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Research Article

A System Dynamics Model to Optimize Purified Water Supply from the Dam for Residences Use in Rural Communities

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ABSTRACT

The effective management of water supply is important to ensure sustainable health and wellbeing of residents in communities. This paper presents a system dynamics model to optimize the delivery of clean water from dams to communities more especially in rural areas. The developed model includes elements such as water inflow, purification processes, storage capacities, distribution channels as well as consumption patterns. The dynamics of water supply is influenced by various factors such as seasonal fluctuations or variations, maintenance schedules, as well as population growth. The developed model employs feedback loops to simulate the interactions between these components and identify potential inefficiencies in the system. This study aims to suggest and develop strategies to enhance the reliability and efficiency of water supply to the targeted areas. Different scenarios are analysed to evaluate the impact of management and administrative practices, such as adjusting purification capacity, optimizing storage levels, as well as improving distribution methods. The objective of the study is to provide insights for policy makers and stakeholders to ensure sustainable and equitable water supply for rural communities. The results of the study demonstrate that system dynamics modelling can effectively identify key areas of improvement in the water supply chain and better service delivery. This approach presents a comprehensive framework for addressing the complex challenges associated with rural water supply systems and support informed decision making in water resource management.

Keywords: Water supply management, System dynamics modelling, Rural communities, Sustainable water delivery, Water resource optimization

1. INTRODUCTION

Effective management of water resources is crucial for ensuring the health, wellbeing, and sustainability of communities, particularly in rural areas where infrastructure and resources may be limited[1]. This paper introduces a system dynamics model designed to optimize the supply of purified water from dams to rural communities. The model incorporates key components such as water inflow, purification processes, storage capacities, distribution networks, and consumption patterns, while accounting for factors like seasonal variations, maintenance schedules, and population growth. By utilizing feedback loops, the model helps to simulate the interactions within the water supply system, identifying inefficiencies and potential improvements. The aim of this study is to explore strategies that can enhance the reliability and efficiency of rural water supply, offering valuable insights for policymakers and stakeholders focused on sustainable water resource management. Through scenario analysis and evaluation of management practices, the study provides a comprehensive framework for addressing the complex challenges faced by rural water supply systems.

Fig. 1 The study area of Damani map by google map.

2. LITERATURE REVIEW

Effective water supply management is critical for ensuring the health and wellbeing of communities, particularly in rural areas where access to clean and reliable water is often limited. Previous studies have highlighted the importance of developing comprehensive water management strategies that account for various factors influencing water availability, distribution, and consumption patterns [2]. System dynamics (SD) modelling has emerged as a powerful tool for addressing these complexities, providing a holistic framework for simulating the interrelated components of water supply systems.

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A. System Dynamics in Water Resource Management

System dynamics modelling has been extensively used in water resource management to understand the feedback driven nature of complex systems. Forrester's (1961) introduction of SD as a methodology for simulating complex systems has paved the way for its application in numerous fields, including water management[3]. SD models enable the integration of various factors such as water inflows, storage, purification processes, and distribution networks into a single framework, facilitating the identification of inefficiencies and optimization of system performance. In this context, [4] emphasized that SD can provide valuable insights into long-term behaviour and policy impacts within dynamic systems, such as those seen in water resource management.

Several studies have applied system dynamics to optimize water resource systems. For example, [5] used SD modelling to evaluate water management strategies in urban settings, demonstrating how feedback loops between population growth, water demand, and supply can lead to unsustainable outcomes if not properly managed. Similarly, [6] applied system dynamics to integrated water resource management, showing how the approach can assist policymakers in balancing environmental, economic, and social considerations in water distribution. These studies underscore the importance of SD in creating adaptive strategies that can respond to changing water supply and demand dynamics.

B. Water Supply in Rural Communities

The unique challenges of providing clean and reliable water to rural communities have also been widely studied. Rural areas often face inadequate infrastructure, limited access to water sources, and vulnerability to seasonal variations in water availability [7]. In such contexts, optimization of water supply systems becomes crucial for ensuring sustainable development and health outcomes. Studies by [8] and [9] have shown that rural water supply systems are prone to inefficiencies due to poorly maintained infrastructure, lack of financial investment, and insufficient policy support. These inefficiencies are exacerbated by factors such as population growth and climate change, which increase demand and put pressure on existing water resources.

The role of dams in rural water supply has also been a subject of focus in the literature. According to [10], dams play a vital role in storing water for agricultural, industrial, and domestic use, particularly in arid and semiarid regions. However, the operation of these systems is often hampered by seasonal fluctuations in water availability, inefficient distribution networks, and delays in maintenance. Research by [11] explored optimization techniques for dam operations, highlighting the importance of maintaining an optimal balance between water storage, supply, and consumption.

C. Factors Affecting Water Supply Dynamics

Water supply systems are highly dynamic, influenced by a range of environmental, social, and technological factors. Seasonal variations in rainfall, population growth, and maintenance schedules are some of the key factors affecting the efficiency and reliability of water systems. Studies by [12] and [13] have shown that variability in water inflows, caused by changing climatic patterns, can lead to significant water shortages in both urban and rural settings. The ability of a system to adapt to these changes, through optimized storage capacities and improved distribution networks, is crucial for ensuring a stable supply.

Maintenance of water infrastructure is another critical factor. Inadequate maintenance schedules lead to deterioration of pipelines, storage tanks, and purification systems, which can result in leakage, contamination, and reduced supply efficiency. [14] emphasized that improving maintenance practices and investing in new infrastructure can significantly enhance the performance of water systems, especially in underserved rural areas. Additionally, water purification capacity is a major component of ensuring that the water reaching households is safe for consumption. Research by [15] suggests that increased investment in purification technologies can have a significant impact on reducing waterborne diseases in rural areas.

D. Application of System Dynamics in Optimizing Water Supply Systems

The application of system dynamics in optimizing water supply systems, particularly in rural communities, provides an integrated approach to managing the complexities associated with water inflows, purification, storage, and distribution. By incorporating feedback loops that simulate interactions between different system components, SD models can help policymakers and water managers identify bottlenecks and inefficiencies in water supply chains. A study by [16] demonstrated how system dynamics modelling can be used to simulate different scenarios for improving water distribution in rural areas, providing insights into the trade-offs between water supply reliability and cost. Moreover, SD models can be used to test the impact of various management and administrative practices, such as adjusting purification capacity or optimizing storage levels, on the overall performance of the water supply system. This approach aligns with the findings of [17], who applied SD modelling to optimize urban water distribution systems and found that scenario analysis was critical for assessing the impact of policy changes on water supply resilience.

3. MATERIALS AND METHODS

A. Study Area Location

On the Mbwedi River, close to Thohoyandou the former Venda capital, Damani Dam is the earth fill in Limpopo, South Africa. It was established in 1991. It is primarily intended for use in rural communities, Municipal usage, and local industries. It has been determined to have a considerable risk of harm. The reservoir has total capacity of 11 000 000 m^3 and surface area of 130 ha with the height of 35 m. it is operated by the department of water affairs and forestry. It is characterized by a desert climate with scant annual precipitation averaging 3.5 in/year and notably high evaporation rates reaching 86.6 in/year. Rain formation processes at Thohoyandou occurred under isotopic equilibrium condition with a minor evaporation effect during the precipitation, as reflected by the slope of the local meteoric water line of $\delta D = 7.56\delta\ 18_O + 10.64$ [18].

Fig. 1 Thohoyandou weather by month year 2024

Clean water for rural areas like Damani, Khubvi, Makonde, and other villages in the Vhembe district is provided by the Damani Dam. Additionally, it fosters regional agricultural sectors, such as Tshivhase Agridam, thereby advancing economic growth. The dam improves agricultural production and food security by guaranteeing consistent water for irrigation, which benefits local livelihoods. Furthermore, it helps maintain local ecosystems and mitigate the consequences of drought, which contributes to sustainable water management. By lowering the risk of disease and supplying clean water, the dam enhances public health. The dam's main purpose is to supply water, but it also has the potential to produce hydropower in the future, which would improve regional sustainability.

Fig. 2 Damani Dam Location coordinates (22°50′7″S 30°31′22″E)

B. Water purification process and systems

The below figure illustrates the three water processing levels in the plant in use of poly chlorine for purification purposes.

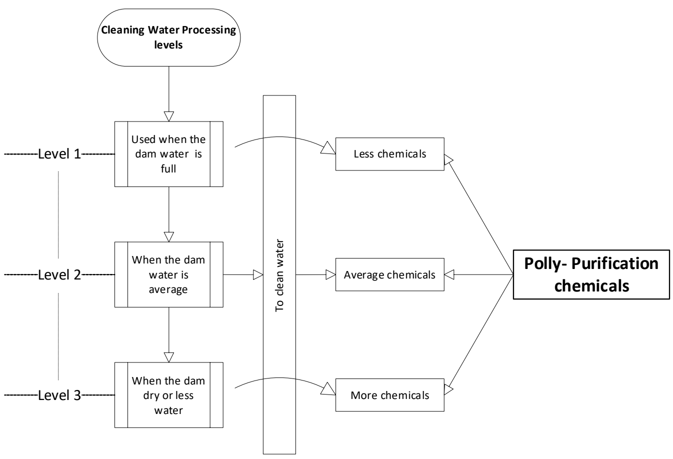


Fig. 3 The three water processing levels

There are two plants involved in the purification process, the raw water plant, and the mixing chamber plant. The raw water plant receives water from various sources, including the dam, groundwater, surface water, and precipitation. This raw water is then transferred to the second plant, known as the mixing chamber, where poly chlorine, a chemical used in the initial purification stage, is applied to clean the water. The purification process involves three levels at which the chemical is used, as shown in the figure above, when the dam is full it requires less chemical and when is dry it requires more chemicals.

The below figure illustrates the 8step purification process to supply the rural communities.

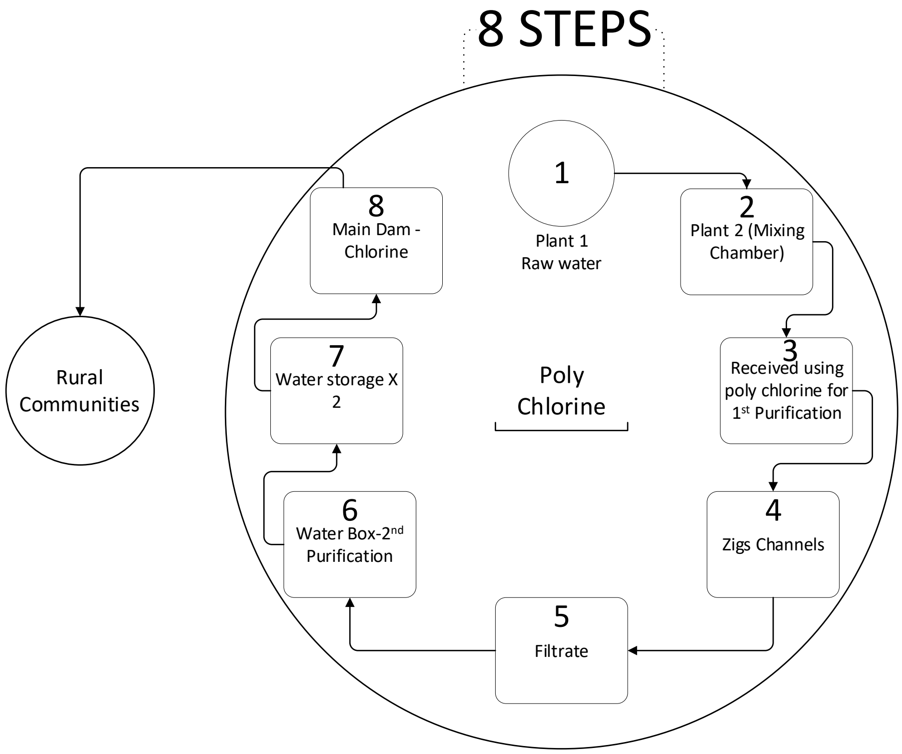


Fig. 4 The 8 steps to water supply to the rural communities

The water supplied to the communities undergoes an 8step purification process, as illustrated in the figure above. In Plant 1, water from various sources, as mentioned above, is received, and transferred through pipes to Plant 2. At Plant 2, the water is purified using poly chlorine. After this, the water moves to the second stage of purification, entering the water box where it passes through zigzag channels and filtration systems before being fully processed in the water box. The next step is water storage, where the water is held in two separate storage facilities. Following this, the water is released and flows into the main dam through gravitational flow, with chlorine applied during this final purification stage. The purified water is then stored in a community dam, from which it is distributed to various subcommunity dams using engines. At this stage, the water is clean and ready to be supplied to the rural communities.

C. System dynamics modelling approach.

This study develops a framework to evaluate the effects of different water supply system and policies on the sustainability of water resources over the long term by integrating the SDM approach with a novel scenario design methodology. The research includes a thorough mapping that includes subsystems of regional water supply and demand. A causal loop diagram (CLD) and thorough stock and flow diagram (SFD) development are used to accomplish this. The rate of population increase is determined by economic development in addition to a sustainable water supply for the populace as emphasised by [19].

The system dynamics model, as was previously discussed, can represent the water supply and groundwater system concurrently. A conceptual model of the groundwater flow in the region was first built [20].

The figure below illustrates the study framework as a map to developing the system dynamics model for this study.

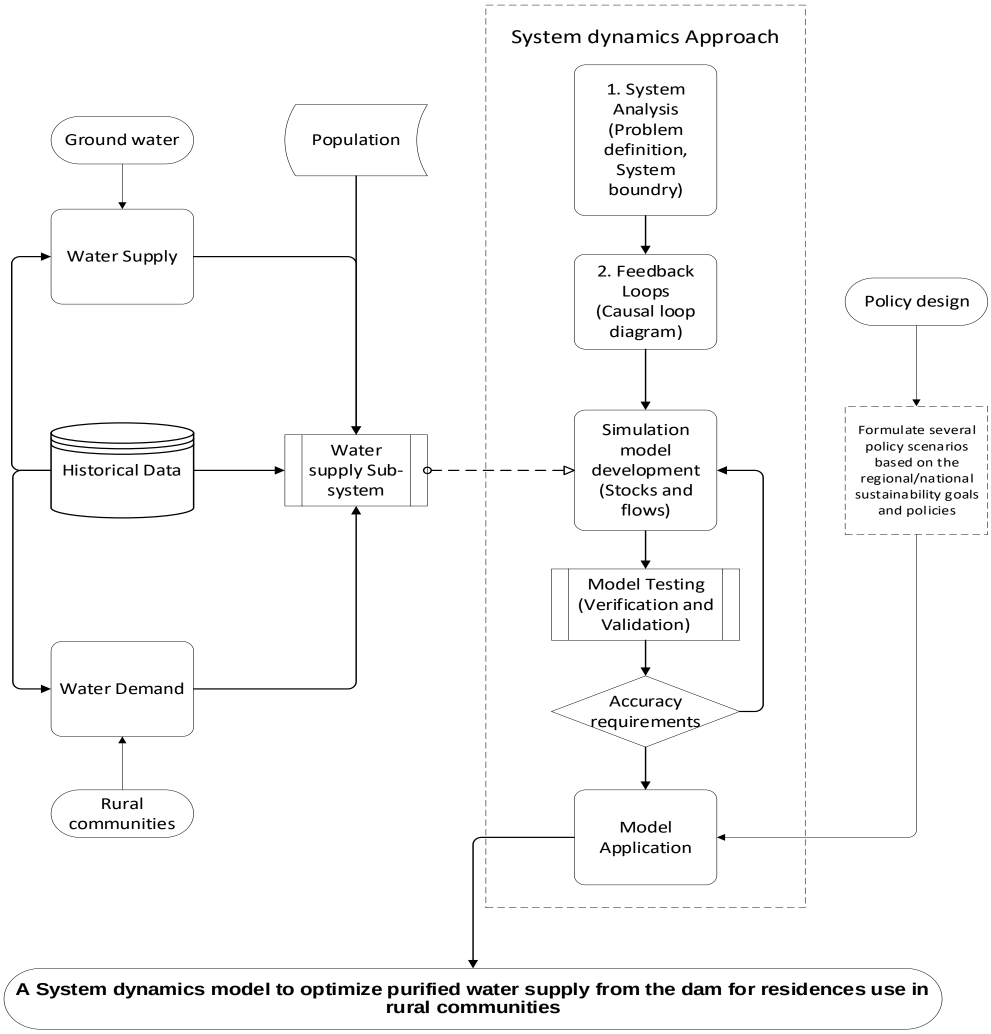


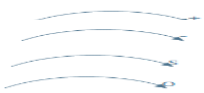
Fig. 5 Study Framework

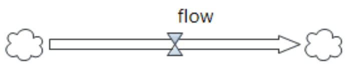
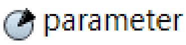
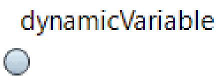
D. Causal loop development

The causal loop diagram (CLD) for the system dynamics model of water supply from the dam to consumption involves identifying key variables and their interactions of the dynamic variables such as water inflow from dam, water purification capacity, water storage levels, water demand/consumption, population growth, seasonal fluctuations, maintenance schedules, and distribution efficiency, demonstrating the feedback loops that drive system behaviour.

Table 1 below Refers to an element within a system dynamics model that represents a factor or component that influences the behaviour of the system. These variables are stocks, flows, dynamic variables, or parameters.

TABLE I BASIC COMPONENTS OF SYSTEM DYNAMICS MODELS

Symbol	Name	Definition
	Link	A connection between two variables that indicates a relationship or interaction. In system dynamics, links can represent how one variable affects another, either positively or negatively.

	Flow rate	The rate at which a quantity enters or leaves a stock variable. It determines the speed at which a stock increases or decreases over time, influencing the accumulation or depletion of resources.
	Parameter	A fixed value in a system dynamics model that influences the behaviour of variables but does not change during the simulation. It provides structure to the model by defining key constants like capacity, efficiency, or time delays.
	Stock	A variable that represents an accumulation of resources, materials, or quantities that build up or deplete over time. Stocks are affected by inflows and outflows and represent the current state of a system.
	Dynamic variable	A variable that changes over time based on the interactions and feedbacks within the system. These variables are influenced by other variables or parameters and directly impact the behaviour of the model.
	Reinforcement loop	A positive feedback loop where the interactions between variables reinforce or amplify changes, leading to exponential growth or decline. It creates a cycle where an initial change leads to further changes in the same direction.
	Balancing loop	A negative feedback loop that seeks to bring the system to equilibrium or stability. In this loop, changes in one variable lead to adjustments in the opposite direction, counteracting the initial effect to maintain balance within the system.

In this study, system dynamics model is developed for water supply systems, variables are categorized into stock, flow, dynamic, and parameters, which together form a feedback loop impacting the overall system. Stock variables, such as water in the dam, purified water in storage, and water delivered to households, represent quantities that accumulate or deplete over time. Flow variables indicate the rates of change, like water inflow to the dam, purification rates, and water consumption by households. Dynamic variables, such as population growth, water demand, and seasonal variations, influence these rates and interact with the system. Parameters, including purification capacity, storage limits, and water loss rates, define the system's structure and efficiency. This interaction between variables forms feedback loops, which either reinforce or balance the system's dynamics, allowing for the modelling of water supply management. These loops help optimize the distribution of water in rural areas by identifying inefficiencies, anticipating demand fluctuations, and guiding decision making for sustainable resource management.

The below figure illustrates the causal loop diagram of this study.

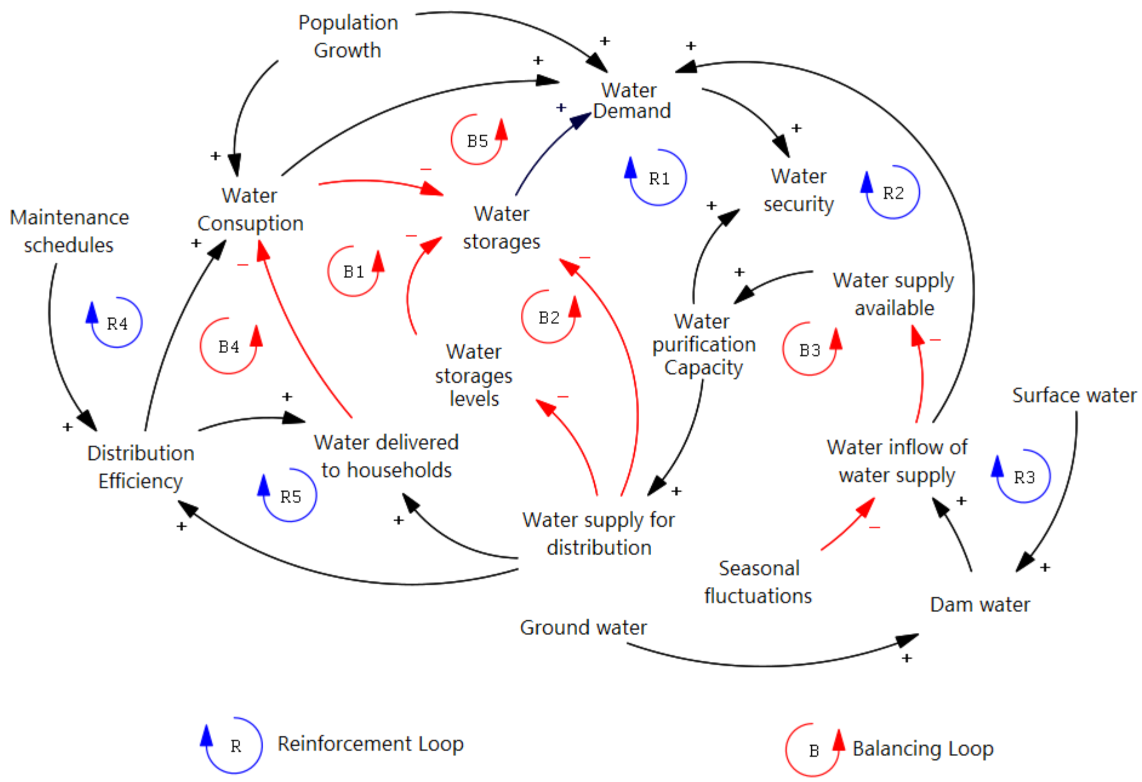


Fig. 6 Causal loop diagram of the rural water supply network

The dynamic variables are discussed and addressed properly in the tables below.

TABLE II

THE WATER SUPPLIES CAUSAL LOOP'S FEEDBACK LOOPS.

Feedback Loops

Balancing Loop (B1): Water Storage vs. Consumption	Water Storage Levels (+) → Water Supply for Consumption (+) → Water Consumption (+) → Water Storage Levels ()	**Reinforcing Loop (R1): Population Growth and Water Demand**	Population Growth (+) → Water Demand (+) → Water Consumption (+) → Need for Increased Supply (+)
	As more water is stored, more water can be supplied for consumption, but this eventually reduces the storage levels, requiring replenishment.		As population grows, it drives up water demand and consumption, which increases the pressure on supply systems.
Balancing Loop (B2): Seasonal Fluctuations and Inflow	Seasonal Fluctuations (+) → Water Inflow from Dam (+/) → Water Available for Supply (+)	**Reinforcing Loop (R2): Maintenance and Distribution**	Maintenance Schedules (+) → Distribution Efficiency (+) → Water Delivered to Households (+) → Water Consumption (+)
	Seasonal variations affect inflow, with wet seasons boosting water availability and dry seasons reducing it.		Regular maintenance improves distribution efficiency, leading to better water delivery and higher consumption rates.

TABLE III

THE DESCRIPTION BUILDING OF WATER SUPPLY CAUSAL LOOP DIAGRAM.

Water Inflow to Water Supply	**Water Purification Process**	**Water Storage Levels**	**Distribution Efficiency**	**Water Demand and Consumption**
Water Inflow from Dam (+) → Water Supply Available (+)	Water Supply Available (+) → Water Purification Capacity (+)	Water Supply for Distribution (+) → Water Storage Levels (+)	Water Available for Distribution (+) → Water Delivered to Households (+)	Water Consumption (+) → Water Demand (+)
A higher water inflow from the dam increases the overall water available for supply.	More available water increases the need for greater purification capacity.	A higher volume of purified water leads to more water stored in tanks or reservoirs.	More water in storage allows for higher volumes delivered to households.	Increased consumption drives higher demand for water, requiring further adjustment in supply.
	Water Purification Capacity (+) → Water Supply for Distribution (+)	Water Storage Levels () → Water Shortages ()	Distribution Efficiency (+) → Water Delivered to Households (+)	Population Growth (+) → Water Demand (+)
	Increased purification capacity leads to more clean water available for distribution.	Increased storage reduces the likelihood of shortages during high demand or low inflow periods.	Improved distribution networks increase the efficiency and reliability of water delivery.	An increasing population heightens demand for water in rural communities.
		Water Storage Levels (+) → Water Available for Distribution (+)	Water Delivered to Households (+) → Water Consumption (+)	
		More stored water ensures a continuous supply for distribution to consumers.		

Water supplies for a project can come from surface or ground sources, expansion of current systems, or purchasing from other systems. Choosing a supply source depends on factors like water availability, quality, cost, and the lifespan of the project. Various supply options, including purchasing water and expanding independent sources, should be considered, and evaluated economically and physically. Combining surface and ground water may sometimes be beneficial.

The below illustrates the standard water supply system.

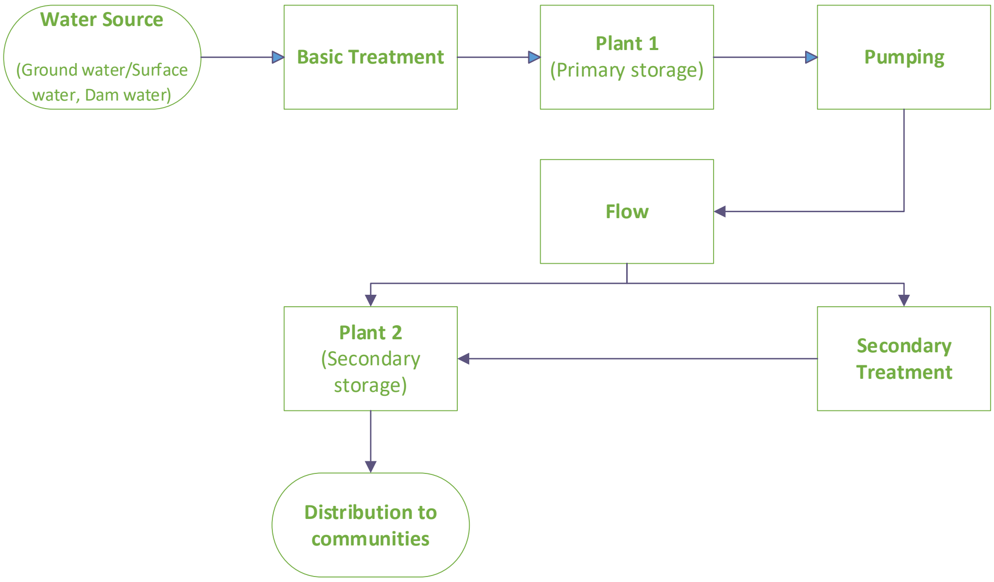


Fig. 7 Standard water supply system

Most water supply projects focus on expanding or upgrading existing systems rather than creating new ones. Existing sources must be assessed for capacity, reliability, and the feasibility of meeting future needs, especially during droughts. Any increase in withdrawal from an existing source should consider impacts on water quality.

The figure below illustrates the water supply network.

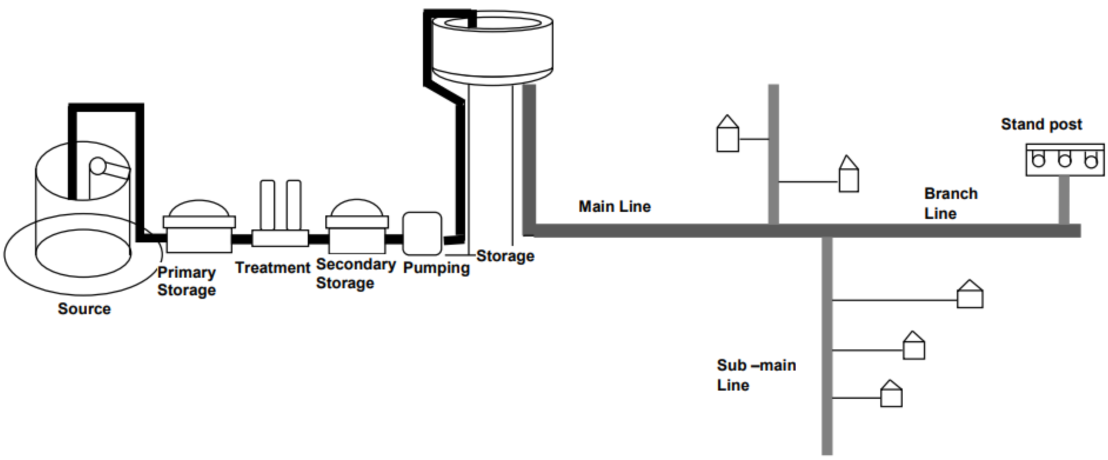


Fig. 8 Water supply network [21]

If located near a municipal or private water system, the feasibility of using this system should be investigated, assessing its capacity to meet both current and future demands at reasonable costs. This review includes supply quality, drought resilience, pumping, treatment, storage, and distribution capacities. Long supply lines require economic studies to determine optimal pipeline size, balancing construction, and operational costs. Additionally, the public water supply system's management and maintenance adequacy should be reviewed to ensure reliable service.

E. SD model development

The system dynamics model in this study was developed using AnyLogic software. The model consists of two key segments namely water supply and population.

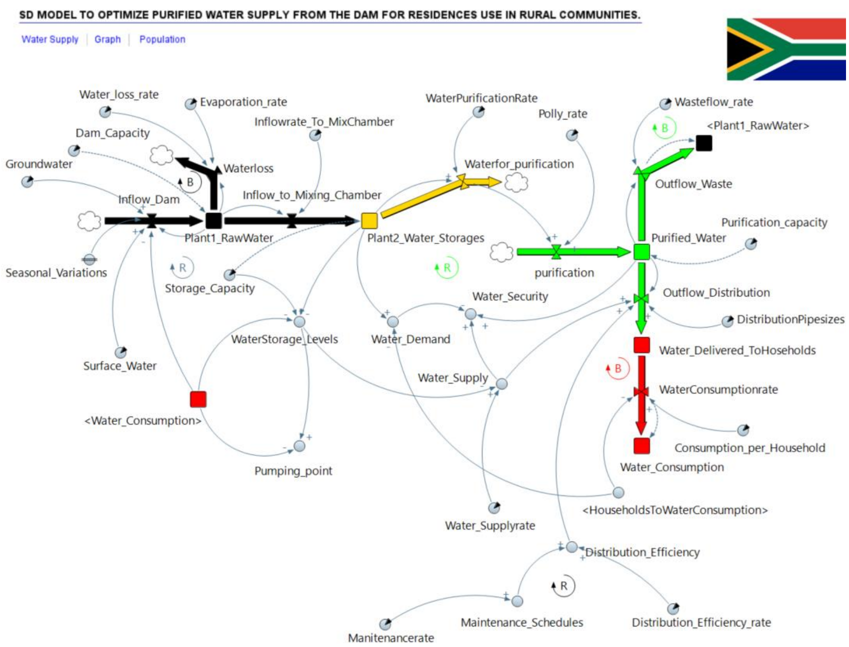


Fig. 9 Stock and flow diagram of the rural water supply network

The water supply process from the dam to community consumption involves several interconnected stages that ensure efficient water management. It begins with water inflow, where water is sourced from dam/rivers, rainfall, or runoff and stored in the dam. This flow depends on natural inflow rates and seasonal variations. The next step is the purification process, which includes pre-treatment to remove debris, chemical treatments such as chlorination to eliminate pathogens, and further filtration to meet health standards, followed by quality testing to ensure safety. After purification, water is stored in reservoirs or tanks, acting as a buffer to manage fluctuations in supply and demand. From storage, water enters the distribution network, where it is pumped through pipelines and managed for consistent pressure across communities. Maintenance ensures the system remains efficient. The water then reaches households for consumption, where it is used for various domestic purposes. Throughout the process, feedback loops monitor usage patterns and system performance to inform future adjustments, ensuring water is clean, safely distributed, and available when needed.

The below figure illustrates the second part of the water supply model which highlights a Reinforcing Loop (R1) that captures the relationship between population growth and water demand. As the population increases, the demand for water rises proportionally. This heightened demand leads to an increase in water consumption across households and communities.

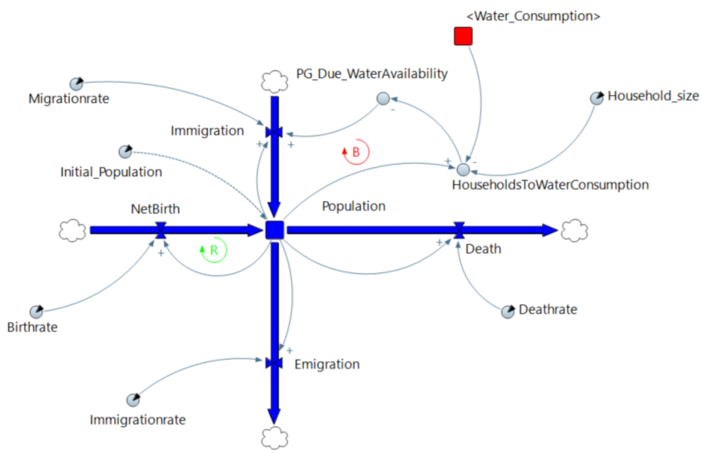


Fig. 10 Stock and flow diagram of the rural population

As a result, the system experiences greater pressure to meet the growing water needs, prompting the necessity for an increased supply. This creates a reinforcing feedback loop: higher population growth continuously pushes the system to provide more water, which in turn, reinforces the cycle as consumption and demand further escalate. Without proper management and system adjustments, this loop could lead to overextension of resources, potentially stressing the water supply infrastructure and reducing the availability of water for future needs. Addressing this loop is essential for sustainable water management, especially in growing rural communities where resources may be limited.

4. RESULTS

Below table shows the initials values of the model variables in the base line conditions of this study.

TABLE IV

INITIAL VALUES OF MODEL VARIABLES IN THE BASELINE CONDITIONS

Variable	Value	Unit	Variable	Value	Unit
Initial Population	1245015	Person	Evaporation rate	0,0018	Dmnl
Population Growth rate	3%	Dmnl	Ground water rate	0,015	Dmnl
Average people per household	7	Person	Immigration rate	0,0012	Dmnl
Water consumption per household	18	m^3	Inflow rate to mixing chamber	0,0012	Dmnl
Reservoir volume /Storage capacity	8358878,42	m^3	Maintenance rate	0,013	Dmnl
Total capacity (Dam)	11 000 000	m^3	Migration rate	0,008	Dmnl
Surface area	130	ha	Poly rate	0,005	Dmnl
Height	35	m	Purification capacity	336768	m^3
Reservoir volume allowance per person	0,09	m^3	Surface water	0,062	Dmnl
Birth rate	0,004	Dmnl	Waste flow rate	0,000015	Dmnl
Death rate	0,003	Dmnl	Water loss rate	896,75	m^3
Distribution efficiency	0,0012	Dmnl	Water supply rate	0,054	Dmnl
Distribution pipe sizes	0,034	Dmnl	Water purification rate	0,0025	Dmnl

In the baseline conditions of the water supply model, several key variables define the system's functionality. Initial population and population growth rate drive water demand, influenced by household size and water consumption per household. The reservoir volume and total dam capacity determine how much water can be stored, with surface area and height affecting evaporation. The distribution efficiency and pipe sizes impact how effectively water is delivered, while the reservoir volume allowance per person helps allocate water resources.

Population dynamics are shaped by birth and death rates, along with migration and immigration rates, which alter long-term demand. On the operational side, the inflow rate to the mixing chamber, groundwater rate, and surface water defines water sources, while maintenance rate and purification capacity affect system efficiency. Poly rate controls the chemical treatment of water, and waste flow rate manages system by products. Water purification rate and water supply rate indicate how fast raw water is purified and distributed. Lastly, evaporation rate and water loss rate account for natural and systemic losses, ensuring the system's water resources are optimized for consumption. These variables together provide a comprehensive baseline for managing the water supply in rural communities.

The below figure shows the model's baseline experiment settings which are discussed below.

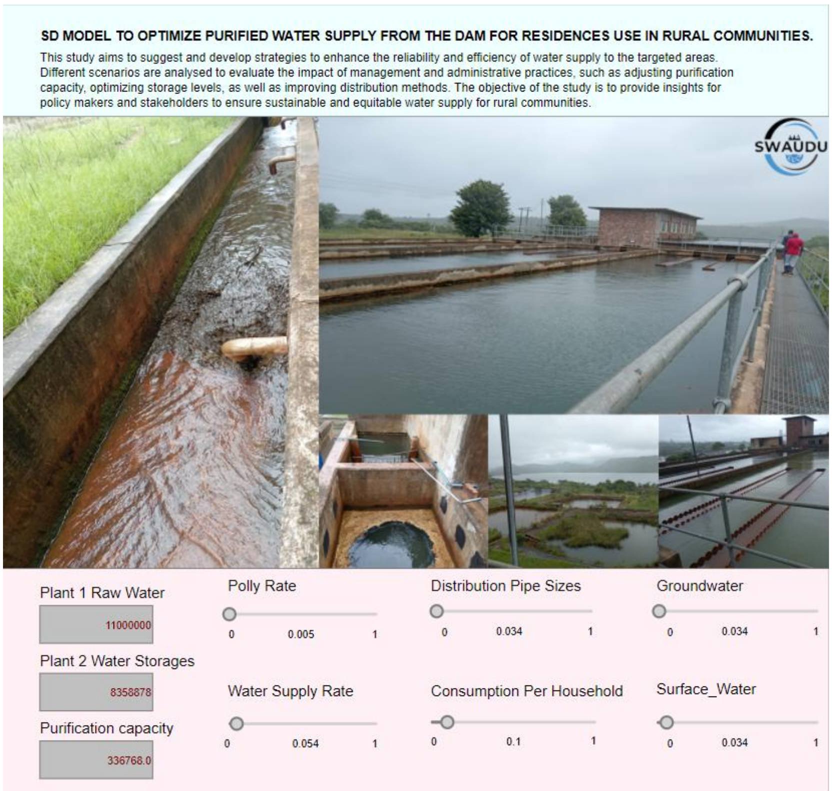


Fig. 11 Model Baseline experiment settings

The baseline model experiment settings focus on key factors influencing water supply. Plant 1 raw water capacity and Plant 2 water storage determine water intake and buffer capacity. Purification capacity and poly rate (chlorine) ensure water is treated effectively. Distribution pipe sizes influence delivery efficiency, while groundwater and surface water act as primary water sources. Water supply rate controls how quickly water reaches households, and consumption per household affects demand. Together, these elements define system performance, ensuring efficient water supply for rural communities.

The figure below illustrates the comparison between population and water consumption overtime.

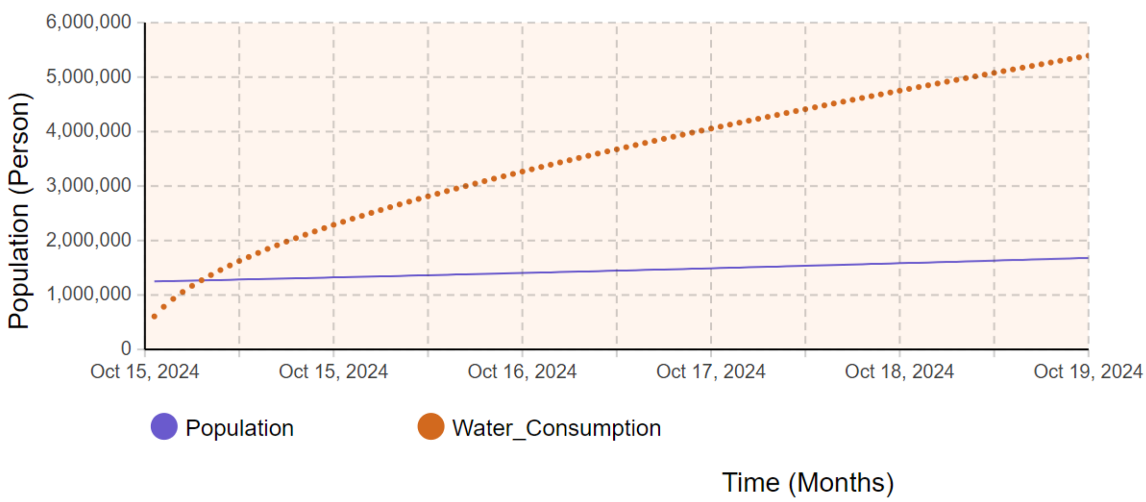


Fig. 12 Population and Water consumption

The figure above illustrates the data from the system dynamics model which indicates a steady increase in population alongside a corresponding rise in water consumption over time. Initially, with a population of approximately 1.249 million, water consumption starts at around 606,547 units. As the population grows to 1.681 million by the end of the 100period simulation, water consumption increases significantly to 5.394 million units. This growth aligns with the abstract's assertion that population growth drives water demand, influencing the dynamics of water supply and the pressure on purification and distribution systems.

The model incorporates key factors affecting water supply, such as storage, purification capacity, and distribution. The feedback loops simulate the relationship between increasing population and water consumption, emphasizing the need to adjust resources and improve system efficiency. This simulation suggests that to sustainably manage water supply, adjustments in purification capacity, storage levels, and distribution efficiency are essential, as rising demand could lead to potential system inefficiencies.

The findings support the abstract's claims by demonstrating that system dynamics modelling helps to pinpoint areas for improvement, providing a framework for developing effective water management strategies tailored for rural communities. The study underscores the importance of policy adjustments to enhance the reliability and sustainability of water supply, offering valuable insights for stakeholders in water resource management.

The figure below illustrates the data generated by system dynamics model that provides insights into the trends of water security and supply rate over time.

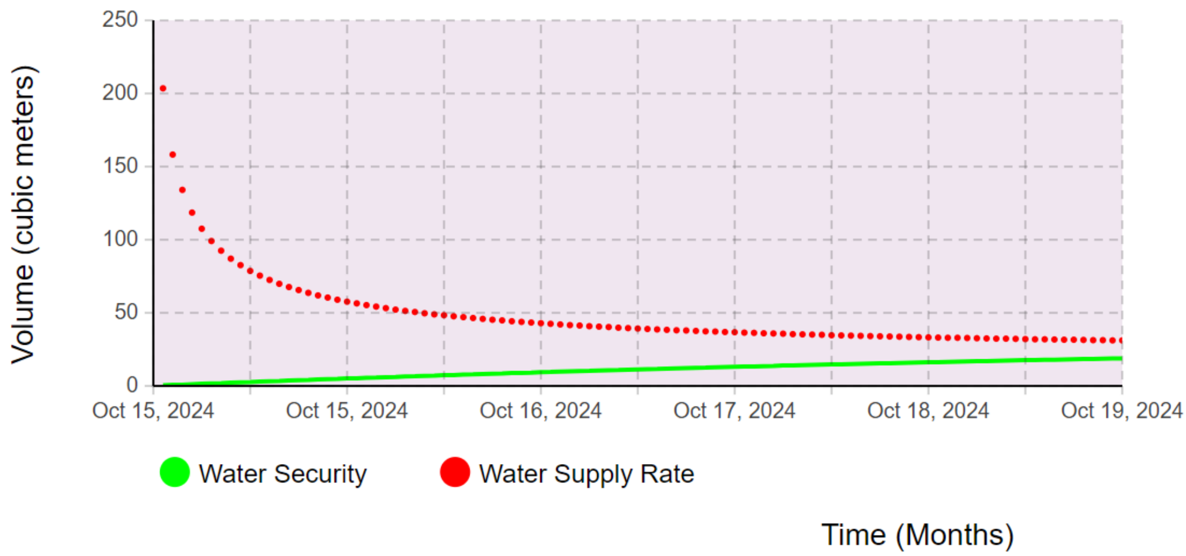


Fig. 13 Water security and water supply rate

The figure above illustrates the data from the system dynamics model that provides insights into the trends of water security and supply rate over time. Initially, the water security index is low, at 0.399, with a water supply rate of 203.53 units. As time progresses, water security steadily increases, reaching 18.893 by the 100th period, while the water supply rate gradually declines to 31.119 units. This trend suggests that as the system becomes more efficient and secure, there may be a controlled reduction in water supply rate to maintain sustainability and meet demand without overburdening resources.

These findings align with the abstract's claims that system dynamics modelling can optimize the water supply process for rural communities. By including elements like storage, purification, and distribution efficiency, the model identifies potential improvements and highlights the need for adjustments in purification and storage. The gradual improvement in water security reflects the system's increasing resilience, likely due to adjustments in purification capacity, distribution methods, and storage management. This aligns with the study's objective to enhance reliability and efficiency in water supply, providing insights for policymakers to manage rural water resources sustainably. The use of feedback loops in the model allows for continuous assessment and adaptation to changing conditions, supporting informed decision making in water resource management.

The figure below illustrates the evolution of three critical variables in the water supply system for rural communities: raw water supply from Plant 1, water storage in the mixing chamber, and population growth over time.

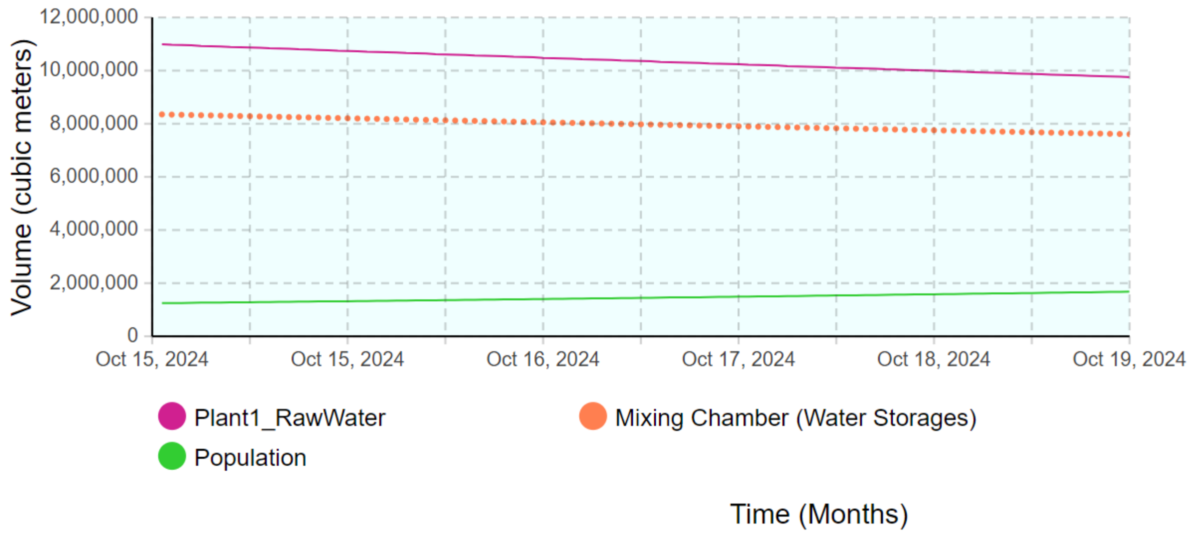


Fig. 14 Water supply system for rural communities.

The figure above illustrates data from the system dynamics model which shows evolution of three critical variables in the water supply system for rural communities: raw water supply from Plant 1, water storage in the mixing chamber, and population growth over time. These trends and how they align with the claims of the study are explained below.

1) *Plant 1 Raw Water Supply*

The raw water supply from Plant 1 starts at approximately 10.99 million units and gradually declines over the simulation period to 9.757 million units. This controlled reduction in raw water supply suggests an optimization strategy that may be balancing the inflow with the actual demand and storage capacity, preventing overuse or wastage of water resources. The model's goal of effective management and efficient use of water is evident in this trend, as it suggests that the system is conserving resources while maintaining adequate water availability for purification and distribution.

2) *Mixing Chamber (Water Storage)*

The water storage levels in the mixing chamber also decrease slightly over time, from 8.351 million units to 7.608 million units. This decline, though gradual, might indicate that the system is optimizing water storage to match supply with consumption needs while minimizing excess storage. This aligns with the study's objective of adjusting storage capacities for improved efficiency. By maintaining optimal storage levels, the model addresses potential inefficiencies in water handling and ensures that water is readily available for purification and distribution to meet community needs.

3) *Population Growth*

The population starts at 1.249 million and steadily increases to 1.681 million by the end of the simulation period. This increase reflects a growing demand for water over time, as more people in rural communities depend on this water source. The model incorporates population growth as a dynamic factor affecting water demand, which is a crucial consideration in system dynamics modelling. This aligns with the population growth as a significant factor influencing water supply dynamics. As population increases, the system must continually adjust supply and storage strategies to ensure that demand is met sustainably.

The trends in this data support the study claims that system dynamics modelling can effectively identify inefficiencies and suggest strategies to optimize water supply systems for rural communities. The controlled reduction in raw water input and water storage levels reflects a focus on sustainability, ensuring that resources are used effectively as the population grows. By simulating interactions among supply, storage, and demand components, the model provides a framework for adjusting supply and storage according to real-world conditions, such as seasonal changes, maintenance schedules, and consumption patterns.

These findings demonstrate the model's potential to help policymakers and stakeholders make informed decisions to achieve a sustainable, equitable water supply for rural communities. The data confirms that the system dynamics approach can provide insights into managing water resources more effectively and reliably, aligning with the study's objectives of supporting sustainable water management practices.

The figure below illustrates the water supply optimization for rural communities.

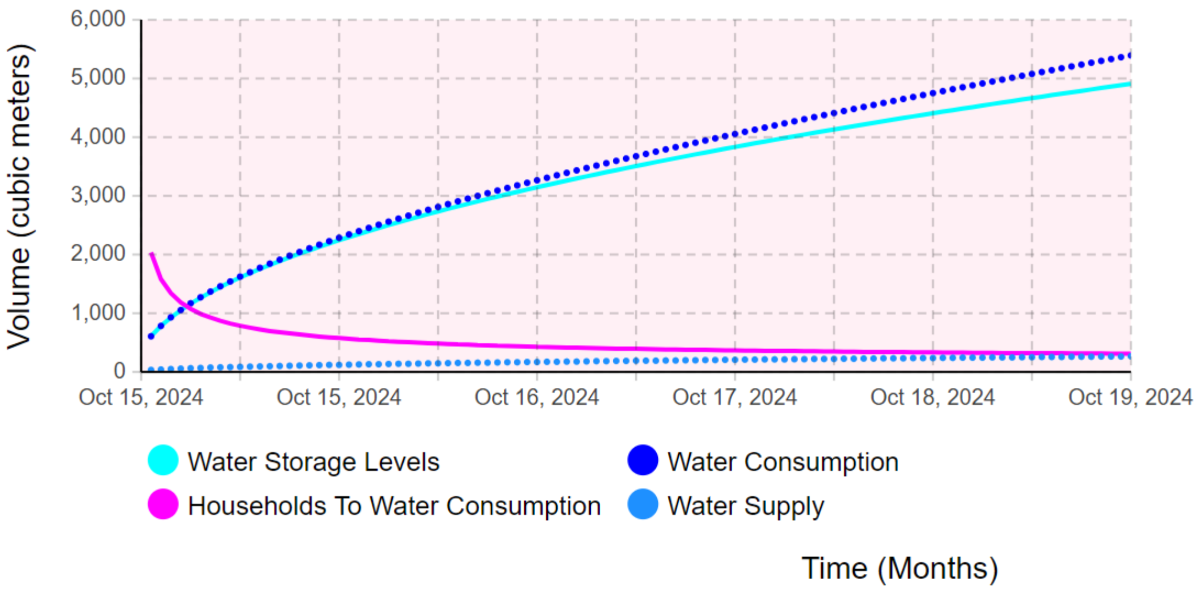


Fig. 15 Water supply optimization for rural communities

The figure above illustrates the data generated by system dynamics model on water supply optimization for rural communities highlights several key observations, aligned with the study's aim and goals of ensuring sustainable water management.

1) *Water Storage and Consumption Balance*

The water storage levels consistently increase from 605.989 to 4908.891, indicating an effort to maintain or increase storage as demand rises. This aligns with the study's goal to optimize storage capacity.

Consumption rises alongside storage levels, from 606.547 to 5393.55, reflecting increased demand likely driven by population growth. The consistent growth in both storage and consumption reflects the need for a balanced approach to ensure sufficient supply.

2) *Households to Water Consumption Ratio*

The data under "Households to Water Consumption" gradually decreases from 2035.305 to 311.189 over time, showing that, although more water is being supplied, there is a larger number of households requiring water. This aligns with the model's inclusion of factors like population growth impacting demand, suggesting the model captures the strain on resources due to an increasing number of consumers.

3) *Water Supply Efficiency*

Water supply values steadily increase from 32.723 to 265.08. This growth indicates improved water supply mechanisms, suggesting the model's feedback loops are helping to identify ways to meet rising demand. This reflects the study's aim to improve efficiency and reliability in distribution.

4) Impact of Population Growth

The data reflects a population influenced increase in water consumption and demand. As population grows, both storage and supply levels must be optimized to ensure that water needs are met, which corresponds to the study's objective of examining factors like population growth in system optimization.

5) Dynamic Interactions and Feedback Loops

The gradual adjustments in storage, consumption, and supply demonstrate the system's ability to dynamically respond to demand changes, consistent with the model's use of feedback loops. For instance, increasing storage levels while increasing supply suggests adaptive mechanisms to prevent shortages.

6) Long-term Sustainability

The upward trend across water storage, consumption, and supply reflects a systemic approach to long-term sustainability. This model allows stakeholders to see how rising demands impact water resources and identifies areas for improvement, such as increasing storage capacity or refining supply methods.

The system dynamics model data supports the abstract's claims, showing how feedback mechanisms help adapt water management to population growth and demand. The model's outputs, such as increased water storage and supply, reveal potential strategies for policymakers to enhance water distribution efficiency, sustainability, and equity in rural communities. This approach provides a structured way to address challenges in rural water supply and improve decision making in water resource management.

The figure below illustrates the data generated by the system dynamics model for optimizing purified water supply from a dam for rural residential use.

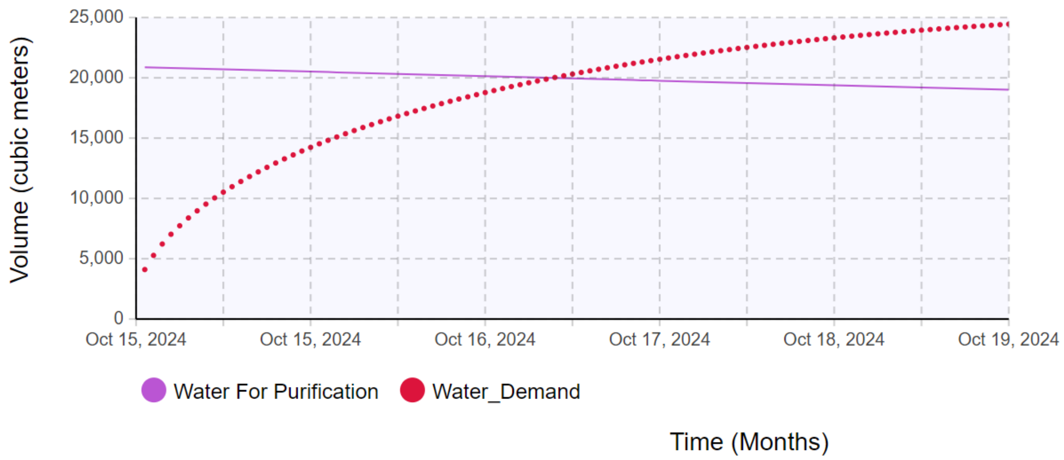


Fig. 16 Purification processes, Demand patterns

The figure above illustrates the data generated by the system dynamics model for optimizing purified water supply from a dam for rural residential use reveals several key trends that align with the study 's claim, highlighting the role of factors like purification processes, demand patterns, and feedback mechanisms.

1) Water for Purification

The initial volume of water available for purification starts at 20,877.956 units and gradually decreases to 19,019.395 units by the end of the simulation. This slow decline over time could reflect ongoing usage, seasonal fluctuations, or evaporation losses, all factors which the model might be accounting for to simulate real-life conditions.

The gradual decrease suggests that the model includes mechanisms to monitor and manage purification resources, aligning with the study's goal to optimize purification processes. The depletion rate also seems controlled, implying that purification capacity is being managed to support sustainable supply over time, which aligns with the study's focus on reliability.

2) Water Demand Growth

Water demand starts at 4,103.161 units and climbs steadily to 24,447.357 units by the end of the simulation. This rise reflects the impact of population growth and increasing demand on water resources. The model captures this demand pattern, consistent with the study's focus on how population dynamics affect the water supply system.

The data shows a growing gap between the decreasing purified water available and the rising demand. This emphasizes the need for optimization and efficient management to keep up with demand, supporting the study's aim to suggest strategies for enhancing supply reliability.

3) Feedback Loops and Demand Management

The model uses feedback mechanisms to respond to increasing demand and depletion in water availability for purification. This can be inferred from the controlled rate of decrease in purification water, despite rising demand. The feedback loops may involve adjusting storage, managing purification output, or regulating distribution actions that align with the model's purpose of simulating complex system interactions and identifying inefficiencies.

4) Long-term Sustainability and Optimization Goals

The consistent increase in demand relative to the available water for purification suggests that the model emphasizes the sustainability of water resources. The need for sustainable practices is clear, as the model projects the strain on resources if no adjustments are made to account for rising demand.

The gradual decline in water for purification shows that strategies such as improving purification capacity or optimizing water storage would be necessary to meet the needs of the rural communities sustainably. This supports the study's goal of providing insights for policymakers to ensure a sustainable and equitable water supply.

5) Impact of Management Practices

The controlled decrease in purification resources despite rising demand implies that the model may incorporate adjustments such as refining purification processes, improving efficiency, or enhancing storage. This aligns with the study's exploration of different scenarios to evaluate the impact of administrative practices and distribution methods.

This system dynamics model data reflects the claims in the study by capturing the interaction between water purification resources and increasing demand due to population growth. The data emphasizes the importance of sustainable water management practices, controlled purification capacity, and adaptive feedback mechanisms to optimize supply. The trends in purification water availability and demand provide actionable insights for stakeholders on ensuring the longevity of water resources for rural communities, supporting informed decision making in water resource management.

The figure below illustrates the water distribution to the rural communities.

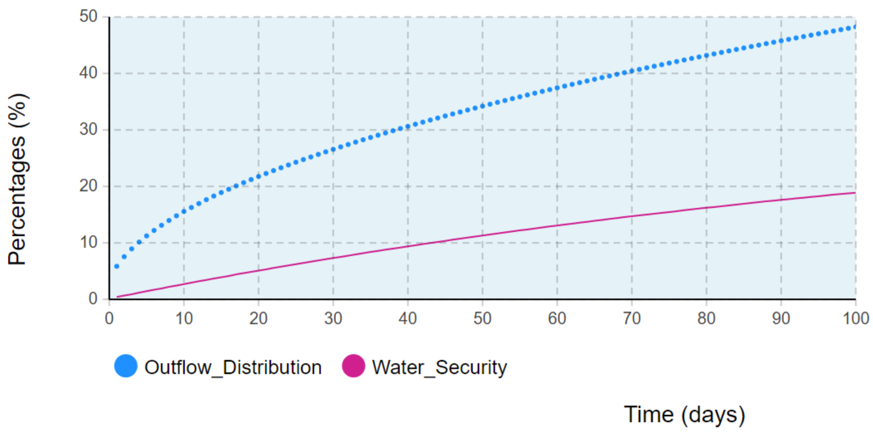


Fig. 17 Water distribution

The figure above illustrates the data from the system dynamics model for optimizing purified water supply from a dam in rural communities provides insights into Outflow Distribution (the amount of water distributed to communities) and Water Security (the resilience and reliability of the water supply system).

1) Outflow Distribution

Steady Increase in Outflow: The outflow distribution starts at 5.847 units and increases to 48.226 units by the end of the simulation. This gradual increase in distribution indicates a strategy to match rising demand in rural areas over time, likely influenced by population growth and water needs in communities.

Growth in Distribution Channels: The steady rise in outflow aligns with the model's intent to optimize distribution methods, as stated in the abstract. It suggests that adjustments are being made to distribution infrastructure, storage, or purification processes to ensure that water supply meets community demands progressively.

Impact of Management Practices: The model’s increasing outflow trend may represent efforts to improve storage and distribution methods. This aligns with the study's aim to analyse different scenarios for enhancing distribution methods, supporting the model's goal of meeting growing demand reliably.

2) Water Security

Water security, starting at 0.399 and reaching 18.893 by the end of the simulation, represents the system's resilience and reliability over time. The increase suggests that the model incorporates mechanisms to boost water security, likely through feedback loops and adjustments in response to fluctuations in demand, storage levels, and distribution efficiency.

The data shows that as outflow distribution increases, water security improves. This implies the presence of feedback loops that balance distribution with sustainable water availability, consistent with the abstract's focus on using feedback mechanisms to address inefficiencies.

Policy and Management Implications: The rise in water security over time underscores the model’s effectiveness in identifying and mitigating risks associated with water supply, providing critical insights for policymakers. Improved water security suggests the model can help manage seasonal fluctuations, maintenance schedules, and increased demand, aligning with the study's objective to support sustainable water resource management.

3) Alignment with Abstract's Claims

Improved Reliability and Efficiency: The increasing outflow and water security values reflect the model's purpose to enhance reliability and efficiency in water distribution. As water security rises alongside increased outflow, the model demonstrates its capacity to manage demand growth sustainably, aligning with the study’s goal to ensure sustainable health and wellbeing for rural residents.

Optimization of Storage and Distribution: The steady rise in distribution and security aligns with the study's objective of optimizing storage and distribution systems. The model’s scenario analysis likely tested various management strategies to improve these aspects, resulting in a distribution system that adapts to demand without compromising security.

Insight for Decision Making: The data offers valuable insights for stakeholders and policymakers, showing how distribution adjustments can lead to a stable water supply. The increasing water security metric implies that the model supports informed decision making by providing a comprehensive framework for understanding the complex challenges in rural water supply.

4) Sustainability Implications

The model’s system dynamics approach successfully demonstrates how a sustainable increase in water distribution can be achieved while simultaneously enhancing security. This suggests that the system is capable of addressing challenges associated with water scarcity, demand fluctuations, and infrastructure capacity, which are critical for long-term sustainability.

The upward trends in both outflow and security indicate that the model can adapt to rising demand, population growth, and potential seasonal variations without sacrificing the resilience of the water supply.

The data reveals that the system dynamics model effectively manages the trade-off between meeting community water demands and maintaining water security. The steady increase in outflow distribution, paired with the growing water security metric, reflects a robust model that adapts to increasing demands sustainably. This aligns with the study's aim to support rural communities with reliable, equitable, and sustainable water supply systems. The findings suggest that optimizing distribution, adjusting storage, and implementing feedback mechanisms can significantly enhance water security, providing critical insights for policymakers aiming to address water supply challenges in rural areas.

5. RECOMMENDATIONS

Based on the results of the system dynamics model, the following recommendations are suggested to further improve water distribution and ensure sustainable water security in rural communities.

1) Optimize Distribution Infrastructure

- Invest in expanding and upgrading distribution channels to ensure an efficient water supply that meets increasing demand. This could include adding storage facilities or strengthening existing pipelines and delivery systems to reduce water losses.

- Regular maintenance and monitoring of distribution channels are essential to prevent leaks and ensure reliable water delivery, particularly during high-demand periods.

2) Enhance Purification Capacity

- With rising demand, it's critical to periodically assess and expand purification capacity. This will ensure that the inflow from dams can be consistently treated to meet community needs without compromising quality or reliability.

- Implement adaptive purification strategies to respond to seasonal changes and demand fluctuations, allowing purification facilities to be more resilient and responsive.

3) Implement Seasonal and Demand-Based Adjustments

- Seasonal demand fluctuations should be anticipated with proactive adjustments to storage and distribution practices. During peak periods, increasing storage reserves and adjusting purification rates will support uninterrupted supply.

- Conduct demand forecasting and population growth assessments to align water supply with projected needs, ensuring that rural communities receive a consistent water supply even as demand evolves.

4) Strengthen Water Security Mechanisms

- The model's feedback loops for water security should be enhanced to manage risks associated with demand surges and supply constraints. Real-time monitoring of water security indicators can help pre-emptively address issues and ensure continuous availability.

- Stakeholders should establish emergency response plans for water scarcity, including alternative water sources or rationing protocols, to maintain water security during droughts or unforeseen events.

5) Policy and Stakeholder Engagement

- Engage policymakers and local leaders to develop and implement policies that support sustainable water management in rural areas, ensuring that resources are allocated efficiently and equitably.

- Facilitate community involvement in water management practices to promote water conservation and establish a collective approach to managing demand.

6. CONCLUSION

The study demonstrates that a system dynamics model is a valuable tool for optimizing water distribution from dams to rural communities, as it effectively captures the complexities of demand fluctuations, storage capacities, purification, and distribution channels. By simulating various scenarios, the model provides insights into how distribution and water security can be enhanced sustainably to ensure the health and well-being of residents.

Results indicate that a gradual increase in water outflow, coupled with rising water security, suggests that a balance between supply and demand can be maintained through efficient infrastructure management and adaptive practices. These findings reinforce the need for strategic investments in infrastructure, purification capacity, and seasonal adjustment mechanisms. Additionally, the implementation of feedback loops within the model shows how water security can be strengthened, helping to mitigate risks associated with water scarcity or supply disruptions.

By applying the insights gained from this model, policymakers and stakeholders can make informed decisions to ensure equitable, sustainable, and resilient water distribution in rural areas. The approach provides a framework for addressing the challenges of rural water management and supports the goal of reliable water access for all, fostering sustainable development and community well-being in rural settings.

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