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An Integrative Approach to Regional Water Resource Management in Kebumen, Indonesia Through Dynamic Systems Modeling

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ABSTRACT

Kebumen Regency in Central Java faces significant challenges in water resource management due to imbalances between availability and demand, agricultural dominance in water usage, and inadequate infrastructure. This study employs an integrative approach using dynamic systems modeling to analyze and design sustainable water management strategies. The research identifies key variables—such as rainfall, river discharge, agricultural land use, and population growth—and constructs causal loop and stock-flow diagrams to simulate various management scenarios. Simulations reveal that adopting low-water-requirement food crops significantly enhances water sustainability, whereas increased rainfall does not improve supply due to infrastructure limitations. The findings highlight the need for integrated policies, infrastructure development, and adaptive-holistic management to address future water challenges. This study underscores the importance of demand-side strategies, particularly in agriculture, to ensure long-term water resource resilience in Kebumen.
Keywords: *System Dynamics, IWRM, SDG, Water Management, Scenario Analysis*

INTRODUCTION

Water is one of the most vital natural resources for life and sustainable development. Although water covers about 71% of the earth's surface, only about 2.5–3% of the total water is freshwater, and less than 1% is truly accessible for daily human needs, both for consumption, agriculture, and industry (Gleick, 2020; Mekonnen & Hoekstra, 2016). This limitation makes clean water a very valuable commodity, especially with the fact that more than 2 billion people in the world still do not have access to safe drinking water (WHO & UNICEF, 2021; Bain et al., 2014). In Indonesia, although access to decent clean water has reached more than 90%, the challenge of providing safe and quality drinking water is still a significant issue (Hadipuro, 2010; Putri et al., 2023; Susanti & Pratiwi, 2022).

The problem is increasingly complex along with the increasing demand for water due to population growth, industrialization, and expansion of the agricultural sector (Falkenmark, 2013). According to the World Bank (2022), nearly two-thirds of the world's population experiences water shortages for at least one month of the year, and more than 2 billion people do not have access to safely managed drinking water (UN Water, 2024). In *Indonesia*, uneven water distribution, pollution, and rapid population growth pose major challenges in the provision of clean water, even though the country has a freshwater potential of around 3,400 billion m^3 per year (Ministry of PUPR, 2023). The high dependence on the agricultural sector is also reflected in the national water use pattern, where around 68% of water is used for agriculture, 21% for industry, and 11% for domestic needs (BPS, 2023; Ministry of Public Works and Housing, 2024).

One of the main challenges in water resource management in Indonesia is water pollution that is getting more serious. The Ministry of Environment and Forestry reports that about 60% of Indonesia's rivers have been polluted due to domestic, industrial, and agricultural waste. This has an impact on declining water quality and increasing risks to public health and ecosystem sustainability (MoEF, 2023). Several studies emphasize that urbanization, lack of waste treatment facilities, and poor environmental governance are major contributors to the degradation of water bodies in developing countries including Indonesia (Setiawan et al., 2021; Saputra & Lee, 2022). In addition, climate change, which is characterized by extreme rainfall fluctuations and prolonged droughts, has also exacerbated the uncertainty of water availability in various regions, including in Kebumen Regency (Handoko & Nugroho, 2020; Susilawati et al., 2023; Oktaviani et al., 2021).

Kebumen Regency is one of the regions in *Indonesia* that faces the challenge of complex water resource management. High dependence on irrigation water for agriculture, limited water storage and distribution infrastructure, and the threat of pollution and climate change require more integrative and adaptive management solutions. Conventional approaches that are sectoral and fragmentary have proven to be less effective in responding to the changing dynamics of water demand and availability. Therefore, an integrated, adaptive, and data-based approach to water resource management is needed, one of which is through dynamic system modeling that is able to comprehensively simulate the interaction between hydrological, social, economic, and environmental variables (Sterman, 2000; Chaves & Alipaz, 2007).

The formulation of the problem in this study is how to develop an effective and sustainable regional water resource management strategy in *Kebumen* by utilizing dynamic system modeling as a policy analysis and simulation tool. The main problems identified include imbalances between water availability and demand, pressure from the agricultural sector as the main user, pollution of water resources, and limited water storage and distribution infrastructure.

The purpose of this research is to develop a dynamic system model that can simulate various water resource management scenarios in *Kebumen* in an integrative manner. Through this approach, it is hoped that the most effective and sustainable management strategies can be identified to maintain a balance between water availability and demand, as well as support evidence-based policy formulation in regional water resource management.

METHOD

This study uses a case study approach with a research location in *Kebumen Regency*, *Central Java*. The subject of the study is a regional water resource management system involving hydrological, social, economic, and environmental variables. The materials studied included secondary data related to rainfall, river discharge, agricultural land use, demographic data, as well as water quality and distribution data from government agencies and other official sources.

The main tool used is dynamic systems modeling software (*Vensim*), which is utilized to build and simulate models. The research design is based on a dynamic system method, consisting of the preparation of a *causal loop diagram* (*CLD*) and a *stock-flow diagram* (*SFD*) to map the interaction between the main variables. The data collection technique is carried out purposively, by selecting secondary data that is relevant and valid for modeling needs.

The variables measured in this study include: water availability (river discharge, rainfall), water demand (area of agricultural land, population), as well as sustainability and water quality indicators. Data processing techniques include the collection, verification, and analysis of secondary data, as well as the calibration of model parameters based on historical data and related literature. The developed dynamic system model is then validated using actual data and sensitivity tests to changes in key variables.

The analysis was carried out by simulating various water resource management scenarios, such as the development of low-water food crops, increasing irrigation efficiency, and adapting to changes in rainfall. The results of the simulation were analyzed descriptively and comparatively to assess the impact of each strategy on the sustainability of water availability. The statistical model used in this study is sensitivity analysis and validation of scenario-based dynamic system models.

RESULTS AND DISCUSSION

The dynamic system model developed in this study maps the interaction between the main variables that affect water availability and demand in Kebumen Regency. Variable identification is carried out based on hydrological data, land use, population growth, and the needs of the agricultural and domestic sectors. The relationships between variables are visualized in the form of a cause-and-effect diagram to identify feedback patterns that affect system dynamics.

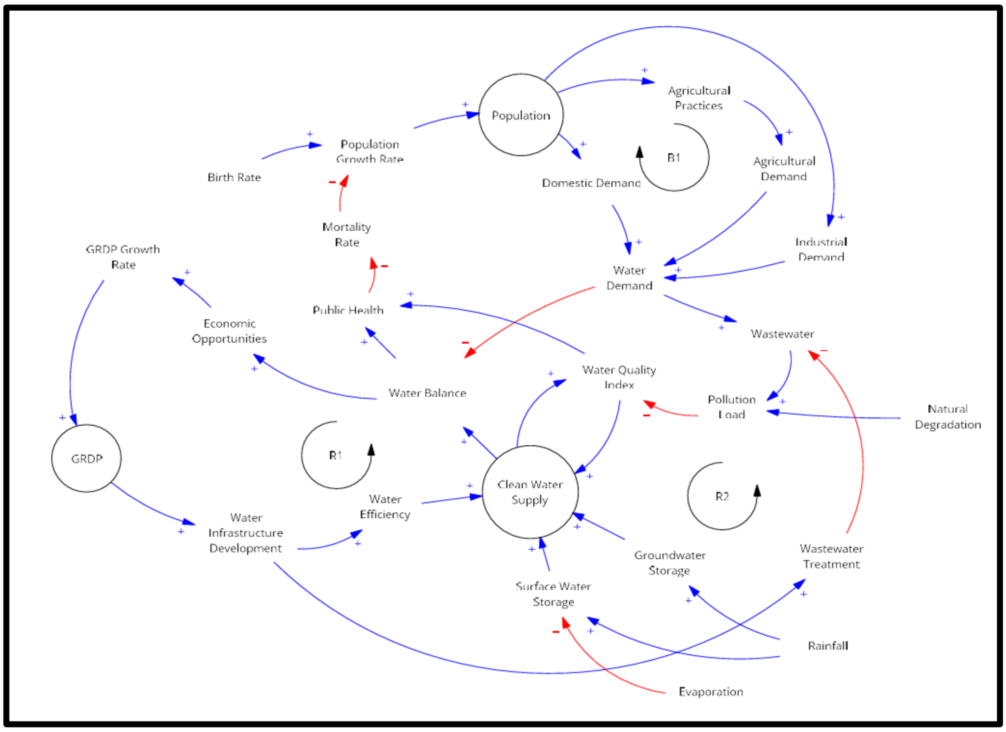

Figure 1. Causal Loop Diagram Depicting Interactions in Kebumen Water Management System

The Causal Loop Diagram (CLD) that has been presented illustrates the dynamic structure of the water resource management system in Kebumen with the Local Governor as the main problem owner. This model receives inputs in the form of population, water demand, water supply, and Gross Regional Domestic Product (GDP), all of which directly or indirectly affect the condition of the system. The main outputs of this system are water availability, clean water supply, and water quality, which are indicators of the success of water resource management in the study area.

In this CLD, there are several feedback loops that interact with each other. Reinforcing Loop 1 shows that economic growth, which is reflected in an increase in GRDP, can encourage investment in water infrastructure and technology, thereby supporting the overall water balance. Balancing Loop 1 illustrates that population growth will increase water demand, which in turn can depress water availability if not offset by increased water supply or efficiency use. Meanwhile, Reinforcing Loop 2 highlights the role of water quality in encouraging infrastructure investment. The better the quality of the water produced, the greater the incentive to increase investment in sustainable water management infrastructure.

The structure of this CLD shows how the dynamics between economic growth, population growth, and water quality affect each other in the water resource management system. The identification of these key loops is the basis for determining strategic intervention points to improve the effectiveness and sustainability of water management at the regional level.

The analysis was followed by quantitative modeling using Stock and Flow Diagram (SFD). The SFD model in this study is divided into five main subsystems: Population Subsystem, Water Supply Subsystem, Water Demand Subsystem, Economy Subsystem, and Water Quality Subsystem. Each subsystem is designed to represent the dynamics and interactions between key variables in a structured manner.

The Population Subsystem describes changes in population that directly affect water demand. The Water Supply Subsystem models water availability as affected by factors such as rainfall, infrastructure capacity, and distribution efficiency. The Water Demand Subsystem captures the dynamics of water demand for various sectors, especially agricultural and domestic, and its impact on regional water balance. The Economy Subsystem attributes economic growth (GRDP) to investment in water infrastructure and its effect on the overall capacity of the system. Meanwhile, the Water Quality Subsystem maps the relationship between economic activity, land use, and pollution levels to the quality of available water.

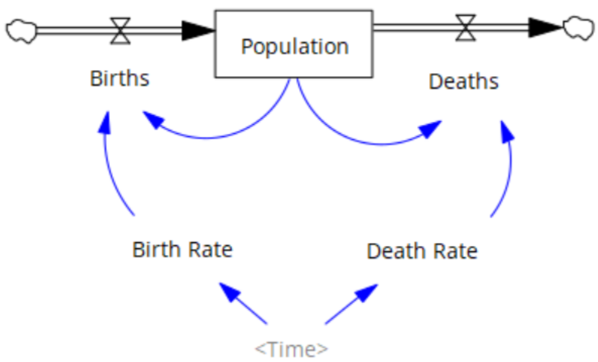

Figure 2. Population Subsystem

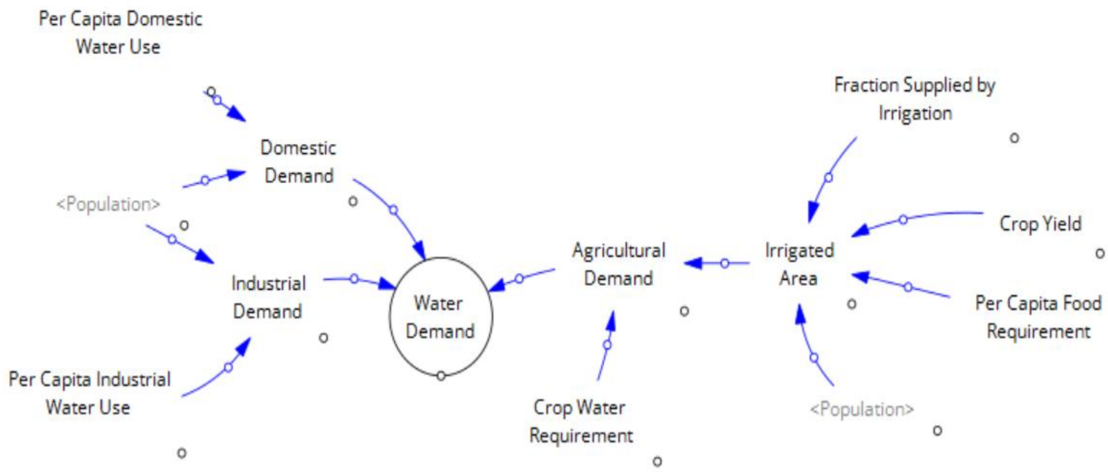

Figure 3. Water Supply Subsystem

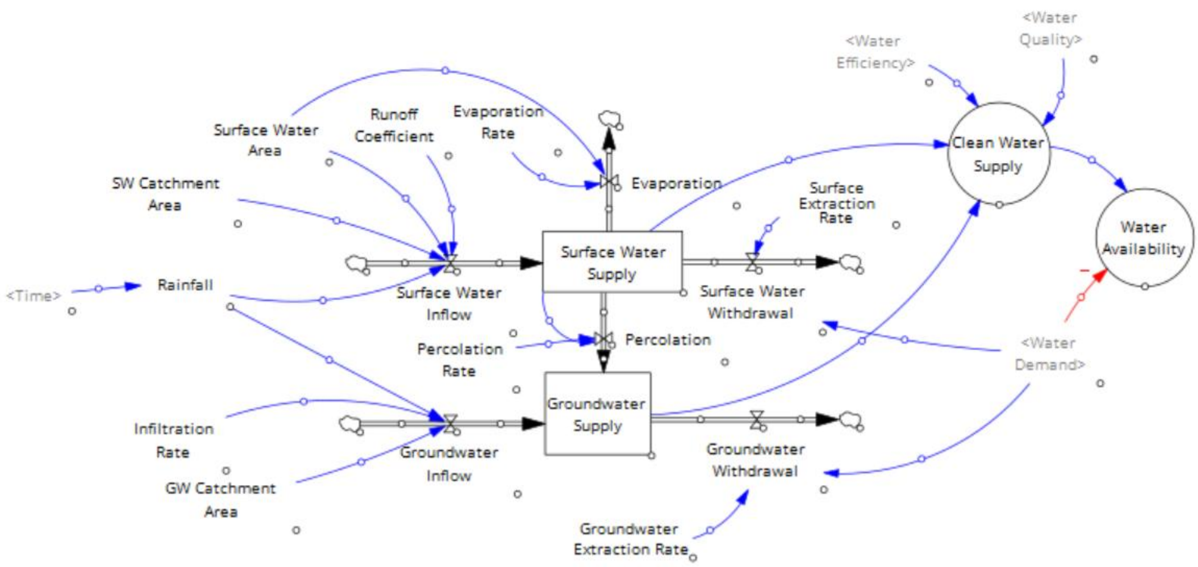

Figure 4. Water Demand Subsystem

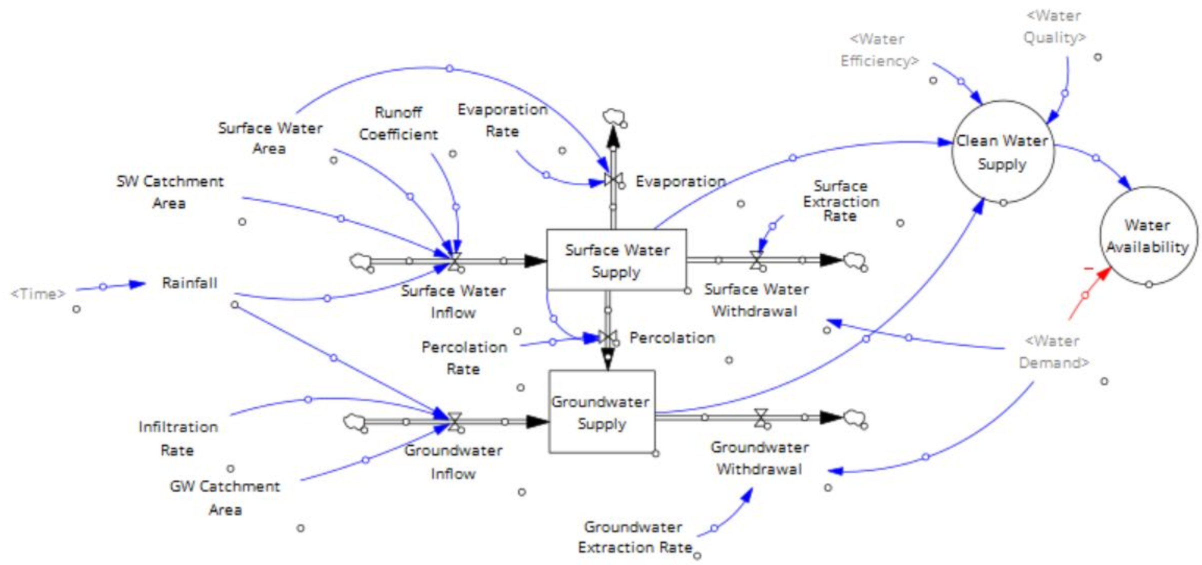

Figure 5. Economy Subsystem

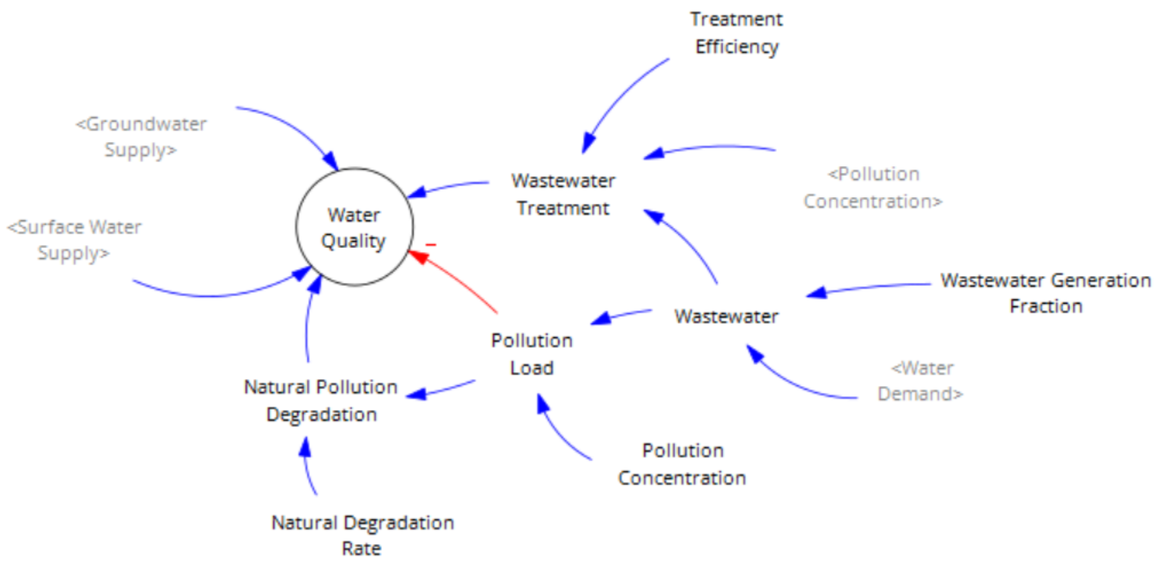

Figure 6. Water Quality Subsystem

Dynamic system model simulation was carried out to describe the behavior of the water resource management system in Kebumen under various conditions. Each of the subsystems that has been described—population, water supply, water demand, economy, and water quality—interacts with each other and forms complex dynamics in the system as a whole.

The baseline (status quo) scenario is used as a reference, describing the state of the system without new policy intervention. The second scenario simulates a decrease in rainfall as a result of extreme climate change, which shows a significant decrease in water availability and clean water supply. The third scenario evaluates the impact of high population growth, which leads to a surge in water demand and pressure on the distribution system and water quality. The fourth scenario focuses on increasing industrial pollution, showing the degradation of water quality and the need to strengthen sewage treatment infrastructure. The fifth scenario tests the impact of prolonged droughts, which exacerbate water deficits and lower the system's sustainability index. Finally, the worst-case scenario combines multiple risk factors at once to assess the overall resilience of the system.

CONCLUSION

The conclusion of this study emphasizes that the strategy of using food crops with lower water requirements than rice has the most positive impact on water availability in *Kebumen Regency*. The simulation results show that diversification of planting patterns to more efficient commodities in water use can significantly reduce the pressure on regional water resources, thereby increasing the system's resilience to demand fluctuations and potential drought. In contrast, increased rainfall does not automatically increase water availability, as the water supply capacity in the study area has reached its maximum limit. This indicates that demand management through changes in planting patterns is more effective than relying solely on increasing supply from external factors such as rainfall. Thus, focusing on adaptation strategies on the demand side, especially through the selection of water-efficient agricultural commodities, is the main key to realizing sustainable and resilient water resource management in *Kebumen*.

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