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System Dynamics Approach to Potable Water Management in Eastern Cape Province of South Africa

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Abstract—Water shortage is due to the mismanagement of resources meant to install, operate, and improve water infrastructures. Considering the increase in population and how it affects the water supply and operations of water systems, a management strategy is required to sustain a water supply system for a lengthy period. Hence, the purpose of developing a System Dynamics (SD) model for the water supply chain is to assess water supply systems, enabling a complete understanding of the underlying dynamics and the potential impacts of various interventions in water supply management. The model was applied as a decision-support tool to achieve sustainable water management. It was observed that System dynamics is a suitable approach for comprehending feedback, policy choices, and cause-and-effect interactions. It has been particularly effective in resolving water management issues. SD model for the water supply chain also helped with determining the lengthy period effect of policy alteration on water status. Overall, the development of the SD model was found to be effective in managing water supply systems effectively.

Keywords- *system dynamics, eastern cape, water, infrastructures, water supply, water management, and water access.*

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1 Introduction

One of the most crucial issues humans are experiencing in this twenty-first century is the insufficiency of water, which affects ecosystems, public health, and general welfare [1]. The causes of problems in relation to water are caused by either general water scarcity or poor management [1]. Shortage of water affects socio-economic development across the world. For instance, South Africa is one of the countries that struggle with potable water accessibility. Lack of sanitation in other parts of the county, especially in rural areas, contributes to the challenge of water shortage. Water resource management is a complex activity requiring a comprehensive approach to address many factors impacting water supply and demand [4]. This is because centralized water systems are often not upgraded to handle the growing pressures of population growth, urbanization, and climate change [5].

However, system dynamics modelling is significant in modelling economic systems, emphasizing its ability to represent intricate interactions through feedback loops and delays [1]. System dynamics is pivotal for simulating behaviors in various contexts, including financial institutions, highlighting the necessity for adaptive models that can accommodate the nonlinearities inherent in complex systems [2]. The study engages water supply managers in simulations that reflect the dual nature of these systems, comprising both physical infrastructure and the human elements involved in water management [3]. Also, research studies highlight the complexities arising from numerous variables and the stochastic nature of water inflows, advocating for integrated decision models that encompass technical, environmental, and social dimensions. Their work emphasizes that while optimization techniques are evolving, simulation models remain central to practical reservoir management, reflecting a critical need for tools to navigate water resource systems' intricacies [1,3]. This approach has been employed to tackle a range of water management issues, such as sustainable water planning, performance analysis, risk assessment, and water quality monitoring [4]. One key benefit of system dynamics is its ability to model the feedback loops and non-linear relationships inherent in water systems. By representing the complex interactions between factors like precipitation, runoff, groundwater recharge, and water demand, system dynamics models can simulate the long-term behaviour of water supply systems and identify potential points of intervention [6]. The interlinked nature of the concerns about water has been approached through a SD modeling approach to finding the challenges of the water supply chain. SD models enable the integration of various biophysical, socioeconomic, and policy-related variables, providing a holistic perspective on water resource management [7]. This approach is particularly useful for evaluating the trade-offs and consequences of different water conservation strategies and engaging stakeholders in the decision-making process [8]. SD provides a powerful tool for evaluating water supply systems, enabling a holistic understanding of the underlying dynamics and the potential impacts of various interventions in water supply management.

2 Study Area

The scarcity of freshwater is one of the factors preventing future growth in South Africa. The rural areas of Eastern Cape province of South Africa are the subject of this investigation. Southeast South Africa's Eastern Cape province shares borders with the Western Cape province to the west, the Northern Cape province to the northwest, KwaZulu-Natal province to the northeast, the Free State province and Lesotho to the north, and the Indian Ocean to the southeast, as shown in Figure 1 [9]. With a projected population of 6,676,590 and a land area of 168,966 km2, it is regarded as the second largest province in the nation as of 2021. The climate is generally pleasant at higher elevations in the province's north, although it varies often around the shore [9]. Summers in the province are hot, and winters bring snow to the high Northern mountains [9]. The Eastern Cape is among the most severely affected provinces in the country, where the problem is made worse by antiquated infrastructure and incredibly unskilled water management. It is situated along the southern coast of South Africa and has a population of around seven million, making up 16% (the third largest) of the country's total population [10, 11]. Oliver Tambo, Amatole, Sarah Baartman, Chris Hani, Joe Gqabi, Alfred Nzo, Buffalo City, and Nelson Mandela Bay are the province's eight district municipalities (Figure 1).
Research has shown that approximately 25% of the Eastern Cape population does not have access to clean drinking water, which implies that not all communities in the area have access to clean water 24 hours a day [12]. Access to potable water provides sustainability to agricultural, industrial, household, recreational, and environmental activities, establishing most human water uses.

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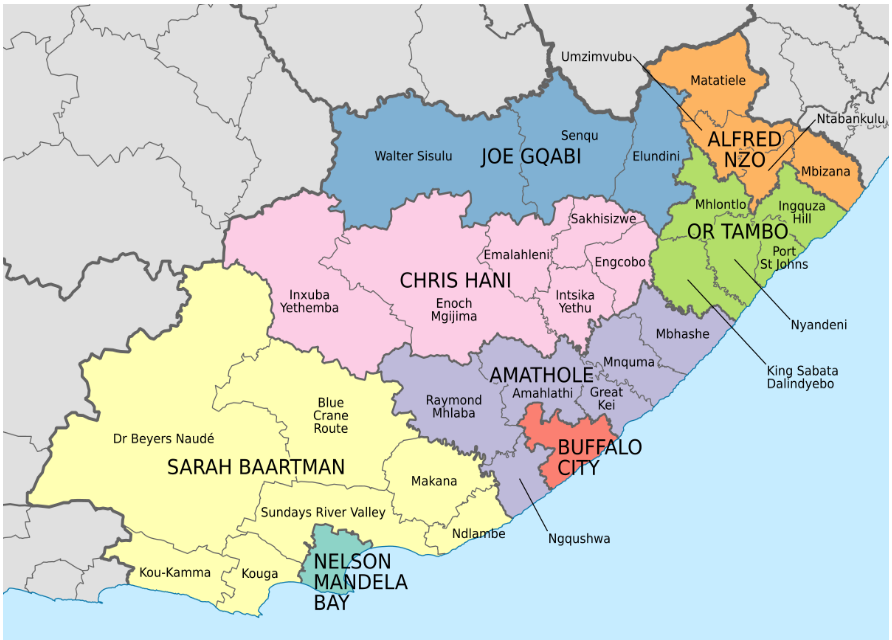

Fig. 1. Map Showing Eastern Cape Province District Municipalities in South African Country Northern [9].

This shortage of clean water in the province is because of the mismanagement of the resources that are meant to install, operate, and improve water infrastructures in the province [13]. Since water resources are complex and interdependent, it is, therefore, difficult to estimate the efficiency of water resource management [14]. Therefore, Effective modeling techniques are crucial for researching and identifying the feedback loops in water resources systems [15, 16]. This research study aims to model the water supply system and identify the types and root causes of water delivery problems. The province should adopt the SD model as a decision-support tool to achieve sustainable water management. SD is suitable for comprehending feedback, policy choices, and cause-and-effect interactions. It has been effectively applied to the resolution of water management issues in particular [11, 17, 18]. (Figure. 1).

3 Method

The research explored the challenges of water access in the Eastern Cape province. Vensim PLE computer software was used to build a computer model based on diagrams of system dynamics. Vensim PLE is a software used for continuous simulation and to produce graphical modelling [11]. This paper introduces the system dynamic approach as a tool for discussing and resolving complicated dynamic issues in the province's water supply and potable water infrastructure management.

The System Dynamics approach effectively solves water problems and ensures the sustainability of the potable water supply through the interaction of local water infrastructures. System Dynamics model is developed in this article to assess the dynamic operations of the water delivery system in Eastern Cape province. The introduction of the System Dynamics model is motivated by the fact that new development and sustainable management of water resources require methods that take into consideration dynamic connections between, among other things, water demand, population, and period effect [19,20,21]. The SD approach can easily solve the delivery of appropriate water service to satisfy human requirements because it helps with the allocation of resources to satisfy the need for water demand. Additionally, the model facilitates the testing of real-world behavior in a synthetic environment [21, 22, 23]. Dynamic simulation examines how a simulated system behaves and reacts to changes over time. Arrows, auxiliary variables, rate, and stock are the components of all SD models [21].

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4 System Dynamics Modeling

The system dynamics model is developed to simulate and study issues related to water supply chain, find solutions for water management, and ensure the sustainability of potable water supply. The model was designed to enhance and secure water supply. Some of the main components of the model include water demand, water catchment, water treatment plants, water recycling systems, and population in the province. In this regard, a 30-year simulation of the water supply system was conducted, beginning in 2021 and concluding in 2051. A casual loop diagram and a stock-flow diagram are used to illustrate the system's dynamics concepts. The causal loop diagram, shown in Figure 2, illustrates the positive and negative causation linkages between population growth, the demand for water, and other factors influencing potable water supply. Understanding system behaviors is aided by the causal loop diagram, which promotes further research into system dynamics techniques to increase their usefulness in a variety of fields, including water supply management [5].

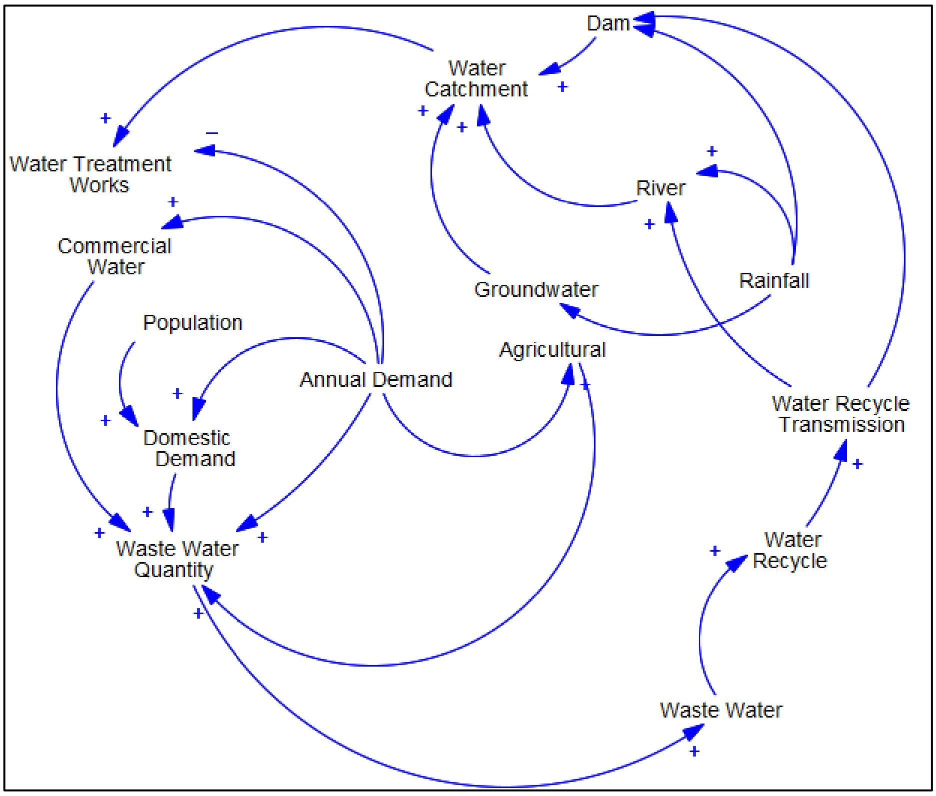

Fig. 2. Casual loop diagram presenting factors contributing to the water supply systems.

The purpose of the stock-flow diagram in Figure 3 is to show how many factors affect the availability and scarcity of water supplies. This analysis of the literature shows a distinct path for applying system dynamics to water supply systems, highlighting the evolution of thought from foundational modelling principles to contemporary integrated approaches that address the complexities of water resource management.

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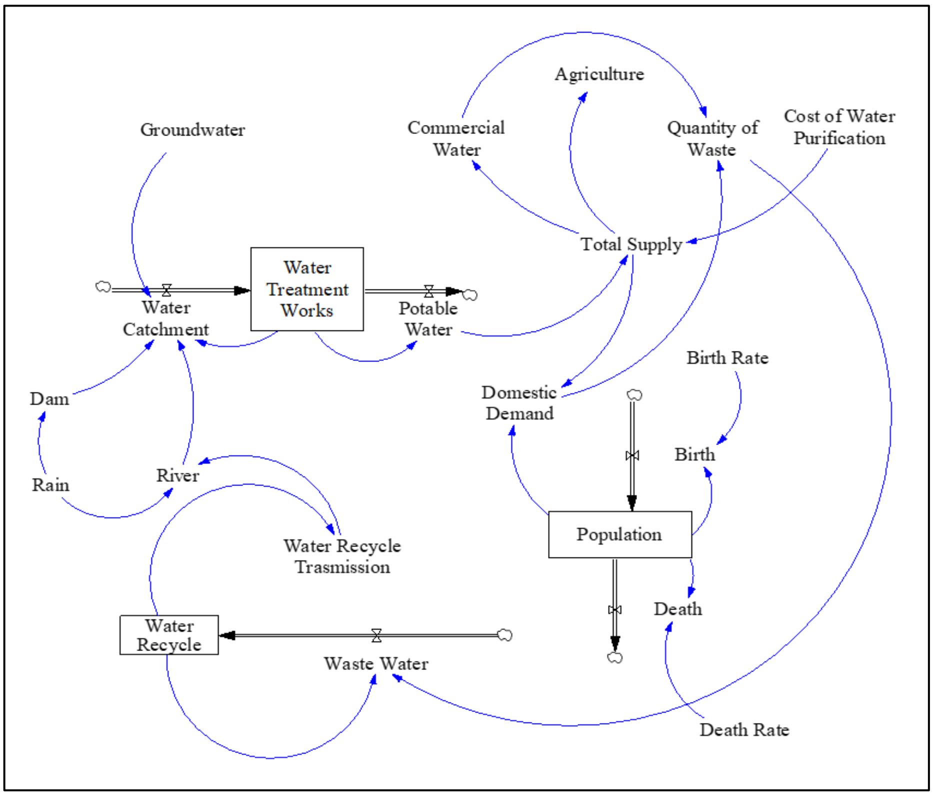

Fig. 3. Stock and Flow Diagram of Water Supply for Eastern Cape Province

5 Results and Discussion

The behaviour in Figure 7 shows the declining trend of domestic water demand, this is due to the increase in population. It is also known that population increase affects the agricultural and commercial sectors; hence, this study focuses on water supply. The total water supply depends on the amount of water from the Water Treatment Works (WTW). It can be seen in Figure 4 that an increase in water being treated increases the total water supply, as shown in Figure 5.

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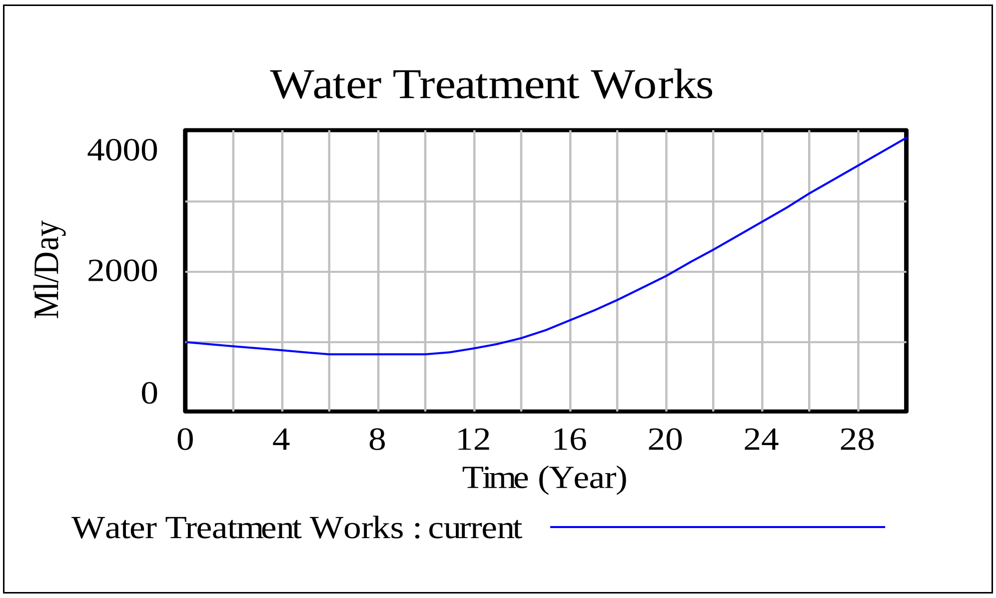

Fig. 4. Simulation Results of Water Treatment Works

In general, an increase in the water supply will also increase the amount of water supply to the agricultural and commercial sectors. On the other hand, the growing population (Figure 6) causes a decline in domestic water demand, as seen in Figure 7. These pose a challenge to water consumers, and if there is no continuous improvement and upgrade of the water systems, there is a risk of water shortage. For this reason, the System Dynamics (SD) model is crucial to help the local municipalities in the province to accurately estimate the amount of water required based on the population increase rate.

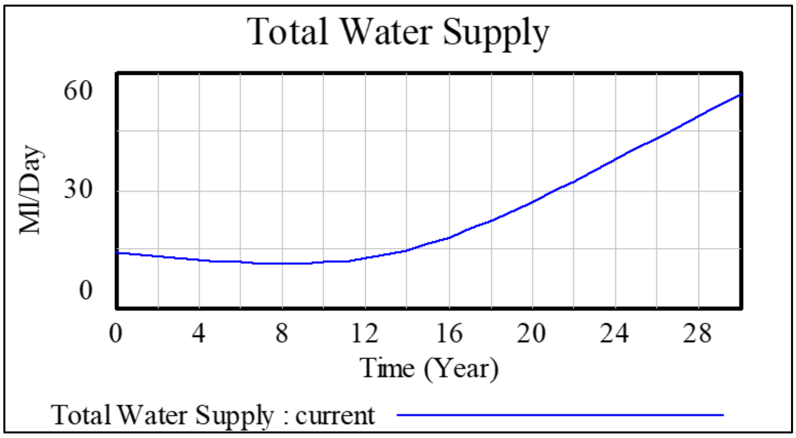

Fig. 5. Simulation Results of Total Water Supply

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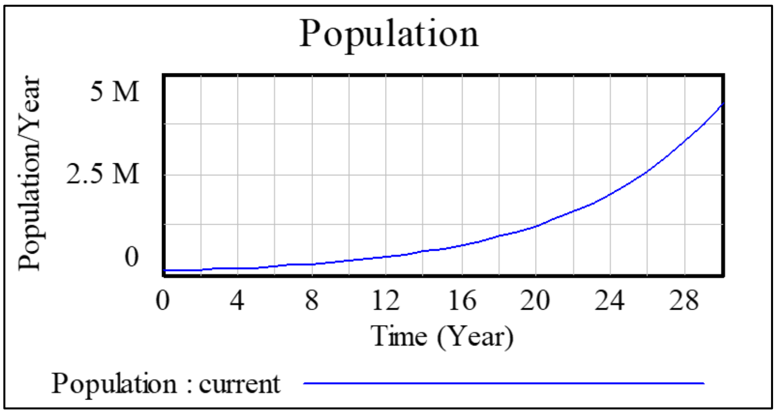

Fig. 6. Simulation Results of Population Rate per Year

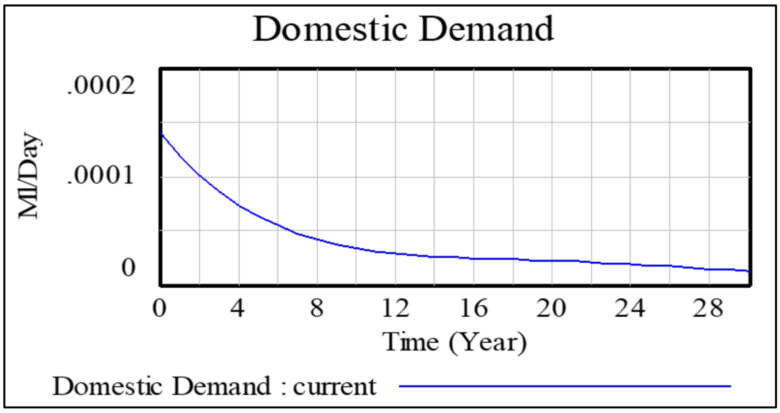

Fig. 7. Simulation Results of Domestic Water Demand

6 Conclusions

In this paper, an SD simulation model was developed to estimate the long-term effect of water supply in Eastern Cape province based on the causal response relationship between population, water demand, and water supply. The result of the simulation model provides a good indicator to the decision-maker on the management of risk of the water system and water distribution networks as the population increases over 30 years. The results show that SD provides a powerful tool for evaluating water supply systems, enabling a holistic understanding of the underlying dynamics and the potential impacts of various interventions in water supply management. SD was enough to develop efficient strategic management for water sustainability. It has been found that with the increase in population, water demand for residential, commercial, and agricultural can be efficiently managed through the development of the SD model. The Eastern Cape has one of the fastest-growing rates of population increase; thus, the SD model for the water supply chain could be used to determine the long-term effect of policy change on the status of water in the province. In addition, the research showed that the SD methodology can help the local government of Eastern Cape province to estimate the amount of water required by its rapidly growing population. The model will also help the local communities from dislocation in their water supply, which shall help in the formation of policy and resource allocation. The result of the optimal allocation model provides a good indicator to the decision-maker on the risk of the water system, water distribution networks, and the cost of the water system. The simulation models could be used as starting points for further research into water management; the models can be improved by incorporating actual data into them. The model can be extended to include more aspects of the water management supply chain, depending on the complexity of the problem being studied.

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