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Scenario-Based Dynamic Modeling for Urban Settlement Management

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Abstract. The growth of residential areas in peri-urban regions of metropolitan areas such as Jabodetabek demonstrates high complexity due to the dynamic interaction between population growth, land use, and environmental degradation. This study aims to develop a dynamic system-based simulation model using a scenario approach to analyze sustainable residential area management policies. The scenarios were developed consists of no intervention, pessimistic, moderate, and optimistic based on parameters such as local government commitment, regional capacity improvement, and the rate of incoming migration. The simulation results indicate that the optimistic scenario is the most effective in controlling population size (a reduction of 29.14%), limiting residential expansion (a 58.57% decrease in the settlement area ratio), and improving the quality of the physical environment (a 95.18% increase) by the year 2040. The findings recommend strengthening spatial planning policies through enhanced cross-sectoral coordination, vertical housing development, and migration control. Although the model has limitations due to its assumption of a fixed system and the exclusion of external dynamics, this research provides valuable insights for the development of dynamic system-based policies in the sustainable planning of complex metropolitan regions.

Keywords: dynamic simulation, urban system modeling, sustainable settlement area, periurban development, land-use control

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1. Introduction

Peri-urban areas in metropolitan areas are experiencing rapid growth pressures as a result of the physical expansion of the main city and increased demand for residential space [1]. This phenomenon, known as urban sprawl [2], has become a key feature of the development of large metropolitan areas such as Jabodetabek. Peripheral areas often develop sporadically, unplanned and beyond administrative boundaries, making coordination and integration in spatial management difficult [3].

The development of peri-urban areas in various urban areas in Indonesia shows complex dynamics and is often not in line with established spatial planning [4]. Despite various policies and development plans, many peri-urban areas have experienced failures in spatial control, environmental degradation, land use conflicts, and gaps in the provision of basic infrastructure and services [5]. These failures are generally caused by planning approaches that are static, sectoral, and not adaptive to the changing social, economic, and ecological dynamics in peri-urban areas [6–8].

Studies show that conventional planning approaches that are linear and static are unable to respond to the complex spatial and institutional dynamics in these areas [9,10]. The weaknesses of current planning are evident in unpreparedness for migration flows, weak inter-regional coordination, and degradation of environmental quality [11]. A new approach is needed that captures these complexities in a systemic and dynamic manner. One of them is the dynamic approach based on scenarios [12,13].

In this context, a scenario-based dynamic systems modeling approach offers novelty as a decision-making tool that can capture the complex interactions between components of urban settlement systems. The model allows stakeholders to explore various possible futures based on different assumptions and interventions and evaluate their impacts systemically [14]. The application of scenario-based dynamic models in the context of peri-urban settlement management is still relatively rare in Indonesian literature, even though this approach has great potential to fill the methodological void in more responsive and sustainable urban management.

This research aims to develop a scenario-based dynamic system model that can be used to support settlement planning and management in peri-urban areas. Specifically, the model is designed to: (1) identify cause-and-effect relationships between factors affecting settlement dynamics, (2) simulate the impact of various policy scenarios, and (3) provide system-based strategic recommendations for sustainable settlement management.

2. Methods

This research was conducted in the periphery of Jabodetabek, focusing on Gunung Putri Sub-district (Bogor Regency), Cimanggis and Tapos Sub-districts (Depok City), and Jatiasih Sub-district (Bekasi City). These areas were chosen because they show the most significant symptoms of urban sprawl, characterized by rapid settlement growth along the main corridors (toll roads), and are the main buffer zones of Jakarta's metropolitan expansion. These areas also cross administrative boundaries between regions making them strategic locations to evaluate the complexity of settlement management across regions.

2.1 Data Sources and Types

The data used consisted of primary and secondary data. Primary data was obtained through in-depth interviews and focus group discussions (FGDs) with officials in the local governments of Bogor, Depok and Bekasi. Secondary data came from spatial plan documents, population statistics, and environmental reports from relevant agencies.

2.2 Dynamic Model Developement

The dynamic model was developed using Powersim Studio software, using a scenario-based dynamic system approach. Four main sub-models were derived from the identification of problems and key variables through literature analysis, field studies, and discussions with stakeholders:

a) Population Sub-model: Represents population dynamics based on births, deaths, in-migration and out-migration. The selection of this variable is based on the fact that population pressure is the main driver of settlement expansion.
b) Settlement Land Sub-model: Describes the change in land use from non-developed to residential areas, which is influenced by space requirements due to population growth and market pressure.
c) Physical Environment Sub-model: Assesses the impact of settlement growth on environmental quality through indicators such as density, waste volume, flooding, and impervious area.
d) Institutional Sub-model: Reflects the level of commitment of local governments in managing space, including coordination, policy consistency, and spatial control.

These four sub-models were organized into Causal Loop Diagrams to map the cause-and-effect relationships between variables and further developed into Stock and Flow Diagrams as the basis for the computational model.

2.3 Parameter and Assumption Setting

Parameters in the model are set through a combination of empirical data and assumptions validated through consultation with experts. For example:

a) The migration rate (5.1% at baseline) was obtained from local population data and BPS projections, as migration is a major contributor to population growth in peri-urban areas.
b) Local government commitment (42.3%) is measured based on a composite index of involvement in cross-regional planning, existence of regulations, and frequency of inter-agency coordination.
c) Regional capacity is measured by the availability of basic infrastructure and environmental carrying capacity.

Scenario simulations were conducted over a 20-year period (2020-2040) to compare the impact of policy interventions on key indicators: population, settlement area ratio, and environmental quality.

2.4 Model Validation

Model validation was conducted using two main statistical metrics:

a) Absolute Mean Error (AME): Measures the absolute mean deviation between simulation results and actual data.
b) Absolute Variation Error (AVE): Measures the absolute variation deviation between the model and reality.

Both metrics were chosen because they provide a simple yet informative measure of accuracy, and have been used extensively in dynamic systems studies. The tolerance threshold was set at 5-10%, and the test results showed that the AME and AVE values were within reasonable limits (AME = 0.0047 and AVE = 0.0086 for population; AME = 0.0284 and AVE = 0.0436 for settlement area).

2.5 Simulation Logic and Sub-Model Interdependencies

Simulations were conducted with intervention scenarios on three main parameters: in-migration rate, local government commitment, and regional capacity building. These three parameters were chosen because they have a direct effect on all sub-models:

a) Population growth affects land demand and environmental pressures.
b) Government commitment affects the ability to control spatial change.
c) Regional capacity determines the ability of infrastructure to support growth.

By setting these parameters in pessimistic, moderate and optimistic scenarios, the model can evaluate the system response holistically and identify the best policy strategies.

3. Results and Discussion

3.1 Results

The dynamic model developed consists of four integrated sub-models: population, residential land, physical environment, and institutions.

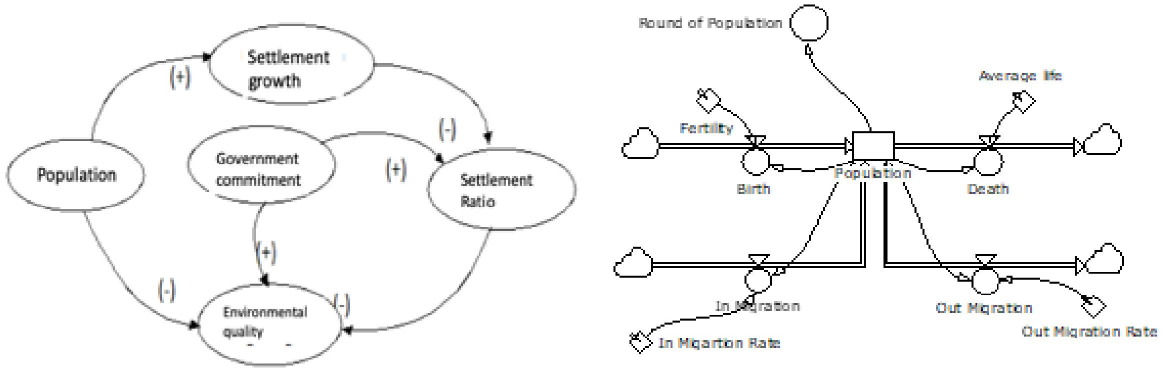

Figure 1. Causal Loop Diagram and Dynamic Model Population Sub model

Figure 1 shows the dynamics of population growth in the study area, which is influenced by the main factors of birth, death, in-migration, and out-migration. These components form a causal cycle that affects the total population as a whole. A surge in population, especially from in-migration, triggers an increase in demand for land and infrastructure. In this context, the population sub-model is the starting point of pressure on the settlement system and directly affects other sub-models.

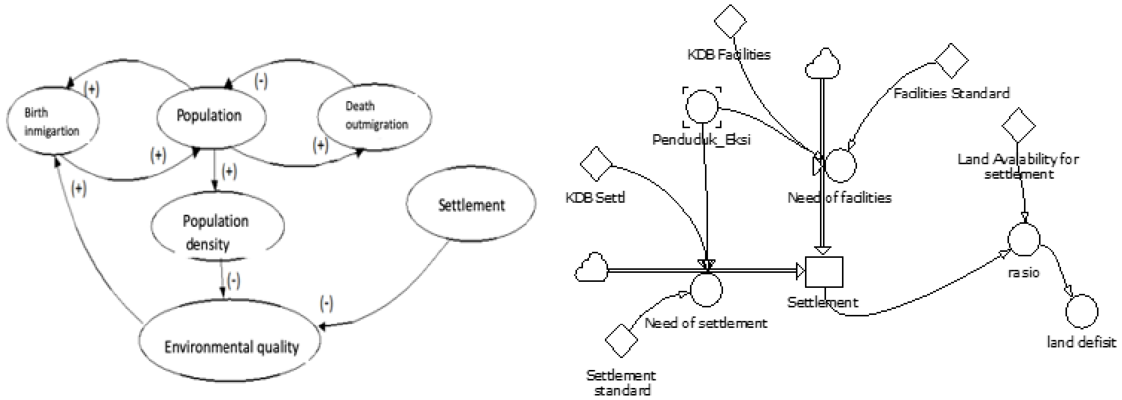

Figure 2. Causal Loop Diagram and Dynamic Model of The Settlement Land Sub-model

The residential land sub-model in figure 2 visualizes how residential land demand increases in response to population growth. As the population grows, the need for residential space increases, which drives the expansion of built-up areas. The causal diagram shows a positive relationship between population growth, land demand and land conversion. Without policy intervention, this process will continue, leading to uncontrolled spatial expansion (urban sprawl) and contributing to environmental degradation.

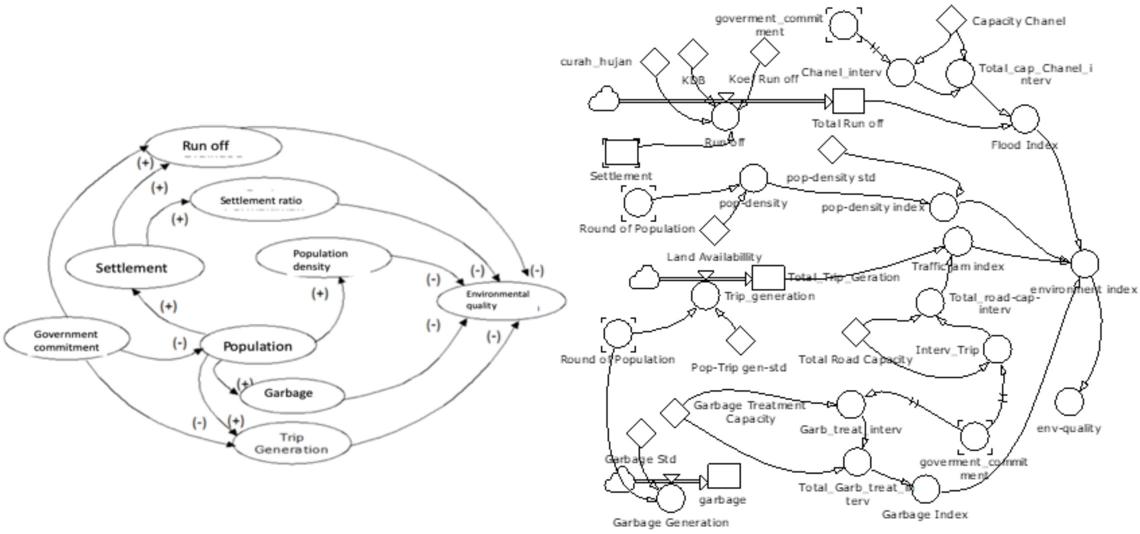

Figure 3. Causal Loop Diagram and The Dynamic Model of The Environmental Sub-model

Figure 3 illustrates the impact of settlement growth on the quality of the physical environment. The increase in built-up area results in an increase in sewage, population density, impermeable surfaces, as well as the volume of water runoff that results in flooding and pollution. The diagram confirms the negative relationship between settlement growth and environmental quality. This sub-model shows that without control, the accumulated pressure on the environment will significantly reduce the carrying capacity of the region.

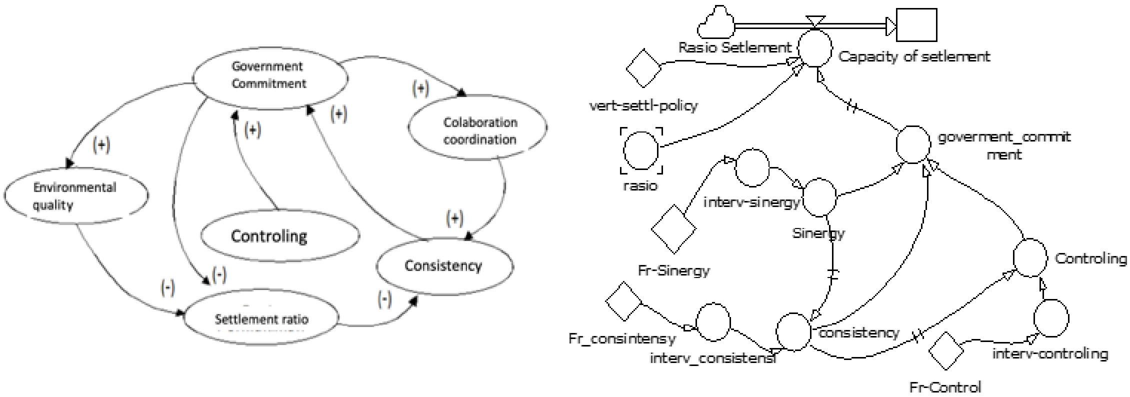

Figure 4. Causal Loop Diagram and Dynamic Model of the institutional Sub-model

The institutional sub-model maps the critical role of coordination between local governments, consistency of spatial planning implementation, and effectiveness of development control in mitigating the negative impacts of settlement growth. The figure shows that increased institutional commitment will inhibit the rate of land conversion and encourage the adoption of sustainability-based policies. The relationship between institutional policies and other variables in the system confirms the importance of institutional interventions in creating a resilient and controllable settlement system.

Table 1. Validity Results

	AME	AVE
Population Element	0,0047	0,0086
Residential Area Element	0,0284	0,0436

The results of the validity test of the model's performance indicate that the Average Mean Error (AME) and Average Variance Error (AVE) values for the population element were 0.0047 and 0.0086, respectively, while for the residential area element, the AME was 0.0284 and the AVE was 0.0436. These values fall within the acceptable deviation threshold of less than 10%, indicating that the model is well-calibrated and able to accurately represent real-world conditions. This demonstrates that the dynamic model can simulate actual changes occurring in the field, particularly in the context of residential area management.

Model simulations were conducted to explore potential policy options through a functional approach where the structure of the model remains constant but parameters are modified, assuming a fixed system environment. Scenarios were developed by simulating interventions on specific parameters such as coordination and cooperation, consistency and control in spatial planning (as indicators of local government commitment), implementation of vertical housing development (as a reflection of regional capacity enhancement), and the rate of incoming migration (as a population control indicator). These interventions were categorized into three scenarios: pessimistic, moderate, and optimistic, each representing different levels of policy intensification. Table 1 outlines the intervention values for each parameter under the various scenarios.

Table 2. Model Parameter Intervention Scenarios

No.	Parameter intervention	Without Intervention (%)	Pessimistic Scenario (%)	Moderate Scenario (%)	Optimistic Scenario (%)
1.	The rate population migrasi	5.1	5	4	3
2.	Local Government Comitment	42.3	60	80	100
3.	Increase in area Capacity	0	0	20	20

The simulation results yield key indicators for the management of settlement areas in the study region, specifically targeting improvements in population size, settlement area ratio, and the quality of the physical environment. The intended outcome of these simulations is to achieve controlled population growth, a balanced settlement area ratio, and a reduced rate of environmental degradation. Scenario-based models for settlement management in the year 2040 present varying outcomes for these indicators, demonstrating how different intervention strategies can lead to significantly different conditions in terms of population control, land use efficiency, and environmental sustainability.

Table 3. Sustainable Settlement Area Management Model Scenario in Year 2040

No	Settlement area	Year	Scenarios of year 2040			
	Management Indicators	2020	Without intervention	Pessimistic	Moderate	Optimistic
1.	Total Population	877.389	1.891.985	1.891.389	1.598.525	1.340.604
2.	Environmental Quality	85.75	41.53	47.27	70.02	81.06
3.	Settlement area Ratio.	81.14	223.46	223.46	110.35	92.58

Table 3 illustrates that the three scenarios produce varying conditions for the study area in 2040, primarily influenced by differences in population growth. Under the optimistic scenario, population growth can be effectively controlled, with the total population projected at 1,340,604 by 2040—a significant reduction compared to the scenario without intervention and other intervention scenarios. This scenario also minimizes land consumption, as indicated by the lowest settlement area ratio of 92.58. Additionally, the optimistic scenario contributes to slowing the decline in environmental quality, achieving a projected environmental quality score of 81.06 in 2040, the highest among all scenarios. Based on these outcomes, the relative impact of each scenario is evaluated and ranked according to its effectiveness compared to the baseline (no-intervention) scenario.

Table 4. The Impact of Sustainable Settlement Area Management Based on Three Scenarios is Compared with The Scenario Without Intervention

No	Settlement area Management Indicators	Scenarios Year 2024		
		Pessimistic	Moderate	Optimistic
1.	Total Population	0	15.51	29.14
2.	Environmental Quality	17.82	68.6	95.18
3.	Settlement Area Ratio	0	50.61	58.57
sequence of scenarios with the greatest impact		3	2	1

The simulation results from the three scenarios indicate that the optimistic scenario is the most suitable strategy for managing settlement areas in the peri-urban regions of the Jabodetabek Metropolitan Area, particularly in light of existing challenges. The development of this scenario is based on the principle of enhancing local government commitment through improved coordination, consistency, and control in spatial planning. A gradual and comprehensive strengthening of local government involvement plays a critical role in enhancing the performance and functionality of settlement areas. This is evidenced by a 95.18% reduction in the rate of environmental degradation, a 58.57% improvement in settlement area ratio control, and a 29.14% decrease in population growth. For comparison, Figure 5 presents the graphical simulation outcomes for all three scenario models.

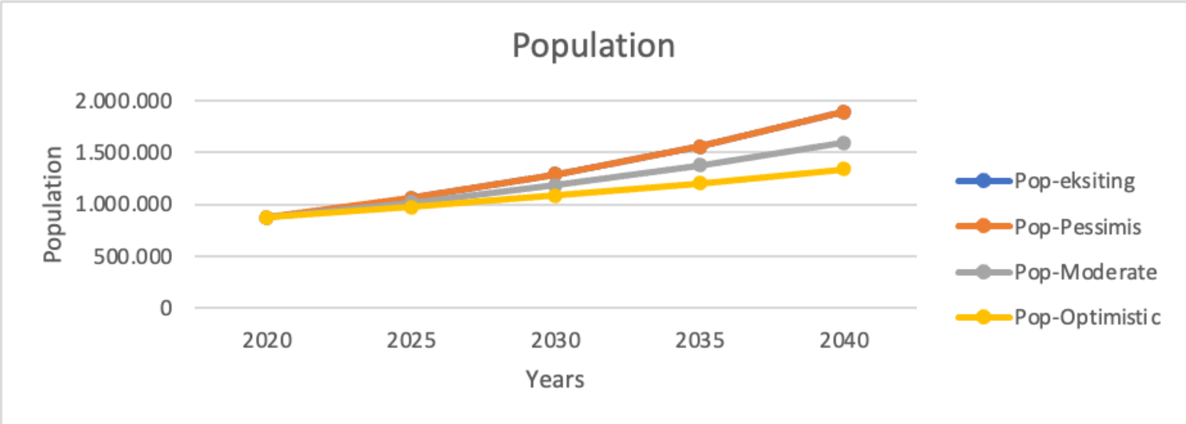

Figure 5. Simulated Population by Scenario

This graph shows the projected population up to 2040 for the three intervention scenarios compared to the no-intervention scenario. In the no-intervention scenario, population growth increases sharply to close to two million, reflecting the absence of controls on in-migration and natural growth. In contrast, the pessimistic scenario shows slightly more restrained growth, while the moderate scenario starts to lower the population curve significantly. The optimistic scenario shows the best results with a population reduction of around 29% compared to the no-intervention scenario, thanks to stronger migration control policies and increased regional carrying capacity.

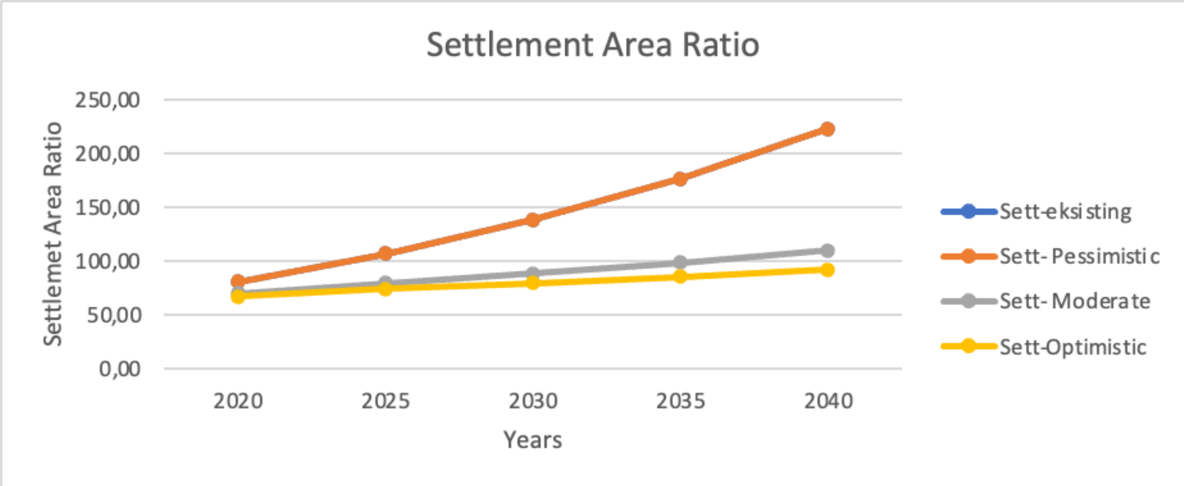

Figure 6. Simulated Environmental Quality by Scenario

This graph shows the decline in physical environmental quality over time under each scenario. The no-intervention scenario shows the sharpest environmental degradation, declining from an index of 85 to 41, reflecting the severe pressures of overcrowding, increased waste and land conversion. The pessimistic scenario provides only a slight improvement. Significant changes are seen in the moderate scenario, which maintains environmental quality at around 70, and the most optimal is the optimistic scenario, which almost maintains environmental quality as in the base year (index 81 in 2040). This confirms that consistent institutional and spatial policy interventions are crucial for environmental sustainability.

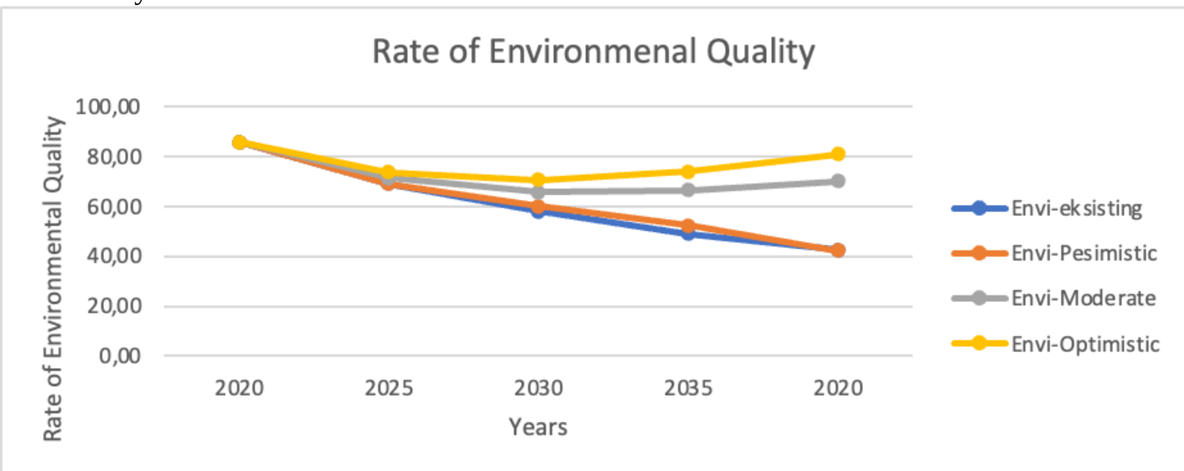

Figure 7. Simulation of Settlement Area Ratio by Scenario

This graph depicts the area of settlements as a ratio to the study area. The no-intervention scenario shows an extreme spike in the residential land ratio, reaching more than double the baseline condition, meaning that land conversion is occurring massively and uncontrollably. The pessimistic scenario makes no significant difference to this trend. The moderate scenario is able to substantially reduce the rate of land conversion, but the best result is shown by the optimistic scenario, with the ratio of residential land remaining within efficient and controllable limits (around 92.58 in 2040). This indicates that strategies to increase regional capacity (such as vertical development) are effective in preventing horizontal expansion of settlements.

3.2 *Discussion*

The results of this study show that the use of a scenario-based dynamic systems approach is able to represent the complexity inherent in the management of residential areas in metropolitan peri-urban areas such as Jabodetabek. In reality, peri-urban areas experience rapid growth in response to urbanization pressures from the core city, but are often not accompanied by adequate infrastructure, spatial coordination, or institutional capacity. The model allows exploration of different policy configurations and allows for more adaptive, systems-based and prospective planning.

The main advantage of this approach lies in its ability to simulate the dynamic interactions between key variables such as population growth, land demand, environmental quality and institutional capacity. An optimistic scenario based on increasing local government commitment, controlling migration, and strengthening regional capacity proved to provide the best results in maintaining regional sustainability. This finding not only reinforces theories of urban systems as adaptive complex systems, but also provides empirical evidence that institutions and governance play a dominant role in steering system outcomes in the desired direction.

Furthermore, the simulation results show that without adequate policy intervention, the pressure on settlement systems will lead to a drastic decline in environmental quality, uncontrolled settlement expansion, and increased density with implications for social and infrastructure problems. This reality is already evident in many peri-urban areas of Indonesia's major cities, which show symptoms of environmental degradation, spatial inequality and land use conflicts. Therefore, this research underscores the need for the integration of quantitative, model-based approaches in the spatial planning process at the regional and metropolitan levels.

Previous studies have demonstrated the effectiveness of the dynamic systems approach in addressing the complexity of settlement management. Feofilovs & Romagnoli emphasizes that dynamic systems are very useful for modeling the interaction of interrelated variables and feedback loops in the long term [15]. Meanwhile, Lu et al. revealed that this approach is able to represent dynamic changes in social and environmental systems simultaneously [16]. Research by Ye et al. also shows that dynamic systems help understand the impact of complex policies on the development of residential areas, especially in the context of rapid urbanization [17].

In addition, research related to the use of scenario-based approaches in dynamic systems has also made many important contributions. Sedighi et al. argues that scenarios allow planners to explore various possible futures by considering uncertainty and the dynamics of change [18]. Research by Datola etl. and Rezvani et al. confirms that the use of scenarios in dynamic systems modelling is very effective in supporting strategic decision-making, especially in the management of areas facing complex social and environmental changes such as metropolitan suburbs [19,20]. Thus, the combination of dynamic systems and scenarios is an appropriate approach to represent the complexity of managing residential areas holistically.

This finding is also relevant to the policy context in Indonesia. Normatively, Law No. 26/2007 on Spatial Planning and Law No. 32/2009 on Environmental Protection and Management have emphasized the importance of controlling spatial utilization and protecting the ecological functions of areas. However, at the implementative level, there is still a gap between policy and reality on the ground, especially in terms of coordination across administrative boundaries and weak development supervision systems. This model can be used as a tool in bridging the gap, by providing data-based simulations that can be used as an argumentative basis in the decision-making process.

Internationally, this approach is in line with planning practices in developed countries that have implemented simulation-based decision support systems, such as UrbanSim in the United States [21] and Land Use Scanner in the Netherlands [22]. The results of this study enrich the dynamical systems literature in the global context by contributing to the case of developing countries, particularly in the context of metropolitan areas that are experiencing very high growth pressures, but face limitations in terms of institutions, inter-regional coordination, and planning resources [23].

However, as with any model, there are some limitations to this study. Firstly, some parameters in the model are based on simplified assumptions due to the limited secondary data available. Secondly, the model has not explicitly incorporated socio-political factors such as community preferences or the interests of certain actors that may affect the effectiveness of policy implementation. Therefore, further development is recommended to incorporate an agent-based modeling approach to capture interactions between actors in more detail, as well as strengthen model validation with longitudinal data and field observations [24].

Overall, this research provides an analytical and operational framework to understand and manage peri-urban settlement dynamics more systemically. The scenario-based dynamic model is not only a simulation tool, but also a reflective instrument capable of improving the quality of policy dialog among stakeholders, facilitating policy learning, and encouraging the creation of more adaptive, collaborative, and sustainable regional governance.

4. Conclusion

The results of the scenario simulation show that the management of residential areas in peri-urban Jabodetabek requires an approach based on strategic policy interventions. Of the three scenarios tested, namely without intervention, pessimistic, moderate, and optimistic-the optimistic scenario proved to be the most effective in controlling the population growth rate (29.14% reduction), maintaining the ratio of residential areas (58.57% reduction), and slowing the decline in the quality of the physical environment (95.18% improvement) until 2040.

The optimistic scenario relies on increasing local government commitment through coordination and consistency in spatial planning implementation, increasing regional capacity, and controlling in-migration flows. Therefore, the main recommended policies include: (1) strengthening the cross-sector and cross-region coordination framework in spatial planning, (2) accelerating vertical settlement development in strategic areas, and (3) limiting migration through an evenly distributed affordable housing policy. This scenario is most likely to be implemented because it can be technically modeled, and institutionally depends on the willingness and capacity of local governments that can be improved through regulations and incentives.

The limitation of this study lies in its assumption of a fixed system environment and the exclusion of economic-political dynamics and external crises that may disrupt long-term scenarios. Therefore, future research should develop adaptive models that account for global uncertainties, such as climate change or disaster-induced migration, and incorporate community participation in the scenario formulation process [25]. The findings of this study offer a valuable contribution to long-term planning based on dynamic systems and can serve as a reference for formulating sustainable urban development policies that are responsive to the complexities of metropolitan areas.

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