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Optimizing Water Resources Through Intelligent Systems: A Systemic Organizational Model

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Abstract

Effective water resource management is one of the most critical challenges for organizations as increasing water scarcity and climate change can complicate business continuity. This study presents a systemic approach based on intelligent systems for optimizing water consumption in the organizational environment. Three systemic models were developed that make use of discrete event simulation using the Monte Carlo method and System Dynamics, in which water supply, consumption and recycling are evaluated under various uncertainty scenarios. The results show the integration of advanced analytical tools allowing the identification of critical points, operational risk analysis and the proposal of highly sustainable solutions. Offering organizations an effective roadmap for the correct implementation of effective and resilient policies in the face of climate change and water scarcity.

Keywords

Engineering Management, Machine Learning (ML), Simulation Model, Sustainable Development and Systems Thinking.

1. Introduction

The scarcity of drinking water is a global problem that continues to worsen, some causes are associated with climate change and overexploitation of aquifers. Aquae (2024) reports that the distribution of drinking water on Earth amounts to 0.007%, an insufficient figure for the more than 1.1 billion people in the world who lack direct access to sources of drinking water, so they suffer water stress, the latter is driven by population growth and rapid urbanization, bringing with it the constant search for the vital liquid accelerating the degradation of ecosystems, overexploitation of rivers, lagoons and bodies of water.

In addition to the deficient and careless management of water resources, the equitable supply of water in society has been put at risk. In Mexico City alone, 17% of neighborhoods are supplied with water only through pipes, that is, there is no infrastructure to ensure access to water resources to meet their needs. Based on the Sistema de Aguas de la

Ciudad de México (SACMEX, 2024), an average person consumes 380 liters per day, however, the water supply in the municipalities is 150 liters per inhabitant, which is in line with the recommendations of the World Health Organization, which proposes the use of 100 liters per day, equivalent to 6 buckets to meet consumption and hygiene needs. On the other hand, 23.1% of homes have a consumption of less than 100 liters, which means that a little more than 77% of the inhabitants do not have the full right to water.

Currently, it is necessary to raise awareness about sustainable management of water resources to ensure long-term supply (Morchid et al., 2024) and promote increased efficiency in the use of resources. Traditional water management systems should be analyzed because often there is no equitable distribution of the vital liquid or thousands of liters are lost in leaks, which leads to the need to modernize and optimize the supply systems, as well as their various uses such as irrigation and the attention of personal and industrial needs.

Factors such as demographics, seasons, consumer behavior, and appliance efficiency affect water consumption, production, recycling, and quality (Hu, 2023). Given the complexity of these interactions and different changes in water systems, it is necessary to model water-related systems using dynamical systems Liu et al., 2024).

Dynamic systems are applied in the study and strategic management of water for modeling the various complex interactions and the different changes that occur over time in systems related to the vital resource. These models are especially useful for understanding how different factors influence water consumption, production, recycling, and quality (Liu et al., 2024).

Complexity Science has established itself as an interdisciplinary field that seeks to understand the behavior of complex systems, which are characterized by a series of properties that distinguish them from simple systems. Addressing these systems involves recognizing the limitations of the traditional scientific method and adopting new methodological and epistemological approaches (Bishop, 2011). Complex systems are composed of many diverse components that interact in a nonlinear fashion, which means that small variations in initial conditions can produce major differences in outcomes (Muir, 2011). Likewise, these types of systems can adapt to changes in their environment through feedback mechanisms (Nolfi, 2011). The behavior of complex systems is strongly influenced by the context in which they operate and the initial conditions (Hooker, 2011). Another significant characteristic of complex systems is that they exhibit a capacity for adaptation and resilience not found in simpler systems. Sustainability approaches should take this adaptive capacity into account and seek to foster resilience rather than attempting to precisely control or predict system behavior (Ryan, 2011).

When analyzing the complexity of water systems, water resources systems are complex and subject to uncertainty, which is why it is necessary to develop simulation and optimization models to address complexity and ensure efficient and equitable management (Zhao et al., 2024).

Scientific and technological progress is advancing by leaps and bounds every time, the development of new technologies such as Internet of Things (IoT) sensors, Machine Learning (ML) in conjunction with Artificial Intelligence (AI), offer opportunities to improve water management, these technologies allow real-time monitoring, more accurate predictions, intelligent control systems. The implementation of intelligent water consumption systems with IoT allows knowing the most significant variables to improve consumption based on climatic conditions (Yang et al., 2024).

Due to the complexity of water systems, the development of predictive models and control systems is required, which is why it is necessary to know and develop water consumption prediction models that allow anticipating the demand for irrigation and residential consumption. Non-intrusive data and machine learning techniques are used to build these models, as well as to develop predictive models of water quality and optimize the allocation of resources based on their availability in real time (Gough et al., 2023).

Robust system design allows the identification of solutions that perform optimally under a variety of future conditions to increase confidence in decision making in an uncertain future, the systems identified in the state of the art seek the most efficient way to optimize the robustness of water management systems in the face of changing conditions (Zhang et al., 2023).

Water is required for more purposes such as health, agriculture, manufacturing, and if there is no way to optimize supply and maximize uptake, water stress could cause agricultural and manufactured products to rise significantly in price due to the law of supply and demand.

On the other hand, the development of this work seeks the implementation of organizational policies and the search for the development of water collection, reuse, and recycling systems, in order to make the most efficient use of available water resources.

1.1 Objectives

Integrate advanced analytical tools to propose sustainable solutions that optimize the use of water resources, minimize risks, and promote organizational resilience to climate change conditions.

- Integrate advanced analytical tools to identify critical points, analyze operational risks and propose highly sustainable solutions.
- To provide organizations with an effective roadmap for the proper implementation of effective and resilient policies in the face of climate change and water scarcity.

2. Literature Review

Drinking water scarcity is a growing global problem, exacerbated by climate change and overexploitation of aquifers. According to Aquae (2024), only 0.007% of the water on Earth is potable, and this percentage is decreasing annually due to pollution. Currently, more than 1.1 billion people lack direct access to safe drinking water, which subjects them to water stress. FAO (2024) defines this phenomenon as a situation in which the demand for water exceeds the quantity available or its use is restricted due to low quality. This stress is driven by population and economic growth, as well as by the degradation of ecosystems, such as overexploited aquifers and dry rivers (Caballero, 2017).

Millions of women and children must travel more than 10 kilometers daily to obtain drinking water. The water crisis not only affects people's health and well-being but also poses serious challenges for agriculture and economic development. An estimated 1,400 children under the age of five die every day worldwide from diarrheal diseases related to lack of access to safe drinking water or inadequate sanitation and hygiene. Every year, 3.5 million people die from water-quality-related diseases. Ninety-eight percent of these deaths occur in developing countries (UNICEF, 2024).

A person needs at least 500 cubic meters of water per year to lead a healthy and hygienic life. Sadly, in the near future, more than 768 million people worldwide will lack access to drinking water, according to the United Nations Children's Fund (UNICEF, 2024), and it is estimated that by the year 2025, close to 2 billion people will live in countries or regions where water scarcity will be absolute and water resources per person will be below the recommended annual water volume (Melo, 2024). Many of these people live in poverty, in remote rural areas or in urban slums, contrasting with the existence of an asymmetrical in water distribution.

Dynamic systems are applied in the study and strategic management of water for modeling the various complex interactions and the different changes that occur over time in systems related to the vital resource. These models are especially useful for understanding how several factors influence water consumption, production, recycling, and quality (Liu et al., 2024).

Based on the modeling of water consumption dynamics, dynamic systems allow modeling how water consumption varies at different scales (household, city, region). Such models can incorporate factors such as demographics, seasons, consumer behavior and appliance efficiency, allowing the analysis of interdependencies between water consumption and other resources such as energy and food. It is also possible to consider as variables the effects of the implementation of self-producing resource technologies, such as rainwater harvesting and graywater recycling systems (Hu, 2023).

The models integrate various data sources and engineering parameters to analyze the interactions between these elements and predict water movement. Optimizing production and resource management, system dynamics is an essential tool for optimizing production and management of water resources, including water recycling. Predictive platforms allow senior management to plan water consumption as well as adjust production master plans in real time, improving efficiency and reducing resource waste (Sharma et al., 2024).

Technological innovation plays a crucial role in the future of water globally, addressing the challenges of water scarcity and growing demand through advanced and sustainable solutions. Emerging technologies are transforming water management, especially in the context of distribution and reuse systems.

The implementation of SWMS (Smart Water Management Systems) includes IoT sensors, which allow the collection of large volumes of data on consumption, water quality and infrastructure conditions, enabling real-time data analysis (Huang et al., 2025). Control systems are essential to improve the efficiency of water management in urban areas; these systems allow continuous monitoring because the sensors could detect leaks and anomalies in the distribution networks, thus minimizing water losses.

The use of emerging technologies such as Artificial Intelligence and Machine Learning facilitate predictive maintenance tasks and significantly reduce costs.

Water reuse through advanced technologies represents a key strategy for water sustainability to ensure the quality and safety of reused water. Some technologies are Membrane Bioreactors (MBR) that are effective in treating wastewater and producing high quality water suitable for various uses. Advanced Oxidation Processes (AOP) are used to remove difficult contaminants from wastewater, ensuring that reused water meets quality standards. Reverse Osmosis (RO) is crucial for desalination and advanced water treatment, producing high quality drinking water. Nutrient recovery to recover nitrogen and phosphorus from wastewater allows its use as fertilizer, creating a circular system. On the other hand, Edge Computing allows processing data close to the source, reducing latency and improving the responsiveness of water management systems Sharma et al., 2024). These innovations not only optimize processes but also improve energy efficiency and contribute to a more responsible and sustainable use of water resources.

3. Methods

For the development of systemic models, three models will be used, as detailed below, in which simulations of water consumption are carried out over a period of one month focused on an organization of 30 people, in which the aim is to identify consumption patterns and how it can be recycled. In order to formulate water consumption policies to combat water scarcity.

1. SimPy model is a framework (Scheme or framework that provides a base structure for developing software and applications (Universidad UNIR, 2022)) of discrete event simulation based on standard processes and Python.

   The Discrete Event Water Management Simulation model, sets the following Model Inputs:
   • **Water Tank Capacity:** Represents the maximum storage of water available for the organization's consumption
   • **Recharge Rate:** The daily supply of water received by the organization
   • **Daily Demand:** The volume of water consumed by people with random variations.

   Process:
   • Each day, the tank is discharged according to the daily demand.
   • After consumption, the tank is recharged to maximum capacity.
   • If the water level is not sufficient to meet the demand, an event of insufficiency is recorded.
   • If the tank exceeds its capacity during refilling, an overflow is registered.

2. Monte Carlo Simulation Modeling is a technique used to study how a model responds to randomly generated inputs (MathWorks, 2025).

   On the other hand, the Uncertainty Evaluation model was developed, which integrates the following input variables to the previous model:
   • **Demand Variance:** To model random variations in consumption.

   Process
   • A total of 1,000 simulations were performed.

- Each simulation represents the evolution of the water level in the tank for 30 days.
- For each iteration, days with insufficient water and overflow are calculated.

3. System Dynamics Model this model will focus on the dynamics of water flow and accumulation, incorporating factors such as:
   Model inputs:
   - Consumption efficiency, which can be described as savings strategies.
   - Recycling rate based on water recovery and reuse.
   - Evaporation losses or leaks.

Table 1. General Comparison of Models

Feature	SimPy Model	Monte Carlo Model	Dynamic Model
Complexity Level	Under	Medium	Medium - High
Uncertainty Management	Limited	High	Medium
Long-Term Analysis	Limited	Possible	High
Critical Events Identified	Inadequacies / Overflows	Full Range of Scenarios	Impact of systemic changes
Key Applications	Daily Operations	Strategic Management	Comprehensive policies

It is possible to visualize that before running the models, the Dynamic Model is more complex because it is contemplating the efficiency in consumption allowing the establishment of organizational policies in terms of promoting the responsible consumption of water resources (Table 1).

4. Data Collection

The initial conditions of the input variables for running the models are as follows:

- **Storage Tank Capacity:** 10,000 Liters.
- **Recharge rate:** 1,500 liters per day.
- **Daily Demand:** 55 liters per person on an 8-hour workday, considering an organization of 30 people, then, 1,650 liters.
- **Simulation Days:** 30 Days.

5. Results and Discussion

5.1 Numerical Results

The main equation used for the development of the Monte Carlo simulation is as follows.

$$N_{t+1} = N_t + R - D_t$$

Where:

- N_t: $Water\ Level\ of\ the\ Tank\ on\ day\ t.$
- R: Daily recharge rate.
- D_t: Daily demand on day t expressed in liters, modeled as a random variable.

In addition, the following conditions are considered:

1. $If\ N_t >$ Tank Capacity, the level that is adjusted to the maximum capacity that represents an overflow.
2. $If\ N_t < 0$, the tank level is set to 0, indicating insufficient water.

The calculation of D_t includes a random component to model uncertainty in daily demand:

$$D_t = \mu_D + \sigma_D \cdot Z$$

Where:

- μ_D: Average daily demand expressed in liters.
- σ_D: Standard deviation of daily demand.
- Z: ZStandard normal random variable $\left(Z \sim N(0,1)\right)$

The main equation used for the development of the system dynamics model:

$$N_{t+1} = N_t + (Recharge_t - Demand_t - Loss_t)$$

Where:

- $Loss_{t_t}$: Water lost due to evaporation or leaks during the time t.

Demand adjusted for recycling:

$$Demand_t = D \cdot (1 - Recycling\ Rate)$$

Losses:

$$Losses_t = N_t \cdot (Loss\ Rate)$$

5.2 Graphical Results

For the Water Management Simulation, a linear behavior is observed, with the conditions, assuming that the 10,000 liter tank is completely full, and that the daily water consumption in a company organization is 1,650 liters per day, with a recovery rate of 1,500 liters. The company does not run the risk of running out of water in a 30-day period, as can be seen in Figure 1.

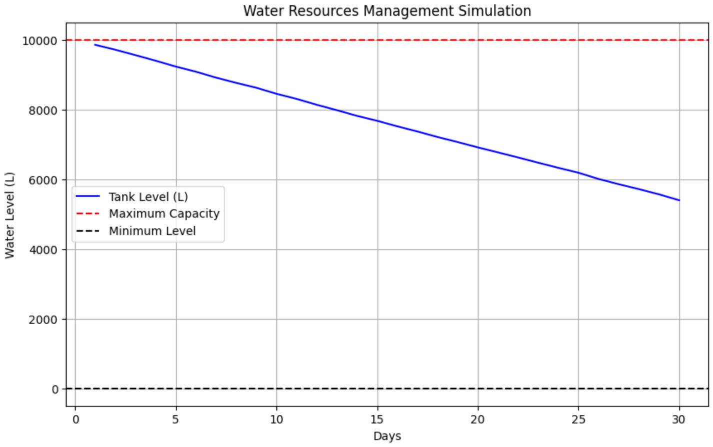

Figure 1. Water Management Simulation

Unfortunately, every day there are water leaks, the water cycle such as evaporation, sometimes people consume more water than they need, that is why model 1 of the water management simulation is insufficient to know the true environment of the organization, more variables should be considered for strategic decision making.

5.3 Proposed Improvements

In order to obtain a better model in which the Monte Carlo Simulation, which allows us to perform iterations to know the behavior of water consumption within organizations, which will facilitate more accurately estimate the consumption, facilitating the formulation of organizational policies to promote savings in water consumption, obtaining as a benefit a significant contribution to Sustainable Development Goal No.6 Clean Water and Sanitation, as well as its ESG commitments.

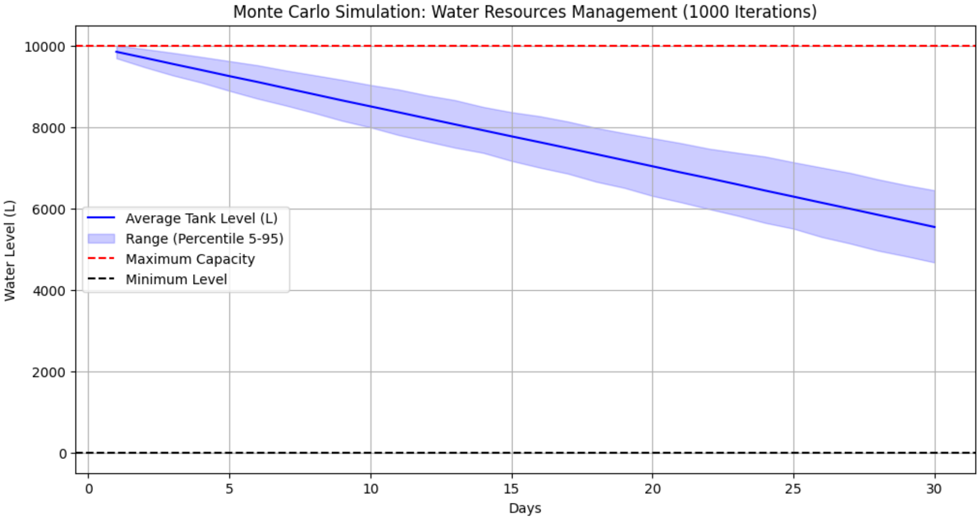

Figure 2. Monte Carlo Simulation

As can be seen in the previous Figure 2, we can visualize that there are already some reductions in water consumption in the blue area, however, there is still a lack of considerations such as the implementation of water recycling policies, evaporation loss, to be a little more precise.

5.4 Validation

The last model, which is already dynamic and includes the random variables that make it complex, is presented below. Assuming that a water recycling strategy is established in which 20% of the water is recycled. And integrating the percentage of loss due to evaporation and leaks, this percentage amounts to 40% in Mexico City according to CONAGUA data (Ramirez, 2024).

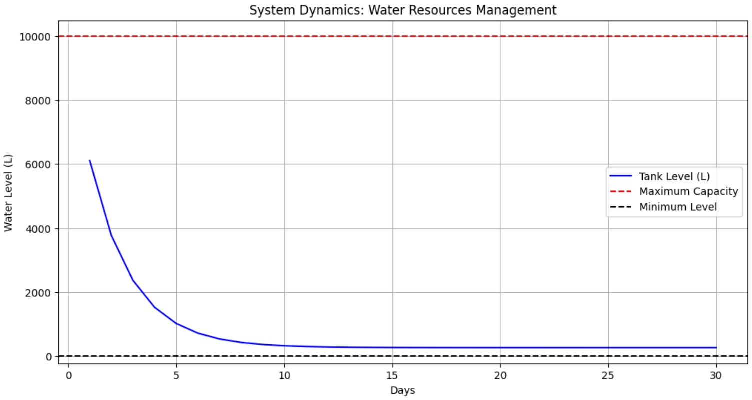

Figure 3. System Dynamics: Water Resources Management

Now it is more realistic the water consumption through the systemic simulation of water resources management (Figure 3), we can determine that the average tank level during the simulation was 756.50 liters, the loss of water due to leaks in Mexico City is very high, even if water recycling policies are implemented, the water tank is barely enough to meet the needs of employees for a month.

6. Conclusion

Each model has a distinct and specific purpose from the point of view of basic operational analysis to uncertainty assessment and comprehensive policy. By developing three models together, a more complete view of the system was provided, as the first two did not consider water loss during supply or the impact of water recycling on the organization.

Increasing the recycling rate and implementing water efficiency technologies can significantly reduce supply shortfalls. Evaporation and leakage loss management is crucial to avoid overflows. Both organizations and taxpaying citizens must demand improvements in water supply infrastructure, as it is unacceptable that nearly half of the resource is being lost.

With the results presented during the state-of-the-art research, technologies such as Membrane Bioreactors, Advanced Oxidation Processes, Reverse Osmosis and Edge Computing are mentioned, senior management should carry out a systemic study to determine which technologies are best suited to their line of business and activities, allowing them to integrate technologies for water recycling. Many of the companies have installed aerators in toilets to reduce water consumption, dry urinals, water recycling for watering green areas, and rainwater harvesting for cleaning activities. These initiatives are important steps towards a more efficient and sustainable use of water.

The integration of technologies such as Membrane Bioreactors, Advanced Oxidation Processes and Reverse Osmosis allows for more effective water treatment, reducing contamination and improving water quality by ensuring that recycled water meets the necessary standards for reuse in various applications, from agricultural irrigation to human consumption.

The implementation of systemic models coupled with advanced technologies has a significant positive impact on sustainable development. These models not only optimize water management but also contribute to achieving several Sustainable Development Goals (SDGs), especially SDG 6, which seeks to ensure the availability and sustainable management of water and sanitation for all.

Integrated water resources management, supported by emerging technologies, strengthens resilience to climate change, better adaptation to extreme weather conditions and ensuring a stable water supply even in adverse situations.

By ensuring access to clean water and adequate sanitation, water-related diseases are reduced, thereby improving the health and well-being of communities, and improving people's quality of life.

Therefore, by combining analytical models with advanced technologies, we achieve not only more efficient water management, but also a move towards sustainable development that benefits both the environment and communities, allowing us to build a future where access to water can be safe and equitable for all.

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Biographies

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