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Integrated Model of Water Infrastructure Development for Water Resources Sustainabilitu (Case Study in Tual City, Indonesia)

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Abstract

Development in Indonesia which is emphasized on the large island/land areas in the Western Region of Indonesia, has resulted in the underdevelopment of the coastal areas and islands in the Eastern Region of Indonesia. Thus, the welfare and economic conditions of the people in the Eastern Region of Indonesia are lower. Development activities oriented in mainland areas or large islands also have the potential to threaten development sustainability, especially in environ-mental aspects. This research aimed to build an integrated model for water infrastructure de-velopment.This study used a quantitative approach by collecting and analyzing data through questionnaires and used dynamic system analysis to build an integrated water infrastructure model.The results of the study found that environmental degradation that occurred in Tual City was caused by high economic activity around the port of Tual, water supply conditions for the people in the exploitative small island of Tual City, as well as pollution and degradation of the soil quality around the residential area of Tual City. The clean water infrastructure integration model with rainwater harvesting and artificial reservoirs can save water purchase costs and increase water supply availability to promote sustainability without causing environmental degradation.

Keywords: *Eastern Region of Indonesia, Water Sustainability Model, Tual City.*

Introduction

Indonesia is an archipelagic state with 16,771 islands and a coastline of 99,083 km. The Indonesian archipelago has a wealth of marine resources and coastal ecosystems, including potential fishery resources and biodiversities such as mangroves, coral reefs, seagrass beds, and potential energy resources with high economic value, such as oil and natural gas, including other mining materials (Dahuri et al., 2001; Utina, 2015; Putra et al., 2001). Indonesia's development has fo-cused on the large land/island areas in the Western Region of Indonesia (KBI), resulting in the underdevelopment of coastal areas and islands in the Eastern Region of Indonesia (KTI). This generally causes the people in the KTI region to have a lower economic ca-pacity than KBI. The development direction needs to look at the archipelagic ecosystem as a whole. During Repelita I to Repelita VI (Five-Year et al. for 1968 – 1997/before the crisis), island territories were a reference for spatial planning to provinces and dis-tricts/cities. However, they had not considered spatial planning in the context of an archipelago. Meanwhile, the island ecosystems are very vulnerable to climate change (Oliveira et al., 2015; Subagiyo et al., 2017; Santoso et al., 2015).

Cities located near water bodies have a high risk of being exposed to the threat of floods and climate change, such as reduced raw water, decreased water quality, and reduced wastewater treatment system capacity, which may cause contamination (Gasper et al., 2011; Baker, 2012; Adelekan, 2016). One of the autonomous cities that have developed an essential function as a regional service center in the Eastern Region is Tual City. Tual City, as part of KTI, has a very strategic role as the Southern Belt Crossing as part of Ilwaki – Saumlaki – Tual – Dobo - Merauke, which connects the southern route of Indonesian territory. The Maluku Province spatial structure describes Tual City as the Tual regional activity center, which has links with Langgur regional activity center. Both work as a buffer for the border area in the Kei Islands and as a growth center for the Kei Islands cluster to encourage the realization of a sustainable National Fish Barn in the Maluku Islands. Based on the regional spatial planning of the Maluku Province, the autonomous region of Tual City is planned as a settlement center with five functions: (1) regional administrative center; (2) trade, service, and marketing centers; (3) transportation and communication center; (4) processing

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production center; and (5) social service centers (health, education, and others). However, some functions mandated in the Maluku Province regional spatial planning have not been operationalized or translated in detail and with clarity in the Tual City regional spatial planning.

The development of Tual City requires water as a fundamental need. The area's character as a small island with limited water sources (Pak et al., 2016) is compounded by envi-ronmental degradation problems. The degradation is due to the development of water infrastructure not based on the island city ecosystem. This problem causes a decrease in the environmental quality of island ecosystems and an increase in the intensity of abrasion. Additionally, the household waste in coastal settlements is directly dis-charged into the sea, which impacts accelerating damage to marine and coastal eco-systems (Burhanuddin, 2015). Furthermore, the development of urban areas affects the urban water cycle and surrounding areas (Vizintin et al., 2009; Donotrio et al., 2009). Urban socio-economic activities impact groundwater extraction and surface water sources, prevent groundwater refilling, and increase the risk of flooding and water bodies contamination due to unmanaged waste (Brears, 2018; Wagner and Breil, 2013; Hoang and Fenner, 2016).

Consequently, the increase in development and economic activity in coastal areas has resulted in the scarcity of water resources. This is in accordance with the warning that by 2030 the world will experience about 40% shortage of fresh water (Essex et al., 2020). It is also projected that 40% of the world's population in 2050 will live in areas that experience a lack of access to better water sources (Stathatou and Kampragou, 2015). Ideally, sustainable development needs to offer a sustainable water resources development model. The sustainability of surface water sources needs to be appropriately managed in the context of an integrated approach. If it is polluted and lost, it results in vulnerability to scarcity of water resources (Essex et al., 2020; Stathatou and Kampragou, 2015; Koop et al., 2017). Water resources management has a gradual paradigm shift globally towards the idea that water management should take a sustainable and integrated approach (Furlong et al., 2017).

Previous studies on sustainable infrastructure were minimal. Few studies discussed increasing environmental degradation due to unintegrated infrastructure development and rapid city development (Furlong et al., 2017; Grimm et al., 2008; Sharma and Tomar, 2010). Several previous researchers have carried out research related to infrastructure development in an integrated manner. However, the study has not considered the complete criteria and indicators of sustainable development for water resources and sanitation infrastructure as a single unit. Therefore, towards sustainable water resources, this research aimed to build an integrated model of developing water infrastructure to preserve water sources with a case study of Tual City, an island city in the Eastern Region of Indonesia.

Materials and Methods

This research approach was quantitative. This research was conducted for twelve months, from August 2022 to June 2023, in Tual City, Maluku Province, Indonesia. The integration model begins in the study of development in island ecosystems and the perceptions of stakeholders and the community towards the sustainability of the urban hydrological cycle. Meanwhile, integration examines the planning and programming stages contained in the city spatial plan document concerning spatial-based and eco-system-appropriate development directions between water resources and sanitation infrastructure.

Sustainability of water resources in island cities is obtained from studying pressures on the sustainability of archipelagic ecosystems based on spatial planning documents and implementation of infrastructure development. The result is an analysis of spatial suitability, carrying capacity, capacity and integration of water and sanitation infra-structure that supports the sustainability of the hydrological cycle. The integrated model of water and sanitation infrastructure development was developed in realizing the sustainability of the hydrological cycle for the sustainability of archipelagic cities by considering the paradigm of integrated water and sanitation with the paradigm of the potential for coastal reservoir development.

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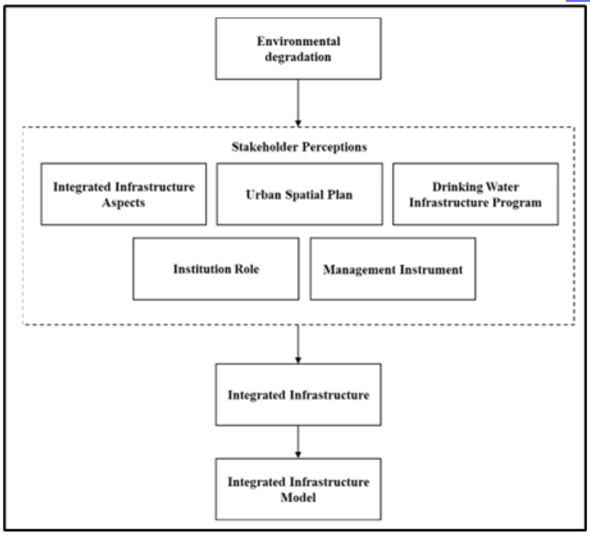

Fig 1. Conceptual Framework

Concurrent sampling data collection procedures used quantitative probability and qualitative sampling combined into independent sampling procedures. The population in this research included all residents in the urban area of Tual City. Respondents and informants in this study were the city government and key stakeholders in urban planning and infrastructure. The key stakeholders include Contractor Associations, Municipal Waterworks (PDAM), Consultant Associations, and Communities around infrastructure projects. The analysis used public and stakeholder perceptions which were carried out using a measurable questionnaire in two locations: the coastal area (location A) and the urban area of Tual City (location B). The measured quantitative value used a score of 1 to 5, where 1 = strongly disagree, 2 = disagree, 3 = moderately agree, 4 = agree, and 5 = strongly agree. The water and sanitation infrastructure integration model was created using the system dynamics model via the Powersim software.

Results and Discussion

Integrated Model of Water Infrastructure Development

Based on the issues and research findings described, a model is needed to build integrated water infrastructure development by optimizing the use of surface water (lake water) to realize the water resources sustainability in light of the potential water source scarcity brought on by population growth. A causal loop diagram (CLD) was created using Powersim, which explained the factors affecting clean water supply and established the appropriate infrastructure integration model for Tual City. Figure 2 illustrates the CLD relationship of factors affecting clean water supply prior to intervention.

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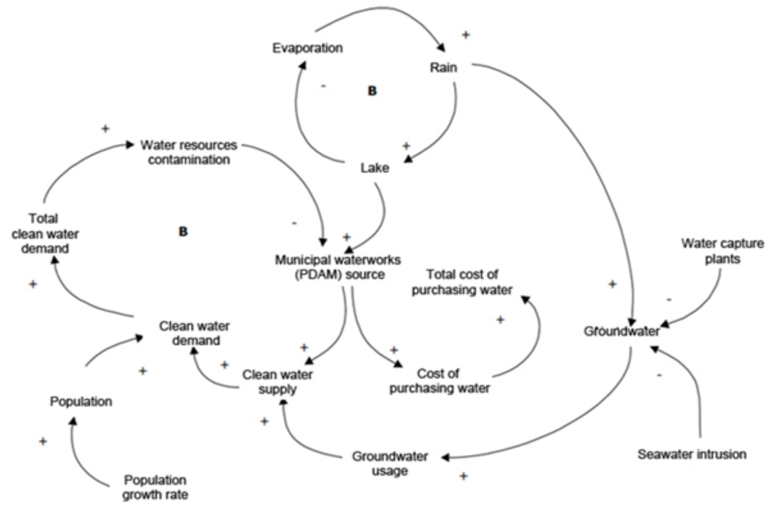

Fig 2. Water Infrastructure Integration Model According to BAU Scenario

Figure 14 explains that the clean water supply in Tual City is influenced by the clean water demand of the population, lake water utilization, water costs, water re-sources contamination, and the capacity of rainwater storage tanks. Clean water supply is directly proportional to the extent of lake water utilization, water recycling efforts, and rainwater storage tanks. Nevertheless, the escalating demand for water leads to rising water resource contamination, reducing the clean water supply. Limited water supply and substantial increase in water demand impact the cost of purchasing clean water, leading to a notable cost escalation. The findings of the integrated model of water infrastructure development in Tual City on a business as usual (BAU) indicate a need for improvement of clean water supply in Tual City. An overview of the water infrastruc-ture development model in Tual City in a business-as-usual manner is presented in Figure 3.

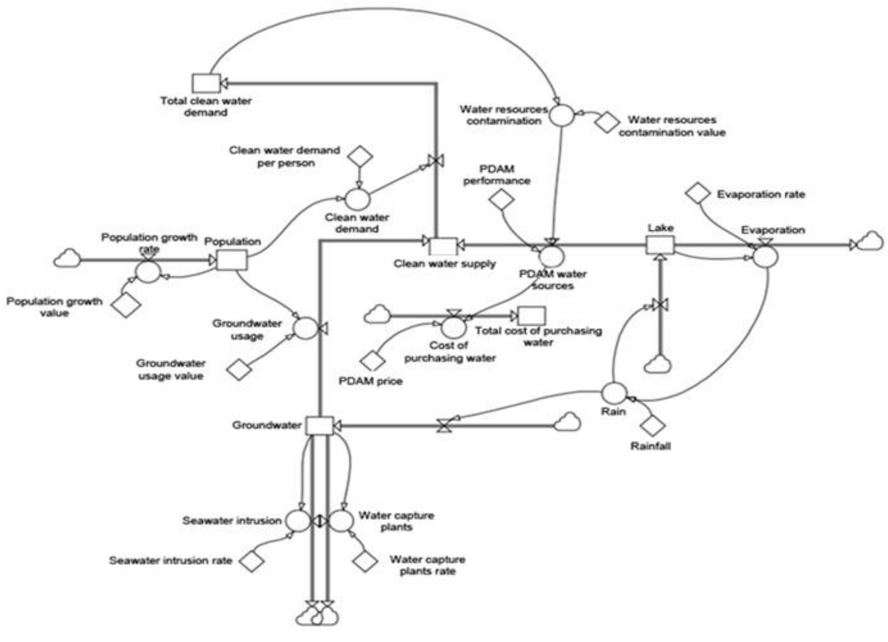

Fig 3. Business As Usual Clean Water Infrastructure Development Model

The projection model using Powersim suggests that the condition of the clean water supply in Tual City is unsustainable. The model predicts a continuous decline in the clean water supply starting from the seventh year (2023) after 2015. In the 20th year (2032), it is estimated that the water supply net will experience a

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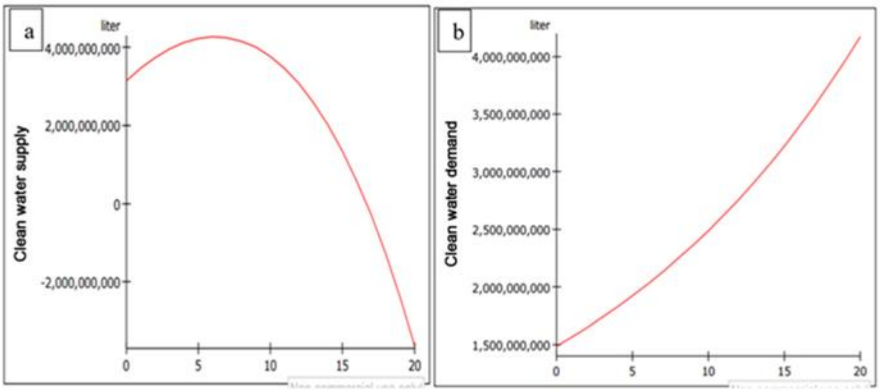
deficit. The water price from the PDAM is IDR 1,050 per liter. The current situation in Tual City reveals an exceeding demand for clean water, surpassing the annual capacity of 8,000,000 Liters available for residents' utilization. The graphical presentation of the clean water supply in Tual City is presented in Figure 16 section (a), while the corresponding graph illustrating the clean water demand in Tual City is shown in Figure 4 section (b).



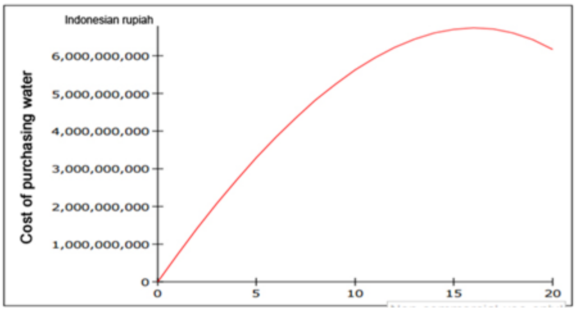


Fig 4. (A) Need For Clean Water, And (B) Clean Water Supply in Tual City

In Figure 16, sections (a) and (b) show an imbalance between water demand and available water supply in Tual City. In addition to having the potential to cause scarcity of clean water, this may increase the poverty rate within Tual City. Furthermore, the lack of access to clean water can have detrimental effects on the overall health of the population. Based on the projection analysis on Powersim, the total costs incurred by the community for clean water needs will persistently rise until the fourteenth year, reaching IDR 6,174,312,880,702 annually. A detail of the total cost of clean water demand in Tual City is presented in Appendix 2. The projected increase in the cost of clean water needs is shown in Figure 5.

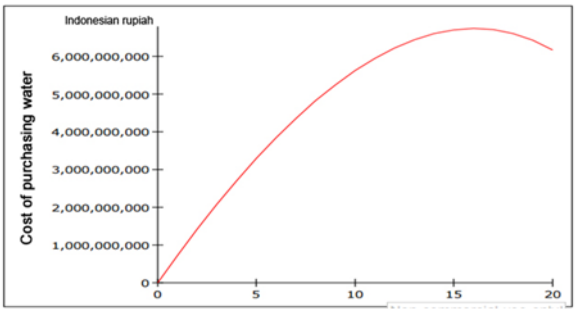


Fig 5. Total Cost of Purchasing Water for Tual's Residents

Based on the results of this projection, policy, and technological intervention must be needed to integrate the water infrastructure development in Tual City. Before the intervention, the researcher validated the simulated data. The validation was carried out by comparing the simulation and actual data. The result of the comparison of simulation and validation data is shown in Figure 6.

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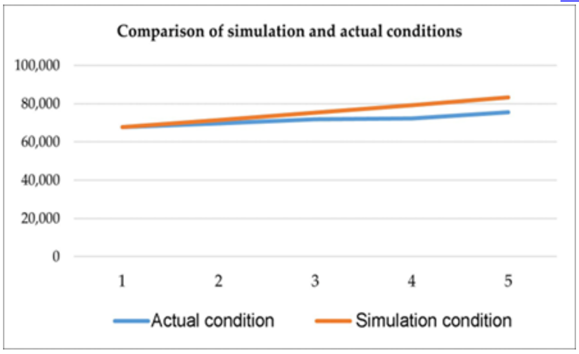

Fig 6. Comparison of Simulation and Actual Conditions

Based on the results in Figure 18, the absolute mean error (AME) value is 0.052. This result can be asserted based on the fact that its value is below 0.3. Therefore, researchers can continue to implement interventions on the model in the form of rainwater harvesting and constructing artificial reservoirs to augment the clean water supply. This action aligns with the policy directions of the Ministry of Public Works and Public Housing of the Republic of Indonesia and is tailored to the landscape of the Tual City area, which encompasses coastal regions and island cities. The selection of rainwater harvesting technology is based on geomorphological conditions in Tual City, which comprises a cluster of small islands. Many coastal areas within this region possess limited rainwater catchment areas.

Consequently, during the rainy season, a substantial amount of rainwater runoff is directly discharged into the estuary or the sea without prior utilization. The interventions carried out rely not only on rainwater harvesting but also utilize surface water (lake) and the construction of artificial reservoirs around rainwater harvesting to integrate this surface water. The relationship between the factors that influence the water infrastructure integration model in Tual City after being given intervention is illustrated as CLD in Figure 7.

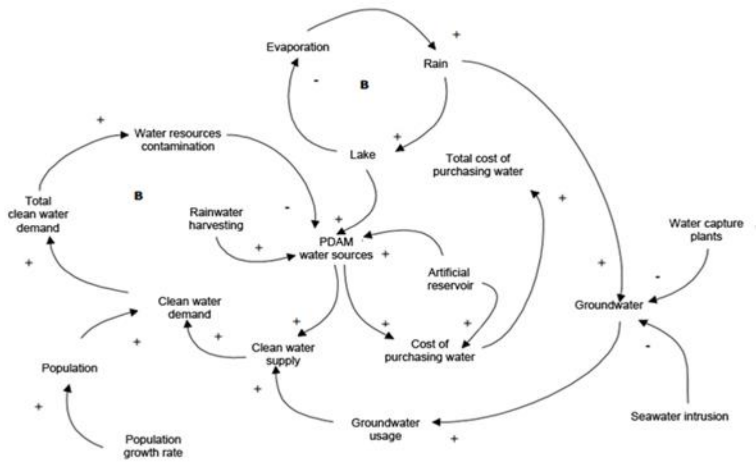

Fig 7. Water Infrastructure Integration Model After Intervention

Figure 19 shows that adding rainwater harvesting infrastructure technology to artificial reservoirs can increase the supply of clean water and reduce the cost of purchasing clean water. Based on this CLD, a simulation model for integrated water infrastructure development in Tual City is created. Integrated water infrastructure model. Additional variables used for model simulation with intervention are artificial reservoirs (reservoir water utilization rate and total reservoir water) and rainwater harvesting (number of units and harvesting rate). The integrated model of water infrastructure development, as depicted in Figure

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8, is economically capable of saving water purchase costs for the next ten years and maintaining the availability of a clean water supply.

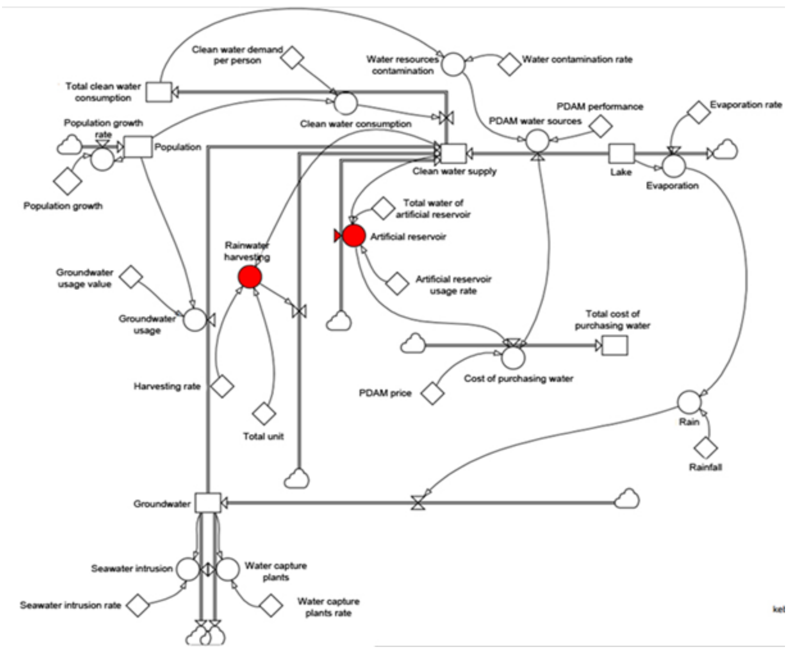

Fig 8. Model of Water Infrastructure Development After Intervention

Based on the results of the model validation test on Powersim, it was found that the water infrastructure development model can control the rate of clean water demand and supply in Tual City. This is in the form of a fluctuating rate of clean water supply in the state of an abundant supply of clean water in the first year to the 10th year, specifically in 2025. The clean water supply will gradually decline in the 10th year and following years. However, the decline is insignificant, and the supply is projected to remain sustainable until the 20th year, as much as 2,931,516,507 Liters per year. The same thing also happens with the clean water demand, wherein there has been an increase in the need for clean water since the 6th year, specifically in 2021. However, this increase is not deemed statistically significant. Consequently, it is projected that by the 20th year, the demand for clean water in Tual City will reach approximately 1,910,649,833 Liters per year. Figure 9(a) illustrates the clean water supply following the intervention, and Figure 9(b) depicts the condition of clean water consumption after the intervention.

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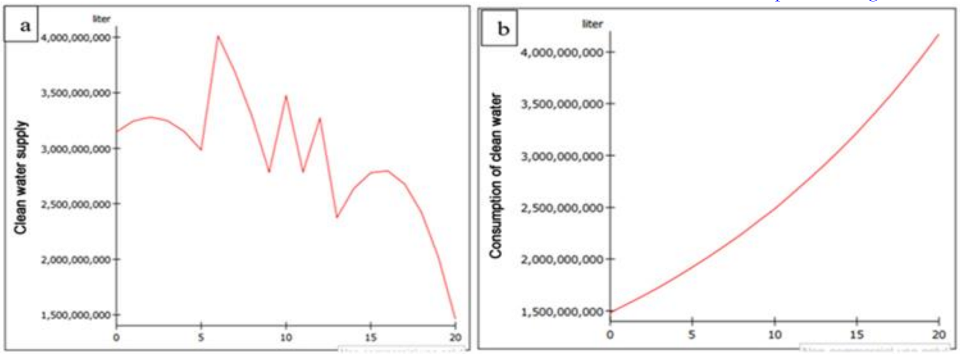

Fig 9. After the Intervention, (A) Clean Water Supply; And (B) Consumption of Clean Water

The intervention scenario is implementing rainwater harvesting installations in 27 villages located in Tual City. Each village will have a single installation capable of storing 10,000 liters of water. The installation will be integrated with the household clean water system around the installation site. The integrated model for developing clean water infrastructure also shows that after adding seawater purification, the community's total cost of purchasing water also increased annually. Nevertheless, the amount paid was cheaper economically, specifically in the 20th year, with IDR 12,287,948,453 liters yearly. This value is more expensive than the amount paid before the intervention, IDR 8,087,948,453 liters per year. However, it can reduce groundwater consumption by up to 4,000,000,000 liters annually. The total cost of purchasing clean water is shown in Figure 10.

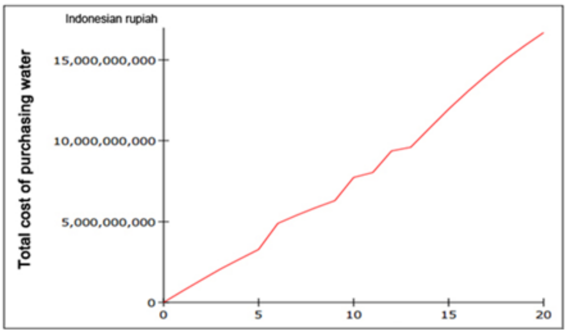

Fig 10. Cost 0f Purchasing Water After the Intervention

Discussion

The integrated model of water infrastructure development in realizing water resources sustainability in this study shows that in the BAU scenario, the water supply in Tual City is projected to decline. This decrease will reach a point where the water supply runs out by 2033, aligning with previous study findings that indicate a gradual reduction in water supply in island areas (Reyes et al., 2017; Shin et al., 2020). The models also included a validation process which shows an AME value of 0.0522. The AME value below 0.3 can be why this model can be continued to the intervention stage, which is in line with other studies (Sari et al., 2019; Tjolli et al., 2021). The intervention contained in this model is carried out by making rainwater harvesting and artificial reservoirs. The other researchers stated that harvesting rainwater (Bailey et al., 2018; Ismail and Go, 2021) and artificial reservoirs can increase the availability of clean water supply in island areas (Georgiadis et al., 2010; Zanor et al., 2023). The results of this intervention model show that the water supply for up to 20 years in Tual City can be fulfilled while reducing groundwater use by 20%.

Other research shows that the integrated model of water infrastructure fulfillment involves the construction of centralized water infrastructure such as dams, reservoirs, or giant water treatment plants; water is collected, processed, and distributed through pipelines to the community; this model has the advantage of efficient water distribution and better quality control (Stip et al., 2019; Scanlon et al., 2023). Other studies

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have also modeled those involving the development of decentralized water infrastructure at the local level, including small-scale water treatment plants, local water resource management, or independent water collection and distribution systems (Makropoulos and Butler, 2010; Mauter and Fiske, 2020). This kind of model aims to provide better access to communities that are remote or difficult to reach by centralized water infrastructure; the advantages of this model are flexibility, independence, and resistance to disturbance (Makropoulos and Butler, 2010; Mauter and Fiske, 2020; Diao, 2021).

Application of the water infrastructure integration model can assist governments, water management agencies, and relevant stakeholders in identifying areas for improvement, allocating resources more effectively, and developing strategies to improve the water infrastructure integration sustainably (Romano and Akhmouch, 2019; Nyam et al., 2020). Water infrastructure integration refers to the effective integration and coordination level between various water infrastructure elements in a system. It includes a harmonious relationship between water sources, water treatment, distribution, storage, and water use (Peng and Reilly, 2021; Ngene et al., 2021). Integration of water infrastructure requires integrated and coordinated planning between various sectors and related stakeholders; this includes identifying water needs, resource allocation, infrastructure development, and managing risks related to water (Waylen et al., 2019; Bohman et al., 2020).

Integration of water infrastructure involves building well-connected networks and systems; this includes the provision of integrated water distribution pipes, drainage channels, irrigation networks, and water storage systems to ensure reliable and efficient water supply (Fuchs et al., 2020; Mourad, 2020). Integration of water infrastructure requires an integrated water management approach, which includes monitor and control of water resources, management of water demand, flood and drought control, and protection and restoration of water ecosystems; integrated water infrastructure involves cross-sectoral collaboration and cooperation, including the government sector, the private sector, and civil society, this includes coordination between relevant ministries, water management agencies, local government, industry, and communities in planning, implementing, and maintaining water infrastructure (Wong and Montalto, 2020; Nika et al., 2020). Technology plays an essential role in achieving integrated water infrastructure; this includes the use of information and communication technology for water monitoring and management, sophisticated water treatment systems, sensors, and remote monitoring, as well as innovations in sustainable water management (Mondejar et al., 2021; Hangan et al., 2022). By achieving the integration of good water infrastructure, water management systems can be more efficient, water resources can be used sustainably, and water-related risks can be managed better; this contributes to environmental sustainability, meeting people's water needs, and sustainable economic development (Boelee et al., 2019; Tsani et al., 2020).

Conclusion

The environmental degradation occurring in Tual City is primarily due to inadequate household waste management in residential areas, direct discharge of liquid waste into water bodies, high economic activity around Tual Port, and the exploitative yet suboptimal use of surface water for meeting the community's water needs on the small island. These factors contribute to pollution and the decline in soil quality in residential zones. Experts perceive that the integration of water and sanitation infrastructure development in Tual City has not yet been achieved, as the implementation of the Integrated Water Supply System (SPAM) and Integrated Wastewater Treatment Plant (IPAL) plans has not been realized. A model for integrated infrastructure development involving clean water supply, supported by rainwater harvesting and artificial reservoirs, can reduce water purchase costs, enhance the availability of water supply, and ensure sustainability without causing environmental degradation. One of the interventions for sustainable clean water supply in Tual City could adopt lessons from the Plover Cove Reservoir. This reservoir is noted for its ability to contain and store seawater within a confined area, being situated in an archipelagic city and positioned along a coastal region.

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