasting and Social Change*, *185*. https://doi.org/10.1016/j.techfore.2022.122092

Huang, L. (2024). A systematic review of planning principles for green infrastructure in response to urban stormwater management. *Landscape Research*, *49*(2), 287–300. https://doi.org/10.1080/01426397.2023.2272784

Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Impacts, adaptation and vulnerability. Cambridge University Press.

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., Fallatah, O., & Kirchner, J. W. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. *Nature*, *625*(7996), 715–721. https://doi.org/10.1038/s41586-023-06879-8

Krueger, E. H., McPhearson, T., & Levin, S. A. (2022). Integrated assessment of urban water supply security and resilience: Towards a streamlined approach. *Environmental Research Letters*, *17*(7). https://doi.org/10.1088/1748-9326/ac78f4

Linggabinangkit, C., & Hermana, J. (2026). Dynamic System Modeling of $PM_{2.5}$ Emissions and Concentrations in DKI Jakarta Based on BAU, Moderate, and Aggressive Scenarios. *Equivalent: Jurnal Ilmiah Sosial Teknik*, *8*(1), 80–93. https://doi.org/10.59261/jequi.v8i1.259

Liu, Z., Ying, J., He, C., Guan, D., Pan, X., Dai, Y., Gong, B., He, K., Lv, C., Wang, X., Lin, J., Liu, Y., & Bryan, B. A. (2024). Scarcity and quality risks for future global urban water supply. *Landscape Ecology*, *39*(2), 10. https://doi.org/10.1007/s10980-024-01832-0

Raza, A., Bilal, M., Aqib, S., & Raza, A. (2026). A System Dynamics Simulation Model for Sustainable Water Resources Management in Pakistan. *Sustainable Futures*, *11*. https://doi.org/10.1016/j.sftr.2026.101959

Rezagama, A., Hartono, D. M., Soesilo, T. E. B., & Hasibuan, H. S. (2025). Developing A System Dynamics Model for Water Resource Management in Urban Coastal Areas: A Case Study of Semarang City, Indonesia. *International Journal of Sustainable Development and Planning*, *20*(5), 2029–2043. https://doi.org/10.18280/ijsdp.200520

Savelli, E., Mazzoleni, M., Di Baldassarre, G., Cloke, H., & Rusca, M. (2023). Urban water crises driven by elites' unsustainable consumption. *Nature Sustainability*, *6*(8), 929–940. https://doi.org/10.1038/s41893-023-01100-0

Shahsavari-Pour, N., Bahador, S., Heydari, A., & Fekih, A. (2023). Water Shortage Simulation Using a System Dynamics Approach: A Case Study of the Rafsanjan City. *Sustainability*, *15*(7), 6225. https://doi.org/10.3390/su15076225

Siddik, M. S., Tulip, S. S., Rahman, A., Islam, Md. N., Haghighi, A. T., & Mustafa, S. M. T. (2022). The impact of land use and land cover change on groundwater recharge in northwestern Bangladesh. *Journal of Environmental Management*, *315*, 115130. https://doi.org/10.1016/j.jenvman.2022.115130

Sun, Y., Wang, Y., Zhang, W., & Ye, S. (2024). Regional water resources carrying capacity in China based on analytic hierarchy process and system dynamics model: a case study of Golmud City. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1450747

UN-Water. (2023). Blueprint for acceleration: Sustainable Development Goal 6 synthesis report on water and sanitation 2023. United Nations.

UNESCO World Water Assessment Programme. (2024). The United Nations world water development report 2024: Water for prosperity and peace. UNESCO.

Vidal-Lamolla, P., Molinos-Senante, M., & Poch, M. (2024). Understanding the Residential Water Demand Response to Price Changes: Measuring Price Elasticity with Social Simulations. *Water*, *16*(17), 2501. https://doi.org/10.3390/w16172501

Zheng, G., Han, J.-C., Li, P., Li, B., Wu, X., Huang, Y., & Ahmad, M. (2024). A system dynamics simulation-based strategic analysis of integrated water resources utilization and management in Shenzhen city. *Environmental Science and Pollution Research*, *31*(15), 23091–23105. https://doi.org/10.1007/s11356-024-32599-1