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MORALITY BEFORE KNOWLEDGE

Modelling the dynamics of flood overflow and its impact on the Ciliwung river basin

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ABSTRACT

Background: Flooding in the Ciliwung River border area, Jakarta, is caused by interactions between natural and human-induced factors. Jakarta's population grows by 1.11% per year, while urbanization increases by 2.7% per year, leading to 48.41% of land being used for housing, including in critical watershed areas. The Ciliwung watershed narrows by 0.65% annually, further aggravated by land subsidence at 2.75% per year. Extreme rainfall, reaching 150 mm, exacerbates flood vulnerability. **Methods:** This study employs the system dynamics (SD) approach to model flood overflow dynamics, focusing on watershed narrowing due to land conversion into illegal settlements, increased rainfall, and land subsidence. The research applies SD by mapping causal relationships through a causal loop diagram (CLD) and simulating scenarios, including business as usual (BAU) and mitigation strategies such as urbanization control, river normalization, and land rehabilitation. **Findings**: The research findings emphasize the need for integrated policies that combine land conversion restrictions, improving water absorption infrastructure, and strengthening river normalization programs. The developed SD model provides a dynamic framework for understanding the interdependence of natural and human factors, so that it can be the basis for sustainability-based flood mitigation planning in dense urban areas such as Jakarta. **Conclusion:** The analysis highlights the need for more detailed data to better understand flood-causing mechanisms, as population decline may help reduce flood risk through proper watershed land use, while natural factors like rainfall and land subsidence remain difficult to control. Despite its limitations, the system dynamics (SD) model effectively maps flood risk factors and can be improved for more accurate mitigation planning. **Novelty/Originality of this article:** The novelty of this research lies in the application of SD modelling to dynamically assess the interplay between natural and anthropogenic factors in flood risk, offering a sustainability-based framework for urban flood mitigation planning in Jakarta.

KEYWORDS: Ciliwung river; flood; land subsidence; system dynamics; urbanization

1. Introduction

Floods are one of the most frequent natural disasters in the world, causing significant economic, social and environmental losses. According to data from the United Nations Office for Disaster Risk Reduction (UNDRR), floods accounted for approximately 44% of all natural disasters that occurred between 2000 and 2019, affecting more than 1.65 billion people globally (United Nations Office for Disaster Risk Reduction, 2020). Climate change, rapid urbanization and environmental degradation are further exacerbating the frequency and intensity of flooding, especially in low-lying areas and coastal regions (Intergovernmental Panel on Climate Change (IPCC), 2023b). In many countries, flooding has become a serious

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threat to sustainable development, threatening infrastructure, agriculture and human life (Ward et al., 2017).

In Asia, flooding is a critical issue due to high population density and rapid urbanization growth. The Southeast Asian region, in particular, experiences frequent seasonal flooding due to high rainfall and vulnerable topography. The study by Dang & Pokhrel (2024) shows that flooding in Southeast Asia has increased by 35% in the last two decades, with economic impacts running into billions of dollars annually. In addition, damage to river ecosystems, such as deforestation and land conversion, has worsened the capacity of rivers to withstand overflows (Ardiansyah et al., 2021). This calls for a more comprehensive approach to flood modelling and management to reduce their risks and impacts.

In Indonesia, particularly in Jakarta, flooding has become a chronic problem that occurs almost every year. Jakarta, as the nation's capital with a population of more than 10 million, is highly vulnerable to flooding due to a combination of natural and anthropogenic factors. The Ciliwung River, which runs through the Jakarta area, is one of the main contributors to flooding due to its limited capacity and high sedimentation (Abidin et al., 2015a). The study by (Firman et al., 2007) showed that uncontrolled urbanization and land use change in riparian areas have reduced the natural ability of rivers to withstand overflows. In addition, climate change has increased the intensity of extreme rainfall in the Jakarta area, exacerbating flood risks (Aldrian & Dwi Susanto, 2003).

Previous research on flood-flow dynamics in the Ciliwung River has used various approaches, such as hydrological and hydraulic models, to understand flood patterns and formulate mitigation strategies. However, these approaches are often limited in integrating dynamic factors such as land use change, population growth and the impact of human policies (Farid et al., 2022). For example, the conventional hydraulic model used by Pratama et al. (2021) in the Ciliwung River study focused on the physical aspects of flooding without considering the complex interactions between natural and human systems. A more holistic and dynamic approach is needed to understand the flood mechanism as a whole. This study therefore seeks to investigate with system dynamics approach to improve the understanding of flood overflow dynamics in the Ciliwung River basin.

This research proposes the use of the system dynamics (SD) model as a novelty in modelling the dynamics of flood overflows in the Ciliwung River. SD models allow the integration of various factors, such as hydrology, land use, and human policies, in a dynamic and interactive framework (Sterman, 2014). This approach has proven effective in modelling complex systems in a variety of contexts, including water resources management and disaster mitigation (Winz et al., 2009). By applying the SD model, this research aims to improve on the limitations of previous approaches by providing a more comprehensive understanding of the dynamics of flood overflows and their impacts on the Ciliwung River basin. This research aims to model the dynamics of flood overflows in the Ciliwung River using the system dynamics (SD) approach. The model is expected to forecast the narrowing of the watershed and analyse flood forecasts based on increased rainfall, land subsidence, and watershed narrowing. This literature review will discuss various aspects relevant to this research, including flood dynamics, factors that cause flooding, and the modelling approach used.

1.1 Flood dynamics and causal factors

Floods are one of the most destructive natural disasters in the world, and according to Ward et al., (2017), they cause global economic losses of $40 billion per year, with more severe impacts in developing countries. Moreover, climate change, rapid urbanization, and environmental degradation are further exacerbating the frequency and intensity of floods (Intergovernmental Panel on Climate Change (IPCC), 2023a, 2023b). In Southeast Asia, flooding has increased by 35% in the past two decades, with economic impacts running into billions of dollars annually (Dang & Pokhrel, 2024).

Furthermore, floods are caused by a combination of natural and anthropogenic factors, where natural factors include heavy rainfall, vulnerable topography, and climate change,

while anthropogenic factors include urbanization, land use change, and land subsidence (Emam et al., 2016). In Jakarta, flooding often occurs due to a combination of extreme rainfall, land subsidence, and watershed narrowing (Abidin et al., 2015a).

In addition, floods have far-reaching environmental, social, and economic impacts, as environmental impacts include soil erosion, river sedimentation, and ecosystem damage (Foley et al., 2005). Meanwhile, social impacts include homelessness, health problems, and increased poverty (United Nations Office for Disaster Risk Reduction, 2020). Lastly, economic impacts include infrastructure damage, reduced productivity, and high recovery costs (Ward et al., 2017).

1.2 Case study: Flooding in Ciliwung river, Jakarta

The Ciliwung River is one of the main rivers in Jakarta, with a length of about 120 km and a watershed area of 141.4 km^2 (Pratama et al., 2021). Moreover, this river has an important role in draining water from upstream to downstream areas, but its capacity is increasingly limited due to sedimentation and narrowing of the watershed (Abidin et al., 2015a). Furthermore, flooding in the Ciliwung River is caused by several factors, including watershed narrowing, where the conversion of land into illegal settlements has reduced the capacity of rivers to hold and drain water (Firman et al., 2007). In addition, excessive groundwater extraction and building loads have caused land subsidence of 2.75% per year (Chaussard et al., 2013). Meanwhile, climate change has increased the intensity of extreme rainfall in the Jakarta area, further exacerbating flood risks (Aldrian & Dwi Susanto, 2003). Therefore, various efforts have been made to reduce flood risk in the Ciliwung River, including river normalization and naturalization programs. However, these efforts have not been fully effective due to limited resources and coordination between stakeholders (Ministry of Public Works and Housing, 2020).

1.3 Flood modelling approach

Hydrological and hydraulic modelling are commonly used approaches to predict floods, where hydrological models are used to predict surface flow based on rainfall, while hydraulic models are used to predict water flow in rivers (Pratama et al., 2021). However, these approaches are often limited in integrating dynamic factors such as land use change and human policy impacts (Farid et al., 2022). Meanwhile, system dynamics (SD) is a modelling approach used to understand and analyse the behaviour of complex systems that are dynamic and interrelated. SD allows researchers to map causal relationships between variables in the system, simulate different scenarios, and evaluate the impact of policy or human intervention on the system (Sterman, 2014).

Furthermore, SD modelling has several advantages in flood studies, including the integration of natural and anthropogenic factors, as it enables the integration of factors such as rainfall, land use, and human policies in a dynamic framework (Winz et al., 2009). In addition, SD provides flexible scenario simulation, allowing the simulation of various scenarios, such as the impact of land use change or flood mitigation policies (Forrester, 1961). Lastly, SD enables the analysis of feedback loops between variables in the system, such as the impact of watershed narrowing on flood risk (Sterman, 2014).

1.4 Related studies and key findings

The study by Foley et al. (2005) shows that the conversion of land to residential use has reduced water infiltration capacity and increased surface runoff. Moreover, in Jakarta, the narrowing of the Ciliwung watershed has reduced the river's capacity to hold and drain water, increasing the risk of flooding (Abidin et al., 2015a). Furthermore, land subsidence in Jakarta has become a serious problem due to excessive groundwater extraction and building loads. A study by Chaussard et al. (2013) shows that land subsidence in Jakarta is reaching 2.75% per year, which exacerbates flood risks. In addition, the study by Pratama

et al. (2021) used hydrological and hydraulic models to predict flooding in the Ciliwung River. However, this approach is limited in integrating dynamic factors such as land use change. Lastly, the study by Winz et al. (2009) shows that SD modelling can be an effective tool to understand and mitigate flood risks.

2. Methods

System dynamics (SD) is a modelling approach used to understand and analyse the behaviour of dynamic, interrelated complex systems. The method was developed by Jay W. Forrester in the 1950s and has been widely used in various fields, including water resources management, environmental policy, and disaster mitigation (Sterman, 2014). SD allows researchers to map causal relationships between variables in the system, simulate different scenarios, and evaluate the impact of policy or human intervention on the system (Forrester, 1961). In the context of modelling flood overflow dynamics, SD is particularly relevant because it is able to integrate natural factors (such as rainfall and topography) with anthropogenic factors (such as land use and development policies).

2.1 Predicting the narrowing of watersheds due to improper land use

Watershed narrowing often occurs due to land use change, such as residential, industrial, and infrastructure development, which reduces water catchment areas and increases surface runoff (Foley et al., 2005). In SD models, variables such as population growth, urbanization rates, and spatial policies are integrated to predict land use changes and their impacts on watersheds. For example, the model can simulate scenarios where green land is converted to impervious surfaces, which will reduce water infiltration capacity and accelerate surface runoff into streams (Arnold Jr. & Gibbons, 1996).

SD models also allow researchers to consider feedback loops in the system, such as the impact of watershed narrowing on flood frequency and intensity, which in turn can influence future development decisions (Winz et al., 2009). Using historical data and population growth projections, the model can forecast watershed narrowing if the wrong land use for settlements continues, and provide policy recommendations to mitigate the negative impacts.

2.2 Analysing flood forecasts based on increased rainfall, land subsidence and watershed narrowing

Flooding in urban areas such as Jakarta is influenced by a variety of interrelated factors, including increased extreme rainfall due to climate change, land subsidence, and watershed narrowing (Abidin et al., 2011). SD models allow researchers to integrate these factors in a dynamic framework. For example, increased rainfall can be modelled as an external variable influenced by climate change, while land subsidence can be attributed to excessive groundwater extraction and building loads (Chaussard et al., 2013).

In the SD model, the relationship between rainfall, land subsidence, and watershed narrowing can be explained through flow diagrams and mathematical equations. For example, an increase in rainfall will increase the volume of water entering the river, while land subsidence and watershed narrowing will reduce the capacity of the river to hold and drain water (Pratama et al., 2021). The model can also simulate different scenarios, such as the impact of policies to control groundwater extraction or reforestation programs on flood risk.

Using SD models, researchers can analyse flood forecasts based on a combination of these factors and identify the most effective interventions to reduce flood risk. For example, the model can show that a combination of reduced groundwater extraction, increased water infiltration capacity and watershed restoration can significantly reduce the frequency and intensity of future floods (Farid et al., 2022).

3. Results and Discussion

3.1 Modelling problem and study context

Flooding in the Ciliwung River has caused significant environmental, social and economic impacts on the riparian area. The narrowing of the watershed area due to land conversion into illegal settlements is one of the main factors exacerbating this condition. With Jakarta's population growth reaching 1.11% per year and an urbanization rate of 2.7% per year, the pressure on land is increasing (Statistics Indonesia, 2020). This has led to the utilization of watersheds as illegal residential land, which in turn reduces the capacity of rivers to hold and drain water. In addition, land subsidence of 2.75% per year and an increase in rainfall of up to 150 mm also exacerbate flood risk (Abidin et al., 2015b).

The Ciliwung River normalization and naturalization program that has been carried out, including the construction of two large dams, has not shown significant results. Only 16.38 km of the total 33.69 km have been successfully normalized, so flooding still occurs frequently (Ministry of Public Works and Housing ,2020). This condition shows the need for a more holistic and dynamic approach in understanding and mitigating flood risks.

3.2 Modelling objectives and simulation results

The purpose of this modelling is to predict the narrowing of the watershed if the wrong land use for settlements continues and to analyse flood forecasts based on increased rainfall, land subsidence, and watershed narrowing. Moreover, a system dynamics (SD) model was used to map the causal relationships between variables that influence flood overflows, such as population growth, land use, rainfall, and land subsidence. Furthermore, the causal loop diagram (CLD) developed shows the feedback loops between population increase, watershed narrowing, and flood risk.

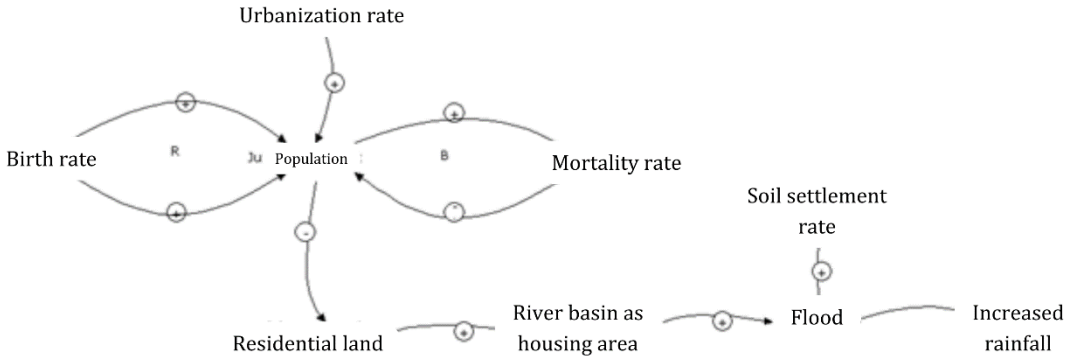


Fig. 1. Casual loop diagram (CLD)

Floods that occur especially in the province of DKI Jakarta show a complex situation due to inappropriate land use in addition to natural factors that cause flooding. Moreover, the causal relationship between the model variables that make up the CLD flood overflow subsystem is shown in Figure 1. Furthermore, the CLD structure in Figure 1 shows the formation of a loop with the following explanation: the increase in population in Jakarta, both by births and urbanization, has resulted in an increase in the amount of land allocated for housing. In addition, due to limited land in DKI, residents use river basins (DAS) as illegal residential land. Consequently, this land use makes the DAS narrow. Lastly, together with increased rainfall and land subsidence, the risk of flooding increases.

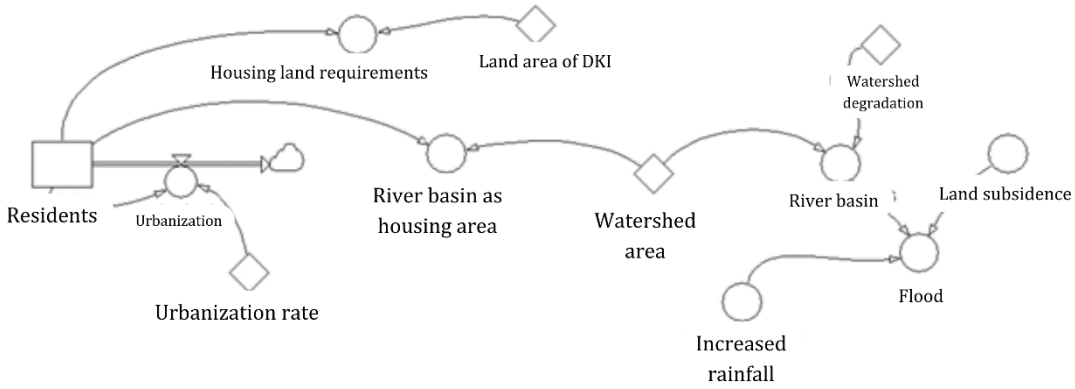


Fig. 2. Flowchart of stock flow diagram of flood events in Jakarta

3.3 Model assumptions and simulation results

The assumptions used are that flooding will increase due to narrowing of the River Basin Area, increased rainfall and land subsidence.

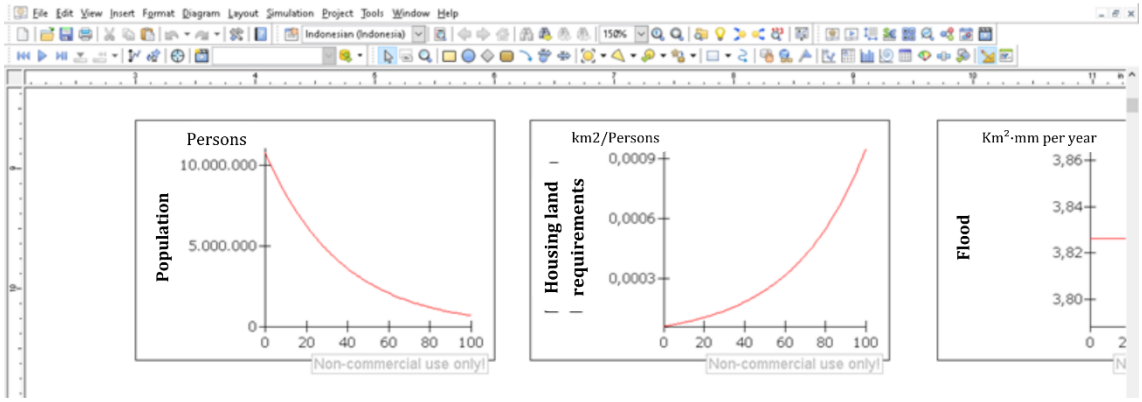


Fig. 3. Simulation results

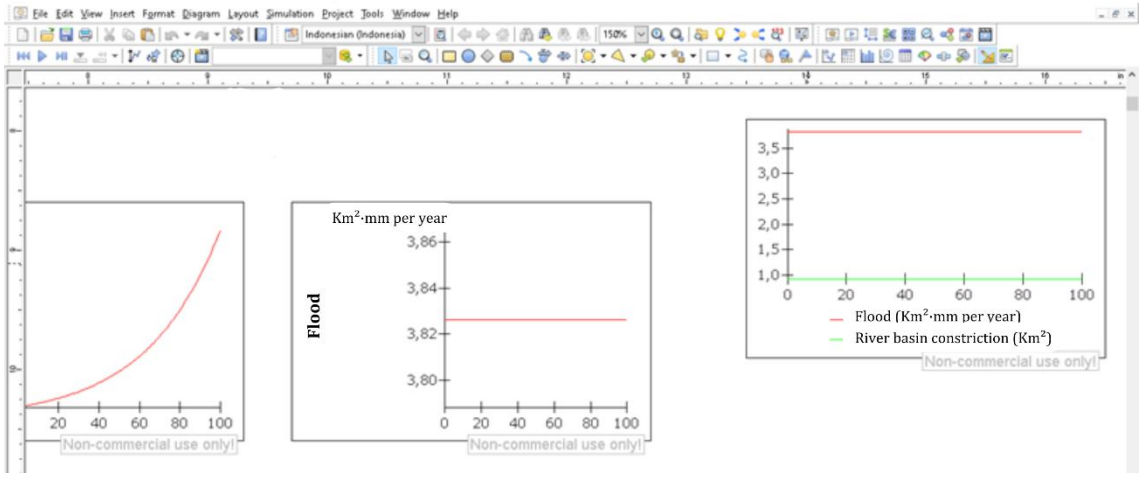


Fig. 4. Simulation results

3.4 Model validation

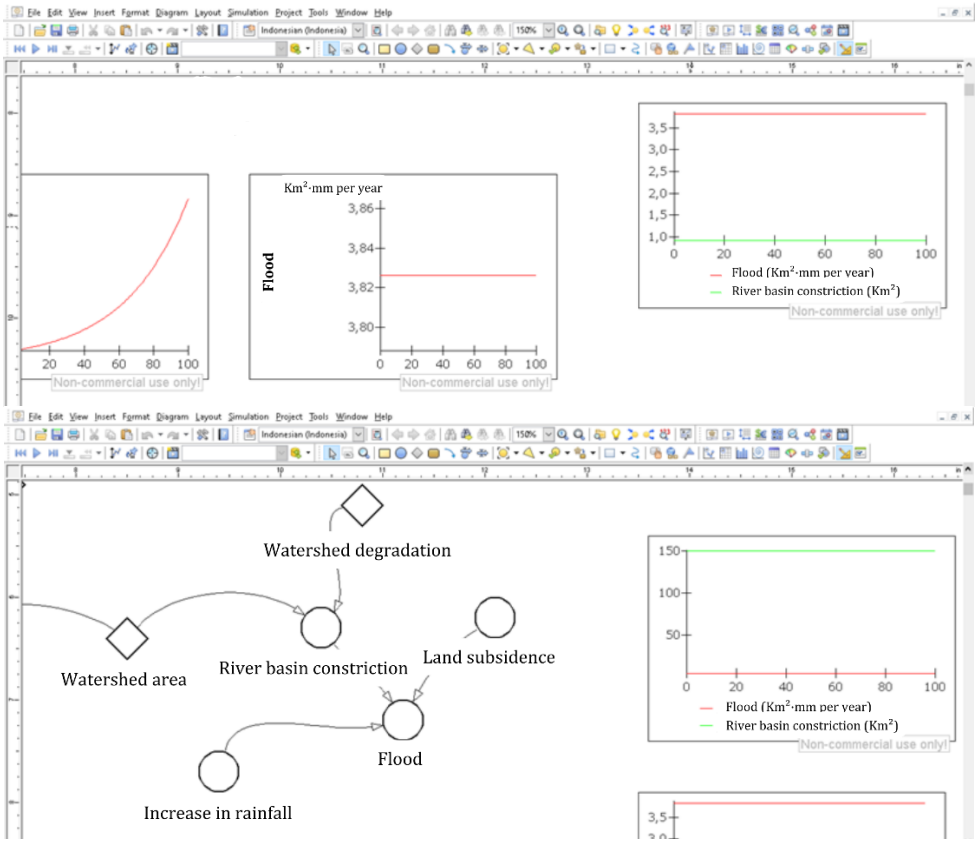


Fig. 5. Model validation

3.5 Business as usual (BAU) simulation results

The BAU simulation was conducted under the assumption that there are no significant policy interventions to address watershed narrowing, increased rainfall and land subsidence. The simulation results show that watershed narrowing will continue to occur along with the increase in population and urbanization. Flood risk will increase significantly due to a combination of watershed narrowing, increased rainfall and land subsidence.

However, the model is not fully valid as it is not able to accurately depict the increase in flood risk. This may be due to inaccurate data input or over-simplification in the model. For example, the model does not take into account factors such as changes in extreme rainfall patterns due to climate change or the impact of spatial policies that may be implemented in the future (Pratama et al., 2021). Based on the analysis of the model and simulation conducted, this modelling cannot be called valid because it does not describe the increase in the effects of flooding from the three causal factors. It is necessary to re-examine the accuracy of the use of input data so that it can show appropriate modelling.

3.6 Simulation results of the forward scenario

Forward-looking scenario simulations were conducted to predict the impact of various policy interventions on flood risk. The simulation results can be seen in Figure 5 above. If the rate of urbanization and population growth can be controlled, watershed narrowing can be slowed down. Moreover, river normalization and naturalization programs, if implemented consistently, can reduce flood risk by up to 30%. However, without significant intervention, flood risks will continue to increase as watersheds narrow and land subsidence occurs. Furthermore, Figure 5 shows the simulation results of the future scenario, where although the model successfully predicts a decrease in population in the

next 100 years, this is not in line with the projected population growth of Jakarta, which is expected to continue to increase (Statistics Indonesia, 2020). In addition, the model is also unable to accurately depict the impact of increased rainfall and land subsidence on flood risk. Lastly, from the scenario simulation, it appears that the factors of flood overflow, reduced housing land, and high rainfall are not well described through this modelling, as the population in the next 100 years is projected to decrease, but along with this, housing land is moving towards being sufficient.

Table 1. Scenario simulation results

Year	Population (Individuals)	Flood (km^2·mm/year)	River basin as a housing area	Residential land	Increase in rainfall
0	10,770,000,00	3.83	1,31e-5	6,14e-5	150.00
20	6,229,777,11	3.83	2,27e-5	1,06e-4	150.00
40	3,603,539,72	3.83	3,92e-5	1,84e-4	150.00
60	2,084,424,26	3.83	6,78e-5	3,17e-4	150.00
80	1,205,710,17	3.83	1,17e-4	5,49e-4	150.00
100	697,428,56	3.83	2,03e-4	9,48e-4	150.00

The main factors affecting flood risk in the Ciliwung River are land subsidence, higher rainfall, and watershed narrowing, according to the modelling study's findings. These results are consistent with earlier studies that showed how anthropogenic and natural factors interact in a complicated way to increase flood susceptibility in urban river basins (Fletcher et al., 2013; Marfai et al., 2015). To guarantee that future studies and policy initiatives are based on solid and trustworthy data, it is crucial to recognize the model's limits even though it offers insightful information about flood risk dynamics. In order to improve the accuracy and applicability of the current model, this paper critically analyses its shortcomings and offers practical suggestions

3.7 Important elements influencing flood risk in the narrowing Ciliwung river watershed

The Ciliwung River's ability to handle large water quantities during periods of intense rainfall has been greatly diminished by the watershed's narrowing, which is mostly the result of fast urbanization and changes in land use. Moreover, this behaviour is in line with worldwide patterns in urban river systems, where flood hazards are increased by impervious surface building and encroachment into floodplains (Michael D. White, 2006; Suriya & Mudgal, 2012). Furthermore, the Ciliwung River's capacity to absorb and hold water has been weakened by the conversion of natural landscapes into residential and commercial sectors, which has raised flood peaks and increased surface runoff.

In addition, the Ciliwung River basin's flood risk is significantly influenced by higher rainfall, according to the model. Climate studies that show a tendency of increasing precipitation intensity in the area, most likely due to climate change, support this finding (Aldrian & Dwi Susanto, 2003; Boer & Suharnoto, 2012). However, the model's dependence on past rainfall data might not adequately account for the unpredictability and variability of future rainfall patterns, especially when considering extreme weather events brought on by climate change.

Lastly, the weight of urban infrastructure and excessive groundwater extraction have caused land subsidence, which has become a major factor increasing the risk of flooding in the Ciliwung River basin. According to studies, ground subsidence is occurring at some of the greatest rates in the world in Jakarta, where the Ciliwung River runs. Some portions of the city are sinking up to 25 cm per year (Abidin et al., 2015a; Chaussard et al., 2013). Because of this subsidence, the land's height in relation to sea level decreases, making floods more likely and severe during periods of heavy precipitation.

3.8 Limitations of the existing model

Even though the current model has improved our understanding of flood risk in the Ciliwung River basin, there are still a number of issues that need to be addressed to make it more reliable and relevant. Moreover, these limitations can be divided into three main groups: validated models, simplified models, and erroneous data input. Furthermore, data inaccuracies play a crucial role, as the quality of the data used as inputs determines any model's correctness. In this instance, the model depends on information that might not accurately depict the actual circumstances, such as variations in rainfall and rates of population growth. For example, estimates of population increase might not account for transient people and informal settlements, which are common in areas like Jakarta (Firman et al., 2007). Additionally, the rising frequency of extreme weather events owing to climate change and localized variations may also be missed by rainfall data (Alley et al., 2007). As a result, there may be notable differences between model predictions and actual results due to these errors.

In addition, model simplification also presents challenges, as the current model streamlines the intricate dynamics of flood risk by concentrating on a small number of variables. Although land subsidence, higher rainfall, and watershed constriction are clearly important, other factors can also have a big impact on flood susceptibility. For instance, the model fails to take into consideration how climate change may alter patterns of extreme rainfall, which may result in more frequent and severe floods (Kundzewicz et al., 2014). Furthermore, the model ignores the effects of spatial planning laws that may reduce or increase the danger of flooding, such as zoning laws or green infrastructure projects (Jha et al., 2012). Lastly, model validation remains a limitation, as the model's validation procedure restricts its capacity to faithfully represent increases in flood risk. To make sure that the model's outputs match observable data and actual circumstances, model validation is an essential step. However, the reliability of the existing model is questioned, as it has not been thoroughly verified. For example, the model might overstate the efficacy of some mitigation strategies or underestimate the risk of flooding in regions with high rates of land subsidence. Consequently, the model's projections might not be accurate enough to guide sensible flood risk management plans in the absence of thorough validation.

3.9 Suggestions to enhance the model

A number of suggestions should be taken into consideration in order to improve the accuracy of flood risk modelling in the Ciliwung River basin and overcome the constraints mentioned above. Moreover, enhancing data collecting, combining the model with additional modelling techniques, and carrying out more thorough scenario simulations are the main goals of these suggestions. Furthermore, more accurate data collection is essential, as making sure that the data utilized as inputs are current and representative of actual situations on the ground can greatly increase the model's accuracy. This involves routinely updating information on rainfall patterns, land use, and population increase. For example, remote sensing technologies and geographic information systems (GIS) can be used to monitor land-use changes and urban expansion in real time (Weng, 2001). Similarly, more precise and localized rainfall data can be obtained from sophisticated weather monitoring systems, which lowers the uncertainty in the model's forecasts.

In addition, integration with other models is necessary to increase the precision of flood forecasts, as the present model, which is based on system dynamics (SD), can be combined with other modelling techniques, such as hydraulic or hydrological models. While hydraulic models can offer comprehensive insights into the dynamics of water flow inside the river channel, hydrological models can replicate the flow of water through the watershed (Todini, 2007). Moreover, combining these methods enables the model to account for a wider variety of flood risk-influencing variables, producing forecasts that are more accurate and trustworthy. Furthermore, more complete scenario simulations should

be conducted to give a more comprehensive picture of flood risk dynamics, and future scenario simulations should take into account a greater variety of environmental and policy variables. Simulations might, for instance, examine how reforestation initiatives affect the watershed's ability to retain more water and decrease surface runoff (Bradshaw et al., 2007). Likewise, the model might evaluate how well groundwater extraction control regulations work to reduce land subsidence (Abidin et al., 2011). To ensure that the model is still applicable in the face of changing environmental conditions, scenario simulations should also take into account the possible effects of climate change on rainfall patterns and extreme weather occurrences (Alley et al., 2007).

Lastly, stakeholder engagement and policy integration are crucial, as involving stakeholders at every stage of the modelling process ensures that the model's results are applicable and actionable for decision-makers. In order to evaluate the model's assumptions and obtain feedback on important variables, this entails working with non-governmental organizations, government agencies, and local communities (Few et al., 2007). Furthermore, the model ought to be incorporated into current policy frameworks to guarantee that its conclusions influence national, regional, and local flood risk management plans. Ultimately, the new model highlights the crucial roles of land subsidence, increased rainfall, and watershed constriction in determining flood risk in the Ciliwung River basin. However, its drawbacks, such as inaccurate data entry, a simplified model, and insufficient validation, highlight the necessity for additional improvement. Therefore, the model's accuracy and applicability can be greatly increased by implementing the above-mentioned suggestions, which include enhancing data collecting, integrating with other models, and carrying out thorough scenario simulations. In addition to enhancing scientific knowledge of flood risk dynamics, these advancements will aid in the creation of long-term, efficient flood risk management plans for the Ciliwung River basin and beyond.

3.10 Comparative insights from flood dynamics modelling and watershed management in Asia

Flood management experiences in other Asian countries provide useful comparative insights for understanding flood dynamics and watershed management in the Ciliwung River basin. Bangladesh, China, and India face similar challenges related to urbanization, land-use change, environmental degradation, and increasing pressure from extreme rainfall. In Bangladesh, flood vulnerability is strongly associated with extensive floodplain areas, high population exposure, urbanization, land conversion, and sedimentation (Ashraf M. Dewan, 2013; Hairan et al., 2021). The implementation of flood management measures, including embankments, drainage systems, and early warning systems, demonstrates the importance of combining structural interventions with broader watershed and land-use management (Adnan et al., 2019). These experiences highlight the importance of limiting land conversion in flood-prone areas and strengthening green infrastructure as part of integrated flood mitigation strategies.

In China, flood management experiences along the Yangtze River demonstrate the importance of balancing structural infrastructure with ecological approaches. Flood risk is influenced by extreme rainfall, upstream deforestation, urbanization, and infrastructure development (Chu et al., 2015; Chen et al., 2023). The impacts of urban development and infrastructure on river systems indicate that flood management cannot rely solely on large-scale engineering interventions. Nature-based approaches, including reforestation and improved water retention, can complement conventional infrastructure by strengthening watershed capacity and reducing surface runoff. These experiences suggest that flood management should balance physical infrastructure with ecological restoration and watershed rehabilitation, particularly in rapidly urbanizing areas.

The experience of Kerala, India, further demonstrates the importance of environmental management and community participation in addressing flood risk. The severe 2018 floods were associated with exceptionally high rainfall and were exacerbated by environmental

changes, including deforestation and land-use change (Mishra & Shah, 2018; Nair et al., 2014). The Kerala experience illustrates how changes in forest cover, land use, and river systems can influence flood vulnerability and emphasizes the need for integrated environmental management. Public participation is also important in climate and disaster adaptation because local communities can contribute knowledge and perspectives that may otherwise be overlooked in top-down management approaches (Few et al., 2007). Such participatory approaches are particularly relevant in densely settled river environments where environmental management is closely connected with local livelihoods and settlement patterns.

Overall, the comparative experiences of Bangladesh, China, and India indicate that effective flood management requires an integrated approach combining land-use regulation, watershed rehabilitation, infrastructure management, ecological restoration, and stakeholder participation. These lessons are relevant to the Ciliwung River basin, where watershed narrowing, land subsidence, increased rainfall, and urbanization interact to increase flood risk (Abidin et al., 2015a; Chaussard et al., 2013; Farid et al., 2022). The comparison therefore complements the system dynamics model developed in this study by demonstrating the importance of combining physical interventions with land-use management and institutional strategies. For Jakarta, the combination of river normalization with watershed rehabilitation and improved land-use management may provide a more comprehensive approach to reducing long-term flood risk.

Table 2. Comparison and recommendations

Aspect	Bangladesh	China	India (Kerala)	Jakarta (Main study)
Dominant Factors	Urbanization, Sedimentation	Dam Infrastructure	Deforestation, Illegal Dams	Watershed narrowing, Subsidence
SD Model	Dynamic Spatial Planning	Ecology-Hydrology Integration	Community Participation	Population-Land Dynamics
Effective Policy	Green Infrastructure	Upstream Reforestation	Forest Rehabilitation	Normalization + Rehabilitation
Limitations	Cross-Country Coordination	Ecological Impacts of Dams	Institutional Capacity	Data Validation

4. Conclusions

Looking at the results of the analysis of the models and simulations made, it can be concluded that there is a need for more detailed supporting data to see the mechanisms that cause flooding. With the decreasing population, it is expected that housing land will be adequate and the risk of flooding will be reduced due to the use of watershed land according to its designation, while natural factors related to rainfall and land subsidence will be difficult to control because they are part of natural factors. System dynamics (SD) modelling has successfully mapped the causal relationship between watershed narrowing, increased rainfall, land subsidence and flood risk in the Ciliwung River. However, the model still has some limitations that need to be improved to increase its accuracy and validity. With improved data input and integration with other models, this model can be an effective tool for understanding and mitigating flood risk in the future.

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Author Contribution

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Data Availability Statement

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Conflicts of Interest

The author declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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