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Original Article

Land Use Effect on Water Resources of Ternate Island and Its Management Strategy

Abdul Halim[1], Rosady Mulyadi[2*], Edward Syarief [2]

[1]*Master Student, Graduate School of Hasanuddin University, Makassar, Indonesia.*
[2]*Department of Architecture, Faculty of Engineering, Hasanuddin University, Makassar, Indonesia.*

[*]*Corresponding Author : rosady@unhas.ac.id*

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Abstract - *The high urbanization rate of Ternate Island, a small volcanic island located in North Maluku Province, Indonesia, has dramatically changed the land-use patterns of the island in the last twenty years. This paper will analyze how these changes, especially forest land and agricultural land being transformed into built-up spaces, affect the recharge capacity of the groundwater and the sustainability of the water resources in general. On the basis of multi-temporal satellite images (Landsat 7 and 8 of 2009-2023), GIS-based spatial analysis, hydrological modeling, and SWOT analysis, the study indicates that the areas under built-up hindrances grew by 943.3 ha in 2009 to over 2,000 ha in 2023, whereas forest cover refers to the decline of about 24 percent. Although the slopes of Mount Gamalama have fairly high potential for natural infiltration, the rising impervious surfaces have decreased the effective groundwater recharge and the risk of flooding during heavy rainfall. Despite having registered a surplus of 38.9 million* m^3 *of water in 2018, the current plans to keep converting land unless the situation is controlled pose a threat to long-term water security. The proposed study is an integrated management framework that incorporates the concept of green infrastructure (retention ponds, biopores), mandatory green open space regulations, and reforestation targets, as well as digital monitoring systems. Contrary to earlier studies wherein the majority of the research concentrated on mainland or larger islands, this study is the first to carry out a comprehensive spatial-hydrological evaluation with specific reference to small volcanic islands with high levels of demographic pressure within eastern Indonesia that can be transferred to other island-like situations of the world.*

Keywords - *Land use, Management, Ternate, Water balance, Water resource.*

1. Introduction

The pretty rapid changes that have occurred on the Ternate Island, part of the North Maluku Province, Indonesia, have been experienced over the past few decades. The city, with its booming population, urban sprawl, and growth in the cycling, industrial, and commercial activities, has changed rapidly in its layout and the natural environment of the city [1]. Among the largest challenges that can be attributed to such development is land use change and its effects on the natural resources and natural water in particular. A landscape with farms, forests, and conservation basins has been much substituted by residential areas, commercial areas, and industrial areas [2]. This widespread transformation of the land usage has directly influenced the water cycle on the island, and the water surface water quality, groundwater reintroduction, and the health of the water systems overall have been of concern.

The disappearance of green spaces caused by undisciplined urbanization has led to an increase in the number of impermeable surfaces, hence stormwater runoffs and urban floods [3]. These transformations increase the dangers of water-associated catastrophes such as seasonal droughts, flash floods, and chronic deficiency of clean water in Ternate, which has a distinct volcanic geography that includes steep slopes and enhanced precipitation [4]. The island's fragile ecological stability is also threatened by destroying important water infiltration zones, which not only increase surface water run off and erosion but also reduce groundwater, which is important in the provision of day-to-day water and the survival of ecosystems in the area [5].

Partially, the research has examined land-use and water management parameters, yet land-use and water management are linked to a considerable lapse in thorough studies, particularly in island ecosystems with unique geographical and climatic characteristics [6]. Also, the combination of land-use change and water resource management in climate change and socio-economic interactions has had the lowest level of attention [7]. The paper will examine the existing land-use and how it is distributed spatially on the Island of Ternate and explore how these developments have impacted the water resource systems in the island in an attempt to address these gaps. It also aims to assess the hydrological impacts of land conversion- primarily in terms of water absorption, retention, and distribution- and to develop appropriate ways of controlling water catchment zones.

Notwithstanding the various studies that have examined the nexus between the change in land-use and water resources in greater islands in Indonesia (e.g., Java, Sumatra, and Bali) and in smaller islands in the Pacific and Caribbean situation, there is an observed research gap in the eastern scenario of Indonesia, which examines the nexus between land-use change and water resources. Past reports on Ternate and the neighbouring islands have predominantly concentrated on individual issues - such as mapping volcanic hazards [3, 8], intrusion of seawater [9, 17] in lakes or even on the overall land-cover change [4, 10] without including long run, island wide, hydrological modelling, with spatially explicit estimation of groundwater recharges. In addition, all such studies have not integrated multi-decadal Landsat time series (2009-2023) analysis and weighted overlay modeling-infiltration potential, a threshold of Thornthwaite-Mather computation of water balance, and an island-specific, grounded SWOT framework to produce actionable, island-specific management strategies.

The current research makes three innovative contributions: (1) it provides the first systematic, island-wide analysis of the decline in effective groundwater recharge caused by rapid urban development on steep volcanic slopes, despite high rainfall and otherwise favourable natural infiltration conditions; (2) it quantifies the spatial mismatch between areas with high natural infiltration capacity (mainly the slopes of Mount Gamalama) and areas experiencing actual recharge losses due to the expansion of impervious surfaces; and (3) it presents a transferable, integrated framework.

These contributions not only address the identified knowledge gap in Ternate but also offer a replicable methodology and policy-relevant insights for other high-density volcanic islands in Indonesia and across the Asia–Pacific that face similar challenges related to urbanisation and climate resilience.

2. Literature Review

2.1. Profile of Ternate Island

The insular Ternate Island, situated between the North Maluku and the Maluku archipelago provinces of Indonesia, is an exquisite island of both geographical and historical value. It is located right off the western coast of Halmahera Island and is characterized by its small size and volcanic origin [11]. The landscape of Ternate is centered around Mount Gamalama, a stratovolcano that is considered active. This volcanic action not only forms an impressive rise but also fertilizes the land, such that production in this land is even more amazing with the small size of the island [12]. It is characterized by steep and rocky topography, which is narrow, mainly in the coastal plains surrounding the mountainous center. Such geography directly influences the way infrastructure is built, land use, and water movement over the island [13].

In terms of weather, Ternate is blessed with a tropical rainforest climate, characterized by abundant and evenly distributed rainfall throughout the year. The island experiences the impact of monsoons, with an average annual rainfall exceeding 2,000 mm [8]. There is always a high humidity, and temperatures generally stay between 25 °C and 30 °C. Such conditions result in the abundance of natural water sources, such as springs and streams that flow down the volcanic ranges [14]. However, they also pose some challenges, such as erosion, landslides, and problems with water retention, especially in areas where the land has been disturbed [15].

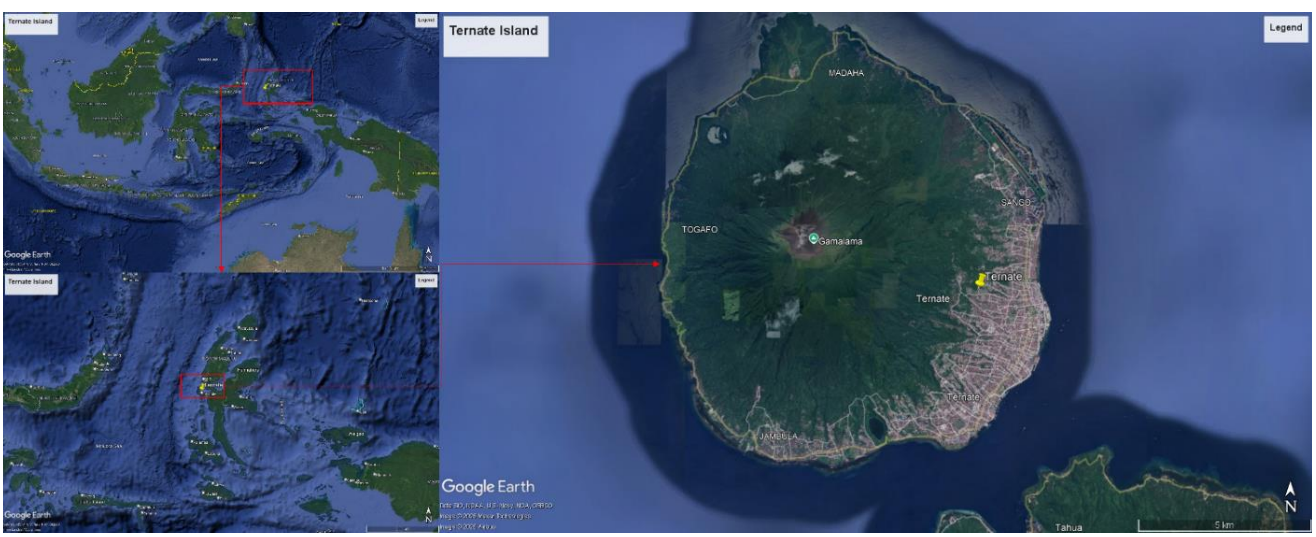

Fig. 1 Ternate island from indonesia's perspective

Demographically, Ternate is one of the areas with the highest population density in the eastern section of Indonesia. Ternate has experienced a rise in population over the past few decades, driven by both natural population growth and immigration in the town of Ternate [9]. The city serves as the hub of the government and the economy; people who arrive to visit the neighboring islands gather here, and that is why the demand for land, houses, and services continues to increase. This population pressure has transformed land use to the extent that it has caused urban sprawl to occur within spaces that were not initially developed or environmentally sensitive areas. The settlement areas have mainly concentrated along the coastal stretch, yet the central mountain zone remains sparsely populated due to rugged terrain and volcanic fear. With more and more individuals and scarcity of land availability, spatial planning and control of resources in the island have become more complex, particularly in terms of accessibility and allocation of water [10]. There are several factors that contribute to the uniqueness of Ternate, including its small geographical size, volcanic geography, tropical climate, and rising population pressures, which result in a challenging town that requires sustainable management of its land and water resources. Familiarity with these physical and human aspects is a precondition for formulating strategies that have the potential to address the environmental and socio-economic shifts affecting the island [4].

The interaction between the rapidly changing land-use and water-resource sustainability has been adequately monitored in large and topographically heterogeneous islands. Urban sprawl and industrialization on relatively low-lying alluvial plains have been found in the application of Java, most likely to be the leading cause of the 25-40% of groundwater recharge in the Ciliwung and Citarum watersheds over the last 30 years. Similarly, the Bali studies have revealed that there has been a 30-35 percent reduction in infiltration, which goes hand in hand with tourism-related alterations in making rice terraces as infrastructure. The problems of most significant interest in low-lying Pacific atoll states (Kiribati, Tuvalu, Marshall Islands) and in the Caribbean small-island states (Barbados, St. Lucia) include sea-level rise and saline intrusion. Topographic gradients and lenses of freshwater are typically very low in these islands; the hydrological issues are, in a literal sense, the converse of those found in steep volcanic islands. By contrast, Ternate Island is the result of too much population density (>22,000 persons/km2 in coastal zones), very steep volcanic slopes (average 15-35 °), considerable rainfall (more than 2,000 mm/year), and almost complete dependence on groundwater and spring capture, locally. Whereas other sources of surface water and/or inter-basin transfers could be available to Java or Bali, whereas salinization of narrow lenses will threaten Pacific/Caribbean atolls, Ternate relies upon the defence of high-infiltration volcanic slope zones, which are actively becoming occupied by informal settlements and infrastructural development. Neither the literature of any small volcanic island in Indonesia, nor of the Pacific Ring of fire more generally, has, as far either of the authors know, pooled multi-decadal Landsat analysis with spatially explicit infiltration modelling, water-balance models, and locally-derived SWOT strategies, all on so narrow a land avenue. This unusual combination of high natural recharge potential, extreme land scarcity, and steep-slope vertical urbanisation renders Ternate unusual as compared to any continental mega-city as well as low-lying island state, and therefore necessitates a particular analytical and management model which can also be applied to model other high-density volcanic islands (i.e., Ambon, Tahuna, or Sao Miguel in the Azores).

2.2. Effect of Land Use on Water Resource Management

The land use actually determines the amount of water present, its purity, and its sustainability- at least in the delicate sites such as the Ternate Island. When individuals replace forests or farms with neighborhoods, shops, or factories, the entire system becomes disturbed. Ternate is no ordinary island; there is not too much flat space, steep hills, and rains fall heavily and frequently. Thus, the changes in the landscape make the effects harder to detect [16]. Without the trees and the plants, the ground is not able to absorb rain in the same way. Trees and green areas act like big sponges- they allow water to trickle into the ground, replenish the underground supply, and ensure streams do not burst at any given time. However, replace them with concrete or asphalt, and rain is quickly drained away. The soil can no longer retain water. It implies reduced groundwater and increased surface water flowing directly into the streets and an increase in the likelihood of unexpected flooding [17]. In Ternate, the city experienced rapid development. Homes and roads continue to encroach into areas that were initially forest or a natural catchment area. This makes the island lose the capacity to retain water, i.e., when there is a dry season, people begin to run out, and when the rain falls in heavy torrents, the floods are even more severe. To top that, all the green areas are shrinking and going into the areas of the protected or the highlands, which only heightens the pressure on the water systems in Ternate [18]. The problem is usually aggravated by land-use changes, which no one is actually watching or planning. Surge water of the new constructions transfers litter, sediment, and any form of pollution to the rivers and ultimately to the sea. This does not only damage the immediate environment; it also complicates the access of the local people to clean water [19]. Ternate is not one of those big islands, and many people live there. This makes sound planning and heavy restrictions on land-use more important than ever. When the city insists on its further expansion, however, to safeguard its water, development must be accompanied by a concern for the environment. That is, preserving whatever remains of the recharge zones, in fact, implementing zoning regulations on vulnerable watershed areas, and establishing green infrastructure that would assist the land to absorb water. Unless Ternate falls in line on this point- unless land utilization continues to occur without consideration of water- there is a concern that there will arise water scarcity, increased pollution, and larger bills of rights in the future to ensure everyone is fed. In the case of Ternate, addressing land utilisation and water management is not only an ask-or-buy question of the environmental aspect. It forms the foundation of ensuring that the city is capable of maintaining its stability and ensuring it is able to develop without overstraining its own future [20].

2.3. Urgency of Water Resource Management in Ternate

There is a need for improved water management on Ternate Island — it is inevitable. It is a small volcanic island with limited space, and even more people continue to arrive. That places much strain on the freshwater on the island [8]. The population here depends on groundwater and that which comes off the land; however, when the land changes in terms of the way it is used, it is simple to see the water supply suffer a blow, either due to natural factors or human actions. The geography, then, is the next thing: the steep slopes and the erratic rainy season, and a live volcano on the spot. All that only makes it more difficult to keep the clean water flowing throughout the year [21]. This is the main issue the island has to deal with: water does not soak into the ground like it always has. Whenever a person cuts down a forest or excavates an area of greenery to construct new structures, the land is deprived of one more small element of its natural capacity to replenish the groundwater. It is not merely that there is less water to share- the remaining supply may become salty, particularly at the coast, when individuals pump excessively from the groundwater and ocean water creeps in [3]. On top of that, all those roads and concrete do not allow rain to seep, thus it speeds away, polluting and dirtying the streets on the way and into rivers and the sea directly [22]. These issues answer the question of how Ternate should smartly manage land and water. Conservation of the places where water takes its natural bath, restoring the ravaged catchment areas, city planning with water in mind, all these count [1]. Planting new trees, installing infiltration wells, and preserving the natural streams are just a few examples of the water system's recovery. And it does not stop there. When the city begins to gather rainwater and use wastewater, the city will have new water supplies and relieve the old ones. That is the way to enter into a water system capable of withstanding everything that follows [11]. Policies and institutional coordination are also crucial. The most technically viable solutions may be less long-term and cost-effective, lacking clear legislation, enforcement, and community participation. Since Ternate has a close social structure and people depend on common resources, community-based events and mass campaigns are particularly essential. Ultimately, the water security of Ternate relies on developing and implementing a comprehensive plan to manage water resources.

This involves the incorporation of hydrological data, spatial planning, and socioeconomic classes in order to ensure that the supply of water keeps pace with urban development and climatic variability. Without such a plan, the increased threats of seasonal lack of water, environmental degradation, and socioeconomic instabilities will pose a threat to the sustainability of the island and its corresponding quality of life.

Table 1. Methodology matrix

Research Aspect	Variables / Focus	Type of Data	Data Sources	Data Collection Methods	Analytical Methods / Tools
Land Use Change	- Land cover in 2009, 2013, 2018- Vegetation index (NDVI)- Spatial planning timeline	Quantitative & Qualitative	- Satellite imagery- Local planning documents- Field observation	- Remote sensing- GIS interpretation- Literature review	- GIS spatial analysis (classification, overlay)- NDVI analysis
Water Infiltration Capacity	- Slope gradient- Rock and soil type- Rainfall- Vegetation density	Quantitative & Qualitative	- Field surveys- Meteorological data- Geological maps	- Topographic observation- Institutional data collection	- GIS overlay- Interpolation techniques- Descriptive statistics
Water Balance	- Water discharge- Population growth- Seasonal variation	Quantitative	- PDAM data- BPS (Statistics Office)- Hydrological reports	- Institutional data request- Documentation	- Statistical analysis- Comparative temporal analysis
Supporting Contextual Data	- Physical geography- Demographic and urban growth trends	Qualitative	- Observations- Interviews- Secondary documents	- Field notes- Stakeholder interviews- Literature review	- Descriptive qualitative analysis
Synthesis and Strategy	- Integrated land-water relationship- SWOT strategic planning	Mixed	- Output from prior analyses	- Integration of spatial and non-spatial results	- SWOT Analysis- Strategic formulation for water management

3. Methodology

This paper uses a mixed-methodology, which is a combination of both quantitative and qualitative information to explore the impact of land use changes on the management of water resources in Ternate Island. The quantitative data involve significant figures such as population levels, levels of water discharges, and geographic area, which are vital in understanding the demographic stress as well as the hydrology of the region. Conversely, field observations and interviews provide qualitative data that present useful context regarding the physical features of the area, land utilization patterns, and local environmental concerns. The information is collected using primary and secondary sources. The primary data was obtained by field survey and semi-structured interviews during the time range of June 2023 to March 2024. A total of 28 key informants who comprised a purposive sample were identified by incorporating 8 local government and PDAM officials, 7 village heads and community leaders of recharge-zone villages, 6 academicians and NGO officials, and 7 farmers/landowners of mixed-garden areas. The desired outcome in interviews was observed change in land-use, trend in water availability, and perceived management opportunities and challenges. Three of the common micro-catchments (south, east, and northwest slopes of Mount Gamalama) were tested in the field in regard to their infiltration and runoffs during the wet season of 2023.

In this study, a number of data collection procedures were applied. The techniques were also instrumental in collecting the necessary information for the study. On-site observations that help to note the actual environmental and spatial situations, institutional data requests that help to find out the existing data related to the aims of this research, and literature reviews of official documents and scholarly publications all belong to these techniques. Moreover, a systematic recording of all the visual and written materials that were reviewed and utilized in the course of the research was also made. Some of the significant variables considered in the study included land use change, which was established by comparing the satellite images of different years, vegetation cover, land area, and time series of spatial planning laws. Besides that, it was found that the infiltration capacity of water depends on the slope gradient, rock type, soil properties, precipitation intensity, and plant cover.

Water balance was measured using indicators of water discharge levels and population data. The methods of analysis used in the research were specifically tailored to the kind of data obtained. In the quantitative data analysis, we applied descriptive statistical methods to derive trends and associations. Conversely, spatial analysis using GIS tools such as ArcGIS assisted us in visualizing and analysing different spatial processes such as land cover change, water absorption potential, and water resource distribution. We also explored the field notes and interviews that provided qualitative data on which we did a descriptive qualitative analysis to understand the context and dynamics that could not be expressed through numbers. The combination of these datasets in the form of spatial overlay methods enabled a comprehensive perception of the interaction between land use and water systems to be realized. Ternate island land cover was determined by using NDVI tools, classification, and interpolated analysis, and ensuring that the data was correct. We divided the work equally and dealt with the research step by step. To test water use: determining the current use of land by satellite pictures and ground survey, measuring the water retention and water infiltration and equilibrium of water, and combining the cover of land and water courses to test the relationship. We applied an overlay analysis to determine the location, contact, and limits of water-absorbing areas and lands in human use. All this information allowed a SWOT analysis that presented the water resources' strengths and weaknesses, opportunities, and threats of the island, and they now form the basis of coming up with actionable strategies to ensure the sustainability of the water resources in the island. Although the basic tools of the proposed research, multi-temporal Landsat images, ArcGIS-based overlay analysis, Thornthwaite-Mather water-balance model, and SWOT analysis are rather old, their integration and adjustment are a breakthrough in methodology selection in a small volcanic island location.

The discussed paper proposes a Volcanic-Island Groundwater Recharge Vulcanity Index [VIGRVI], a composite weighted overlay index created with the direct aim of being applied on steep-sloping, high-rainfall volcanic islands. The index is a combination of five parameters that are spatially explicit (slope gradient, soil/regolith depth, vegetation density through NDVI, land-use imperviousness, and distance to the volcanic cone) and local-adjusted weights that will be attained through field validation and consultations with the stakeholders in 2023-2024. Unlike the generic infiltration models that are applicable in the lowlands or continental setting, the VIGRVI directly considers the speed of vertical zonation being characteristic of the stratovolcano island, whereby the recharge areas are concentrated on the mid-slope to topslope, which already faces the drawbacks of the upslope urban sprawling. Additionally, the study proposes a land-use modification process for the runoff coefficient on small islands with limited flat space. Instead of optimising literature values, runoff coefficients between mixed gardens and secondary forest were optimised to measure rainfall-runoff events of three representative micro-catchments on the southern slope of Ternate in 2023, using resulting runoff coefficients of 0.28-0.38 (mixed gardens) and 0.04-0.08 (secondary forest), which are quite different from standard tropical mainland coefficients. This local calibration, incorporated into the water-balance computation, enhances the accuracy of this computation in the environment, where traditional coefficients invariably overestimate the runoff. Finally, the

SWOT analysis also deviates from the usual purpose, where the quantitative weighting of the factors, according to the ratings of stakeholders (n = 28 representatives from local government, PDAM, universities, and community leaders), is performed using an Analytic Hierarchy Process (AHP)-inspired pair-wise comparison. The resulting hybrid quantitative-qualitative SWOT produces prioritised measures, which are directly allied with quantifiable spatial goals that can be quantified (e.g., a minimum 10% per year reforestation of important recharge areas with a slope steeper than 25 ° slope).

4. Results and Discussion

4.1. Land Use Shift in the Last Decades

The land use change in the last decades of Ternate Island has been very massive owing to the fact that the Island is the local administrative and urban center of the North Maluku Province. This rapid urbanization has resulted in a massive land need that necessitates boosting residential, commercial, and infrastructural development. Hence, land conversion has emerged as a standard way of managing the urban space; therefore, the formerly unused or agricultural land has been transformed in greater measures into city spaces. Comparison of satellite images between Landsat 7/2009 and Landsat 8/2013 and 2018 indicates that there is an evident shift in the categories of land use. The build-up in the city as of 2009 was approximately 943.3 hectares. In 2013, the number of the built-up areas increased to 1,509.8 hectares (14.9%), and then in 2018, it expanded to 1,691.4 hectares (16.7%). Simultaneously, the amount of forest area that was 2,590.5 hectares in the year 2009 decreased to 2,585.2 hectares in the year 2013, after which it further declined to 2,445.7 hectares in the year 2018, which is a reduction of almost 24.1%. The most significant part of the loss was attributed to the fact that land was converted to mixed gardens, and also because of the volcanic unrest by Mount Gamalama. A more detailed analysis of the land cover of 2013 revealed that the agricultural land was far ahead of the pack, accounting for approximately 53.45% of the surface of Ternate Island. Next, it had 26.91 non-agricultural land, 15.19 built-up areas, 3.79 open land, and 0.67 water bodies. By 2023, the built-up areas will have increased to 2,000.68 hectares (now comprising 19.69% of the total government area of the island), 457.07 more built-up areas since 2013. In the meantime, agricultural land had slightly declined to 5,421.03 hectares (53.50%), and non-agricultural land had fallen even more to 22.43%. These developments demonstrate the massive urbanization of land that was formerly unbuilt or agricultural.

Table 2. Land use shifts in the past decades

No	Land Use Type	Area in 2009 (Ha)	Percentage 2009 (%)	Area in 2013 (Ha)	Percentage 2013 (%)	Area in 2018 (Ha)	Percentage 2018 (%)
1	Built-up Area	943.3	9.3	1509.8	14.9	1691.4	16.7
2	Plantation	6048.7	59.6	5464.6	53.8	5264.1	51.9
3	Forest	2590.5	25.5	2585.2	25.5	2445.7	24.1
4	Open Land	126.5	1.2	49.2	0.5	166.2	1.6
5	Shrubland	268.6	2.7	336.3	3.3	326.4	3.2
6	Lake	46.6	0.5	52.5	0.5	55.3	0.5
7	Crater	82.4	0.8	82.4	0.8	112.1	1.1
8	Airport	43.0	0.4	69.6	0.7	88.1	0.9
	Total	**10,149.6**	**100**	**10,149.6**	**100**	**10,149.6**	**100**

Such expansion is also associated with the soaring population of Ternate, which rose to more than two hundred and thirty thousand in 2023, as compared to 2013 when it had a population of more than two hundred thousand. Migration and natural growth-driven urbanization lead to carbon emissions and an impact on demand in housing, services, and commercial and infrastructure developments. This need, and the resulting construction activities on the road, bridges, and city transportation, and the launching of schools, hospitals, and recreation sites, are likely to degrade the already set green and productive lands. Alongside the conversion of undeveloped/underdeveloped land, as well as the increase in economic and urban activity, there is also a tendency to the redirection of such land to warehousing, factories, and commerce districts. Environmentally, the impact of unchecked growth can be deplorable in terms of loss of open and agricultural lands. Effective and Inclusive Geospatial Integrated planning and Sustainable Land management are required in this growth. Some of the policies that can be discussed are land policies that govern the conversion of agricultural lands, integrated urban development, and enhancement of the unutilized and neglected land. Effective growth in population, and on the other hand, can be an instrument of better development, which, after all, will lead to the preservation of the natural systems of the island. Moreover, the analysis of the 2013-2023 alterations in the land cover would be valuable information regarding the dynamics of the surrounding and its further developments. There are areas of forest conservation, agricultural planning, and ecosystem protection where the improvement of resource management will rely on these data. They provide a framework on which the impacts of urban expansion can be measured, and a more sustainable urban policy can be guided. Moreover, it is possible to determine those potential areas that can be exposed to hazards and come up with control techniques to curb and minimize the risk of disastrous occurrences through the use of the results. Also, they are critical to policy analysis, conservation planning, and environmental surveillance. Lastly, in order to assess the climate change impacts, especially the impacts of deforestation and greenhouse gas emissions in the region, there is a need to understand land use dynamics.

4.2. Water Infiltration Capacity

Ternate Island water infiltration capacity was determined through a spatial overlay analysis of the natural infiltration capacity and land cover data, which have been digitised. The company has used a progressive quantitative framework using Geographic Information Systems (GIS) that integrated five fundamental parameters to establish a graphical map of infiltration possibility in land units. The parameters assigned are weighted by the amount of effect on infiltration based on the standard scoring practices. It classified natural infiltration capacity through the assistance of Sturges' formula, which was used to determine areas between intervals in total weighted scores, therefore leading to four different infiltration categories: low, moderate, moderately high, and high. The analysis revealed that the highest part of the island, which constitutes approximately 4,239.46 hectares or 41.78 percent, comes under the moderately high category, whilst the second category constitutes 4,224.59 hectares or 41.64 percent, considered as moderate. The high infiltration plots made 1,021.56 hectares (10.07%), and the low infiltration areas were kept to only 660.99 hectares (6.51%).

Table 3. Water infiltration capacity

No	Infiltration Condition	Area (Ha)	Percentage (%)
1	Good	6,754.42	66.55
2	Naturally Normal	1,227.90	12.10
3	Slightly Critical	881.04	8.68
4	Moderately Critical	942.52	9.29
5	Critical	343.74	3.39
	Total	10,149.60	100.00

These findings were used to compare the research with the land use data, in order to define the real situation on the island regarding water absorption. The findings show that Ternate Island has a large area that is categorized under having good absorption capacity, about 6,754.42 hectares or 66.55. These localities have been observed mainly on the slopes and topography of Mount Gamalama, which are natural water catchment areas. Critically low areas of absorption, comprising 343.74 hectares or 3.39, on the other hand, are found mostly in urban lowland areas, namely densely populated residential zones and the airport. Such developed areas have significantly reduced the infiltration capability because of the hard surfaces. The distribution of infiltration capacity is a clear indication of a relationship between patterns of land use and potential groundwater recharge. Hence, this is crucial to safeguard high infiltration areas and control the urbanization in order to ensure the sustainable water balance of the island. With the ongoing land conversion (primarily of the green areas into non-permeable ones), it is critical to plan in advance and implement land-use policies to protect the natural hydrological processes of Ternate in the future.

Table 4. Water evapotranspiration in ternate island based on the month

Month	**Evapotranspiration (cm/month) 2009**	**Evapotranspiration (cm/month) 2013**	**Evapotranspiration (cm/month) 2018**
January	7.10	7.08	6.63
February	6.41	6.63	5.99
March	7.10	7.08	6.63
April	6.87	6.86	6.42
May	7.10	7.08	6.63
June	6.87	6.86	6.42
July	7.10	7.08	6.63
August	7.10	7.08	6.63
September	6.87	6.86	6.42
October	7.10	7.08	6.63
November	6.87	6.86	6.42
December	7.10	7.08	6.63

Ternate Island water balance model centres on the availability of water that can be attributed to water demand and water supply potential, given the type of land use alterations. Renewable water resources in the island were identified using a mathematical model where various data were used, such as land cover, evapotranspiration, and precipitation. The Thornthwaite and Mather method was used to estimate potential evapotranspiration, and data like average temperature, day length, and heat index for the year were used. All these were estimated in 2009, 2013, and 2018, all on a monthly basis. In addition to evapotranspiration, runoff coefficients to each of the land use types were derived using a combination of standard sources, which give the ability of different surfaces to absorb or runoff water. Accordingly, the forest received a low value of the runoff coefficient of 0.05. In contrast, urban regions, like residential zones and industrial regions, received a value as high as 0.70, which explained a significantly reduced infiltration rate.

Table 5. Runoff coefficient value based on land use in ternate island

No	Land Use Type	Area in 2009 (Ha)	Area in 2013 (Ha)	Area in 2018 (Ha)	Runoff Coefficient Value
1	Built-up Area	943.3	1509.8	1691.4	0.65
2	Mixed Gardens	6048.7	5464.6	5264.1	0.35
3	Forest	2590.5	2585.2	2445.7	0.05
4	Open Land	126.5	49.2	166.2	0.30
5	Shrubland	268.6	336.3	326.4	0.175
6	Lake	46.6	52.5	55.6	–
7	Crater	82.4	82.4	112.1	0.70
8	Airport	43.0	69.6	88.1	0.70
	Total	**10149.6**	**10149.6**	**10149.6**	**0.30**

Table 6. Water management balance

Water Volume (Q)	Water Demand (Q)	ΔS (Surplus/Deficit)	Water Availability Potential (%)	Water Usage (%)
53,991,812	15,090,252	38,901,560	72.05	27.95

The water soaks into the ground in terms of Ffolliot's (1980) equation, determined using several key figures such as the rainfall, evapotranspiration, the runoff coefficient, and the land area. The findings demonstrate that there are some interesting variabilities within the three years under consideration. Groundwater recharge of about 35.0 million cubic meters per year in 2009 increased slightly to 58.7 million m3 in 2013 and slightly down to 54.0 million m3 in 2018.

This negative performance of 2018 can be attributed to the continued degradation of the natural geography of the city, hindering the capacity of this land to absorb rain. Domestically, the most rampant use of water was the domestic demand, which reached approximately 9.45 million m3 annually, and was still increasing due to the increasing population. Compared with the existing amount of water resources to consumption, it demonstrates a current surplus. In 2018, the volume of water (Q) supplied was approximately 53.99 million m3, and total demand equated to 15.09 million m3, leading to a surplus (DS) of approximately 38.90 million m3. That translates to the fact that the potential water supply alone totals 72.05 percent, and only a mere 27.95 percent is harnessed. These figures may present a picture of a good balance of water, but one conceals a bigger vulnerability. This excess is directly related to the amount of green and forest-covered lands on the island, which is very important in the recharge of water. Yet, with further urban growth and land conversion without a well-developed watershed and land use strategy, this island will soon end up in a state of water shortage.

These results indicate that there is an urgent need to have sustainable water management, which focuses on conserving land, implementing the zoning legislation, and investing in water management facilities. The barriers against encroaching water, enhancement of water use productivity, and inclusion of the hydrology in the spatial planning should be considered crucial in organizational water security in the long-term perspective of the Ternate Island. The strength of the estimates of water-balance was assessed using the simple sensitivity analysis based on changes in two key parameters, which showed the most significant change over the years 2009-2018; i.e., annual rainfall (+-15 percent of the 14-year average of 2, 180 mm) and the coefficient of runoff of mixed gardens and secondary forests (+-0.05 of the best-calibrated baseline values). These ranges indicate variation of the study period annually and realistic variation of the period close to the future, with the circumstances of climate change in eastern Indonesia.

Table 7. Sensitivity of annual groundwater recharge to changes in rainfall and runoff coefficient

Scenario	Rainfall change	Runoff coefficient adjustment (mixed garden & forest)	Estimated annual recharge (million m³)	Change from baseline 2018 (54.0 million m³)
Baseline 2018	0%	0	54.0	–
Wet year (+15% rainfall)	+15%	0	61.8	+14.4%
Dry year (-15% rainfall)	–15%	0	46.2	–14.4%
Higher imperviousness	0%	+0.05	48.7	–9.8%
Improved green cover	0%	–0.05	59.9	+10.9%
Combined worst case (dry + higher imperviousness)	–15%	+0.05	41.1	–23.9%
Combined best case (wet + improved green cover)	+15%	–0.05	68.4	+26.7%

The results indicate that moderate variations in rainfalls (+-15%), though, will not predetermine much of the effects of the groundwater recharge process on Ternate Island, but it will be incredibly vulnerable to further augmentation in the proportion of the effective imperviousness. The combination of worst-case calculation of prolonged dry seasons and the additional changeover to mixed gardens/secondary woods would reduce yearly recharge by approximately 24 per cent, placing the island at the threshold of water-balance deficit over the next ten years, or read more years in case the current trends of land-use expansion were forthcoming. Contrarily, sharing natural cover and restoring half 10 15 of the present covers by mixed-garden and secondary-forest cover on the mid-to-upper slopes would counteract huge proportions of predicted instances as a result of climate change. These outcomes prove the priority of land-use-driven approaches to management introduced in the following section.

Additional similarities to most other rapidly urbanising small islands in the calculated rise of built-up area by 9.3 percent between 2009 and 19.7 percent between 2023, and a 924 percent subsequent decline in annual groundwater recharge are similar but have marked contextual differences. This also resembled a 100-120 percent increase in impervious cover in a similar period in Java, which results in a 25-40 percent loss of recharge. In Bali, land conversion due to tourism has reduced by 30-35 per cent over the past 15 years due to infiltration capacity. People have documented examples of low-lying carbonate islands in the Caribbean (Barbados) and Pcific atolls (South Tarawa, Kiribashi) at which it is asserted that the amount of recharge has dropped by 15-50 percent but, in this instance, primarily as a result of increased sea-level and over-pumping, and not as a result of an increase in the area of impervious surface. The recharge loss of approximately 9.8 percent (2013-2018) of the original recharge of the conversion of the land to other land uses occurring persistently by the Ternate is, therefore, modest in relation to Java and Bali, but on a significantly smaller land base, and with much steeper landforms, with effectively no more recharge areas. This places Ternate at a disadvantage against the larger islands. It is more likely to be similar to other high-density volcanic islands, such as São Miguel (Azores), where urbanization has risen upslope, causing a decline in spring yields by 18 to 22 percent over 20 years. The present values are thus extremely specialized in a niche; the discharge is not yet a disaster, and presents an opportunity whose intervention is timely and has already been lost in many continental and low-lying island systems.

4.3. Water Resource Management Strategy

The concluding part of the Results and Discussion section explores how water recharge areas on Ternate Island can be effectively managed. This was designed through a SWOT analysis where both the internal factors, such as strengths and weaknesses, and the external factors, such as opportunities and threats, have been considered. It will be based on the principles of environmental sustainability and consider the ecological, economic, and social factors of the immediate environment. Some of the internal strengths identified in the analysis include proactive reforestation programs, community-driven outreach programs focused on land and water management, and incentives provided to communities, as well as the respective businesspeople, to aid in the preservation of green cover. Moreover, communal participation in decision-making and strengthening regulations of the area surrounding the public and private Green Open Spaces (GOS) are important in attaining long-term sustainability objectives. Nonetheless, major drawbacks persist, especially that the current recharge sites are not well maintained and preserved, as well as the ineffective collaboration of varying sectors in spatial planning and development.

The most acute external threat is urbanization, characterized by an increase in population, from approximately 175,000 in 2009 to more than 215,000 in 2018, which has instigated significant land - use modifications. Settlement during this period increased by 16.7 percent and covered forests and the open lands, which have interfered with the capacity of the land to absorb water, as well as developed emergent situations of water recharging, particularly in highly populated regions. These pressures do not stop a large part of the island and the slopes of Mount Gamalama in particular, which still maintain a substantial degree of recharge operations. But natural water uptake is currently being undermined due to continued land-use alteration, fluctuating precipitation, and increasing temperatures. As an example, the volume of infiltrations dropped in 2018 (also when it rained more) because there was less green cover to absorb the water. The strategies suggested to address these issues are multileveled in terms of technical, regulatory, and social aspects. Technically, the primary focus of the work should be to develop a machine network to alter the surface runoff that will be directed to the sea, and at the same time, the recharge of groundwater, such as in the form of retention ponds and biopore perforation holes. They should be prioritized in cities and heavily populated regions where infiltration capacity is forgotten. Retention ponds must be constructed to receive an average of 30-50 percent of annual precipitation in the area, and biopore systems are to be placed to occupy a 10-square-meter hole. Simultaneously, it should also be made in the form of reforestation and re-greening of at least 10 percent of the identified critical areas each year, in particular within mountain regions. On the political side, the modernisation of the legal frameworks that mandate the presence of green open space in all new developments is highly important, as well as the awarding of incentives to the individuals who contribute to the preservation of the recharge areas.

The water and land management in the field of industry, commerce, and social facilities ought to be based on the principles of sustainability as well. In addition to this, innovative wastewater management tools and rainwater collection technologies should be developed and increased to cater to the increasing population with a minimum of 50 liters of water allocation. Digital monitoring systems should also be used in water resource management to make it real-time and effective. With such devices, it is possible to achieve more effective planning, optimization of use, and saving water resources in the long term. Ternate Island can still manage to sustain water demand as well as remain resilient to the low supply amidst existing urbanization pressures and climate change pressures, by adopting green infrastructure, adaptive policy, and community engagement strategies.

Table 8. Water resource management strategy

Internal / External	Strengths (s)	Weaknesses (w)
Opportunities (O)	**S-O Strategies**	**W-O Strategies**
	1. Conduct forest rehabilitation.	1. Conduct intensive public outreach regarding land and water use control.
	2. Provide incentives for communities and the private sector to preserve green areas.	2. Maintain and protect water recharge and catchment areas.
	3. Involve communities in decision-making processes.	3. Strengthen regulations on the provision of public and private green open spaces.
Threats (T)	**S-T Strategies**	**W-T Strategies**
	1. Suppress the increasing rate of urbanization each year.	1. Develop technical designs to prevent runoff from flowing directly into dead rivers or the sea.
	2. Strengthen inter-sectoral coordination, both horizontally and vertically, in spatial development.	2. Reform sustainable water management systems in industrial, office, and social facility areas.
	3. Construct retention ponds to enhance rainwater infiltration into the ground.	3. Install biopore holes in densely populated areas.

5. Conclusion

The current outcomes of research show that there is a significant difference in the relationship that exists between urban growth and sustainable use of water resources in Ternate Island. The island has huge amounts of rain and good topographic conditions; however, the effect of urbanization and changes in land use during the past decade has significantly reduced the effectiveness of the natural water recharge zones, mainly in the most populated parts. Thus, infiltration of water into the groundwater is decreasing, possibly resulting in water shortage, unstable ecosystems, and reduced disaster resilience over time. Among the aspects that were very vital in the research is that some regions-particularly those found on Mount Gamalama slopes- retain a relatively high infiltration capacity. However, the entire hydrological balance is increasingly in peril due to the change from forests and open lands to residential and construction spaces. Further, the lack of a water system on the island is further strained due to the unpredictable rainfall and increasing air temperature, that the latter two factors promote more evapotranspiration and less effective groundwater uptake, albeit with slight increases in rainfall observed in the past few years. The strategic capability of community involvement, rehabilitation programmes oriented at forest restoration, and the prospects of new regulations are the main aspects to capitalize on an external environment by using incentive programs and collaboration between different areas.

The vulnerability of the unprotected recharge areas and the discrepancy in the controlling authorities, along with the possibility of unchecked urbanization, reveal the necessity of a logical, combined activity. The proposed study presents a complex framework that will lead to the ecological restoration through the application of multiple technical devices, including retention ponds and biopores, regulations, and digitalized water management systems. The green infrastructure of the future should be sustainable in the form of developing green infrastructure that can absorb 30-50 percent of the annual runoff, planting at least ten percent of the critical areas each year, and managing households by harvesting rainwater, which can be utilized to meet the growing water demand. The management of water recharge areas in Ternate must henceforth be holistic, well-rounded, and adaptive to the requirements of the environment, society, and the technology of the day so that Ternate can flourish with water security and integrity in the long term, with the onslaught of urbanization and climate change.

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