**Journal of Information Systems Engineering and Management**
2025, 10(56s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

**Research Article**

# Enhancing Rural Water Supply Systems Through System Dynamics Modelling: Addressing the impact of Power Shortages on Water Availability

Lucas Khashane[1], Tshifhiwa Nenzhelele[2], Constance Hluphi Mafuwane[3],
[1]*Industrial Engineering & Tshwane University of Technology, South Africa*
[2]*Industrial Engineering & Tshwane University of Technology, South Africa*
[3]*Industrial Engineering & Tshwane University of Technology, South Africa*
[1]*Khashanel@tut.ac.za*, [2]*NenzheleleT@tut.ac.za*, [3]*moganec50@gmail.com*

**ARTICLE INFO**

Received: 28 Dec 2024

Revised: 18 Feb 2025

Accepted: 26 Feb 2025

**ABSTRACT**

It is essential to have access to a dependable water supply, especially in rural locations where power outages make water scarcity worse. This study examines how power outages affect water supply in decentralized and centralized dam-based borehole systems using system dynamics modeling. In centralized systems, pumps require consistent power, and load shedding leads to prolonged water outages. Similarly, boreholes rely on electric pumps, and power interruptions force households to seek unreliable water sources. These disruptions increase health risks and intensify burdens on vulnerable populations, especially women and children. The system dynamics model integrates key variables such as electricity reliability, water demand, and community resilience strategies to predict outcomes and recommend targeted interventions. Findings indicate a decline in water availability and electricity reliability over time, highlighting the vulnerability of rural water systems. However, interventions such as solar-powered systems, hybrid energy solutions, and optimized water storage have improved water access and well-being. While significant progress is observed, slowing growth in well-being improvements suggests the need for sustained investment and innovation. This study emphasizes the necessity of sustainable energy solutions, adaptive infrastructure, and proactive policies to ensure long-term water security and improved quality of life in rural communities.

**Keywords:** Water supply systems, Power shortages, System dynamics modelling, Rural communities.

## 1. INTRODUCTION

Access to clean water is essential for the growth and well-being of rural and global communities. In rural areas specifically, reliable water supplies are indispensable for health, livelihoods, and socio-economic progress [1]. However, many regions, particularly those with inadequate infrastructure, face significant challenges such as power shortages or load shedding, which exacerbate water scarcity [2]. These disruptions impede the functionality of both centralized and decentralized water supply systems, leaving communities vulnerable to prolonged water outages and limited access to clean, safe water. Women and children, often at the forefront of water collection, face added burdens during shortages, underscoring the gendered and generational impacts of water access challenges [3].

This study adopts a system dynamic modelling approach to address these challenges, as it is uniquely suited to capturing the complex, interdependent relationships between electricity reliability, water demand, and resource distribution. Unlike other modelling techniques such as statistical models, which focus on historical data trends, or agent-based models, which simulate interactions of individual components without fully capturing system-wide dynamics, system dynamics enables the analysis of feedback loops and time-varying behaviours within the water-energy nexus. These capabilities provide a comprehensive framework for understanding and addressing the multi-faceted challenges faced by rural communities.

Journal of Information Systems Engineering and Management
2025, 10(56s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ **Research Article**

Focusing on two primary water supply mechanisms centralized distribution from dams and decentralized borehole systems, this research investigates how power shortages affect water availability in rural areas [4]. Furthermore, it evaluates the effectiveness of interventions such as solar-powered water systems, hybrid energy solutions, and optimized water storage mechanisms. By simulating various scenarios, the model offers actionable insights that can empower policymakers and stakeholders to develop sustainable strategies for consistent water access [5]. By addressing the difficulties faced by rural areas, these insights seek to improve policy design and execution.

Ultimately, this study contributes to the existing literature by addressing critical gaps in understanding the interplay between energy reliability and water supply in rural contexts. While previous research has often examined these factors in isolation, this work integrates them to provide a holistic perspective. By doing so, it equips rural communities with practical solutions to overcome water supply challenges and improve their overall quality of life.

## 2. LITERATURE REVIEW

Access to reliable water supply systems is a fundamental need, particularly in rural communities where infrastructural challenges such as power shortages exacerbate water scarcity. Numerous studies emphasize the critical role of electricity in water distribution systems, highlighting how power outages disrupt centralized and decentralized water systems [6]. For example, [7] demonstrated that load shedding significantly reduces water availability in centralized systems reliant on electric pumps. Similarly, studies by [8] revealed that decentralized borehole systems are equally vulnerable, as electricity interruptions hinder their ability to provide consistent water access.

The cascading socio-economic impacts of water scarcity are well-documented. Women and children are disproportionately burdened with collecting water when systems fail, according to research by [9]. Due to these difficulties, people are compelled to depend on other, frequently dangerous water sources, which increases health hazards. In addition, inadequate water access limits economic productivity and overall quality of life, as discussed by [10].

An effective method for examining the interdependencies in water supply systems is system dynamics modeling. For instance, [11] outlined the utility of system dynamics in simulating complex interactions between infrastructure, energy reliability, and resource distribution. Recent studies, such as those by [12], have utilized system dynamics to evaluate the effectiveness of sustainable solutions, including solar-powered systems and hybrid energy models. These approaches have been shown to improve water availability while reducing dependency on unreliable power grids.

The literature consistently advocates for sustainable interventions to address these challenges. Solar-powered water systems and hybrid energy solutions are frequently proposed as effective strategies to enhance water supply reliability. Moreover, studies by [13] emphasize the importance of adaptive water storage mechanisms and community-based management practices in mitigating the impacts of power shortages.

This review underscores the interconnected nature of water supply systems, energy reliability, and socio-economic well-being. It highlights the need for integrated approaches combining technological innovation, policy intervention, and community participation to build resilient and sustainable water systems in rural areas.

## 3. METHODS

This study employs system dynamics modelling by integrating both qualitative and quantitative approaches to evaluate the effects of power shortages on rural water supply. A causal loop diagram (CLD) maps key interactions, while a stock-and-flow model quantifies system behaviour using empirical data [14]. Scenario simulations evaluate centralized and decentralized water systems, exploring solar power, hybrid energy, and storage solutions. Findings offer insights for sustainable policy decisions. The causal loop diagram highlights the interplay between electricity availability, water supply systems, and socio-economic challenges in rural communities. Electricity availability directly impacts the functionality of both centralized water distribution from dams and decentralized borehole systems.

Figure 1 presents the developed causal loop diagram, illustrating the relationships between key dynamic variables.

**Journal of Information Systems Engineering and Management**
2025, 10(56s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

**Research Article**

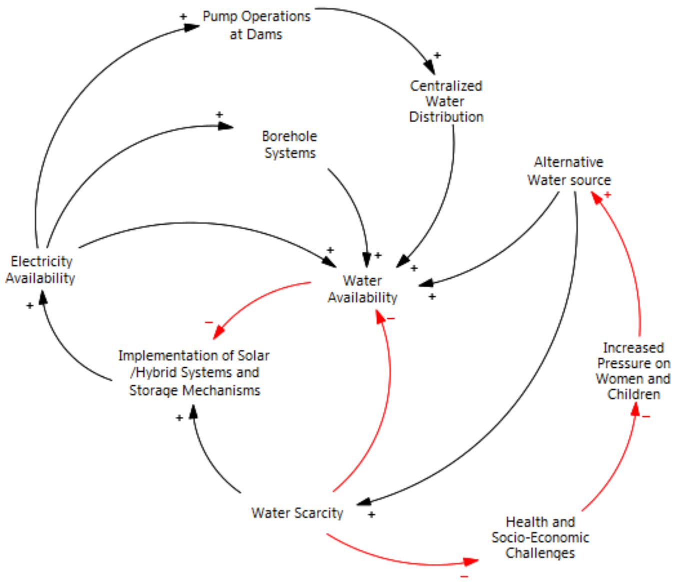


**Fig. 1** Water supply system causal loop diagram.

In centralized systems, pumps rely on consistent electricity to deliver water, while in borehole systems, electric pumps are vital for accessing underground water. Load shedding disrupts both mechanisms, reducing water availability and intensifying water scarcity. Women and children, who frequently shoulder the job of gathering water, are further burdened by this scarcity, which worsens socioeconomic and health issues. In response, communities turn to other water sources such rivers, uncovered wells, or rainwater collection, which can offer short-term respite but frequently carry the danger of contamination, waterborne illnesses, and unstable supplies.

Figure 2 presents the system dynamics model used to analyse the interactions between dynamic variables.

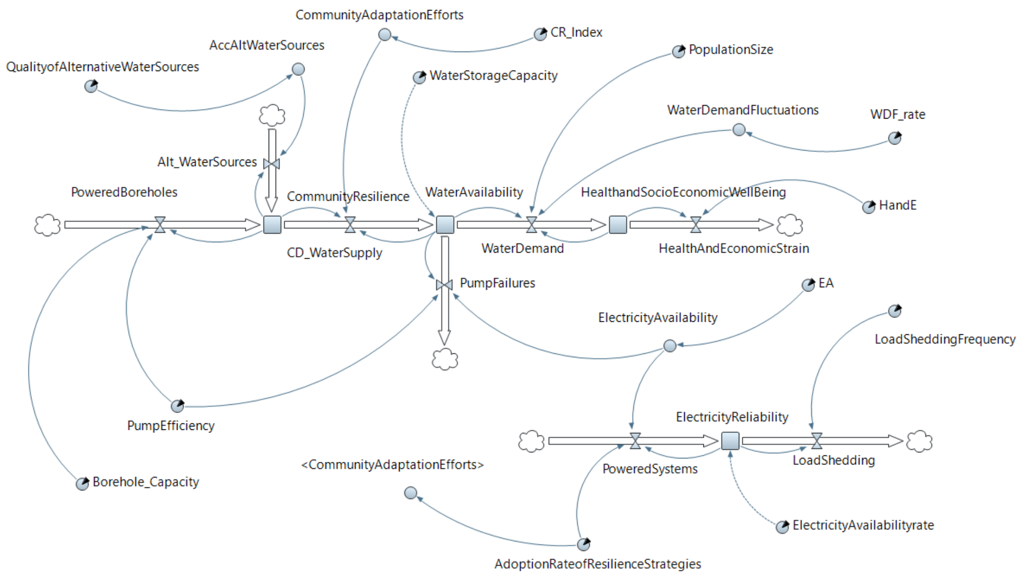


**Fig. 2** Water supply system SD model.

To address these issues, the system includes resilience strategies such as solar-powered systems, hybrid energy solutions, and optimized water storage mechanisms. These interventions reduce reliance on unreliable electricity, enhancing water availability and mitigating the negative impacts of power shortages. The feedback loops in the model illustrate how electricity availability and community strategies influence water supply and demand dynamics. By

Journal of Information Systems Engineering and Management
2025, 10(56s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ Research Article

simulating various scenarios, the system dynamics model helps policymakers identify critical leverage points and design sustainable solutions to ensure consistent water access, ultimately improving the quality of life in rural areas.

## 4. RESULTS AND DISCUSSIONS

The figure 3 below illustrate the water availability results generated by the system dynamics model.

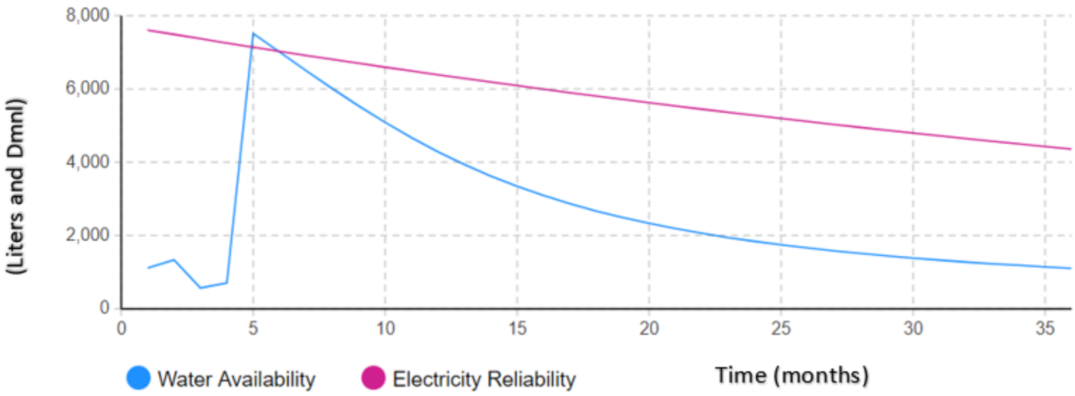


**Fig. 3** Water availability.

The results reveal a clear decline in both water availability and electricity reliability over time, with water availability dropping sharply after the 5th time step (from 7510.721 to 1104.819) and electricity reliability steadily decreasing from 7609.92 to 4359.824. This indicates that rural water distribution systems, both centralized and borehole-based, are highly sensitive to power shortages. The data also underscores the direct relationship between these variables, as diminishing electricity reliability disrupts pump operations, leading to water scarcity. The critical tipping point observed between time steps 3 and 5 highlights the limits of existing infrastructure and resilience strategies under worsening electricity conditions. These findings emphasize the systemic vulnerability of rural water systems to load shedding and its cascading socio-economic impacts. Reduced water availability increases health risks and intensifies burdens on vulnerable populations, particularly women and children. To address these challenges, it is vital to adopt targeted interventions such as solar-powered or hybrid energy systems, which can stabilize water supply despite power shortages. Implementing these solutions will improve infrastructure resilience, mitigate socio-economic challenges, and ensure sustainable water access for rural communities.

The figure 4 below illustrate the water availability results generated by the system dynamics model.

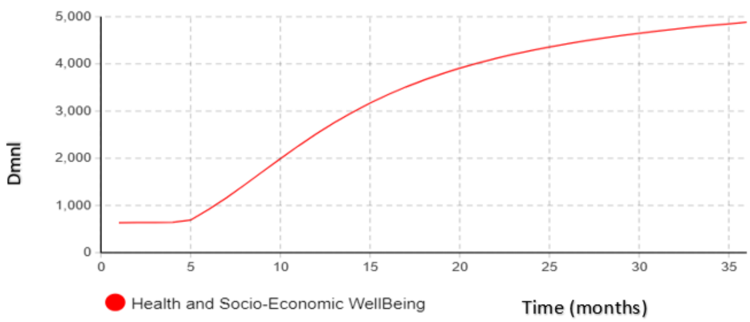


**Fig. 4** Health and socio-economic well-being

The results show a steady improvement in health and socio-economic well-being over time, increasing from 631.669 to 4881.443. This gradual rise reflects incremental progress in addressing the challenges posed by water scarcity and power shortages in rural areas. A significant surge occurs between time steps 5 and 10, where well-being sharply increases from 688.669 to 1990.754, likely due to the implementation of targeted interventions such as solar-powered

**Journal of Information Systems Engineering and Management**
2025, 10(56s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

**Research Article**

systems, optimized water storage, or other measures that enhanced water availability and mitigated the effects of power disruptions. In the later stages, the growth rate of well-being slows, indicating diminishing returns from interventions or increasing systemic challenges as improvements stabilize. These findings align with the abstract's focus on the socio-economic impacts of water scarcity and power shortages, suggesting that resilience strategies have positively influenced community well-being. However, the plateauing growth highlights the need for continuous innovation and investment to sustain progress and further improve quality of life in rural communities.

## 5. CONCLUSSION

The system dynamics results highlight the critical interplay between electricity reliability, water availability, and health and socio-economic well-being in rural communities. The decline in water availability due to persistent power shortages underscores the vulnerability of centralized and decentralized water systems to load shedding, leading to significant socio-economic challenges such as health risks and increased burdens on vulnerable populations. This relationship illustrates the need for robust interventions to stabilize water supply and mitigate cascading negative effects. Despite these challenges, the steady improvement in health and socio-economic well-being indicates that targeted resilience strategies, such as solar-powered water systems and optimized resource management, can significantly enhance quality of life. However, the slowing growth rate in well-being improvements suggests that ongoing investment and innovation are necessary to sustain progress. These results highlight how crucial it is to combine proactive policies, flexible infrastructure, and renewable energy sources to guarantee long-term water security and enhanced rural communities' well-being.

## REFRENCES

1. Bazaanah, P. and R.A. Mothapo, *Sustainability of drinking water and sanitation delivery systems in rural communities of the Lepelle Nkumpi Local Municipality, South Africa*. Environment, Development and Sustainability, 2024. **26**(6): p. 14223-14255.
2. Marchetti-Mercer, M.C., *Resilience is not enough: The mental health impact of the ongoing energy crisis in South Africa*. South African Journal of Science, 2023. **119**(9/10).
3. Jacob, D.E., et al., *Rural Water Crises in the Global South: Understanding the Scope and Impact*, in *Water Crises and Sustainable Management in the Global South*. 2024, Springer. p. 3-44.
4. Al-Saidi, M., E.L. Roach, and B.A.H. Al-Saeedi, *Conflict resilience of water and energy supply infrastructure: Insights from Yemen*. Water, 2020. **12**(11): p. 3269.
5. Badham, J., et al., *Effective modeling for Integrated Water Resource Management: A guide to contextual practices by phases and steps and future opportunities*. Environmental Modelling & Software, 2019. **116**: p. 40-56.
6. Helmrich, A., et al., *Centralization and decentralization for resilient infrastructure and complexity*. Environmental Research: Infrastructure and Sustainability, 2021. **1**(2): p. 021001.
7. Machimana, L.I., et al., *The Impact of Load-Shedding on Scheduled Water Delivery Services for Mohlaba-Cross Village, Greater Tzaneen, South Africa*. Water, 2024. **16**(14): p. 2033.
8. Wijnen, M., et al., *MANAGING THE INVISIBLE: THE GOVERNANCE AND POLITICAL ECONOMY OF GROUNDWATER*. Thematic Papers on Groundwater, 2016: p. 575.
9. Cutter, S.L., *The forgotten casualties redux: Women, children, and disaster risk*. Global environmental change, 2017. **42**: p. 117-121.
10. Okwirry, M., *Assessing Challenges of Accessing Safe Water and Their Effects on the Quality of Life of Urban Communities in Kenya: A Case of Residents of Tyson Estate in Nairobi County*. 2022, Daystar University School of Human and Social Sciences.
11. Sterman, J., *Business Dynamics, System Thinking and Modeling for a Complex World*. http://lst-iiep.iiep-unesco.org/cgi-bin/wwwi32.exe/[in=epidoc1.in]/?t2000=013598/(100), 2000. **19**.
12. Naeem, K., et al., *A literature review on system dynamics modeling for sustainable management of water supply and demand*. Sustainability, 2023. **15**(8): p. 6826.
13. Zakariazadeh, A., et al., *Renewable energy integration in sustainable water systems: A review*. Cleaner Engineering and Technology, 2024: p. 100722.
14. Crielaard, L., et al., *Refining the causal loop diagram: A tutorial for maximizing the contribution of domain expertise in computational system dynamics modeling*. Psychological methods, 2024. **29**(1): p. 169.