Analysis of small island environmental carrying capacity in Panggang Island, Jakarta, Indonesia

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Abstract. To support continuity of life, information on the availability of natural resources is needed. Natural resources need in a region must not exceed their availability. Panggang Island is a small island with an area of 13.76 ha and a population density up to 4,388 people in 2019. The land use of the island is intended as a residential area. With a small area and dense population, the ability of the environment to support life in Panggang Island is concerning. This study aims to determine the carrying capacity of water and land in Panggang Island. Water carrying capacity analysis is carried out by comparing the amount of water resource availability with standard water needs. The Thornthwaite Mather method is applied to calculate the water resource availability. Land carrying capacity analysis is based on a comparison of the amount of actual residential land with minimum space requirements of each individual according to the Indonesian National Standard (SNI 03-1733-2004). The results showed that Panggang Island has a very low carrying capacity for water and land. The water and land carrying capacity index reaches 0.12 and 0.98 respectively. This shows that the demands of residential land and water in Panggang Island are higher than the resources.

1. Introduction

Environmental carrying capacity is an ecological concept defined as a population of an organism that can be withheld in a particular environment in a stable condition concerning the availability of its natural resources [1]. This concept can be used to evaluate the continuity of human population in a certain region, especially in an area with limited resources, including small islands. In order to support the continuity of life, the needs of natural resources must not exceed their availability. Therefore, the information of both resources and availability must be known and thoroughly calculated.

Panggang Island has 4,388 inhabitants per 2019 in its 13.76-hectare land. As the population keeps getting denser, the needs of natural resources will be naturally inclined. Two most fundamental needs that will be considered are water and land, whose carrying capacity will be subsequently calculated.

Spatially, Panggang Island is located in 5°44'18.71" South Latitude and 106°36'4.27" East Longitude. The water carrying capacity are calculated using Thornthwaite Mather’s water balance method using data of monthly temperature, monthly precipitation, land use, soil type, and DEM in 2019 and population in 2019 and land carrying capacity are based on a comparison of the amount of residential land availability with minimum space requirements of each individual, which will be comprehensively deciphered in chapter two. The purpose of this study is to determine water and land carrying capacity in Panggang Island and provide recommendations based on the results.
2. **Materials and Method**

2.1 **Data input**

The data used in this research are population, monthly temperature, monthly precipitation, land use, soil type, and slope based on DEM. The data were collected from primary and secondary sources. Table 1 shows the data used along with their sources.

| No. | Data           | Source                                                                 |
|-----|----------------|------------------------------------------------------------------------|
| 1.  | Population     | Projection from Fanni, 2012                                           |
| 2.  | Temperature    | European Centre for Medium-Range Weather Forecasts (ECMWF)            |
| 3.  | Precipitation  | Centre for Hydrometeorology and Remote Sensing (CHRS)                 |
| 4.  | Land Use       | Google Earth                                                          |
| 5.  | Soil Type      | Google Earth                                                          |
| 6.  | Slope          | DEMNAS                                                                 |

2.2 **Methods**

The procedure of this research is presented in Figure 1.

**Figure 1.** The flowchart of this research

Quantitative analysis method was applied to analyze carrying capacity with mathematical formulas.

2.2.1. **Water carrying capacity.** Water carrying capacity calculation is defined as the ratio between the amount of water available and the demand in the area. The equation is shown in equation 1.

\[
\text{Carrying Capacity} = \frac{\text{Supply}}{\text{Demand}}
\] (1)
If the value is greater than 1, there will be a surplus condition where the ecosystem is able to support the people who live in it. Conversely, if the value is less than 1, it means that there is a condition where the ecosystem is not able to support the people who live in it.

Water carrying capacity analysis was derived by comparing the amount of water resource availability to standard water needs. According to the Ministry of Public Works and Public Housing (known as PUPR), the standard for basic water needs for small areas, such as Panggang Island, with a population of 3,000 - 20,000 people is 60 liters/person/day [2]. In order to obtain the amount of water needed, the number of populations must be known. A calculation for projecting populations from 2013 to 2019 was conducted using equation 2

\[ P_n = P_0 + (1 + r)^n \]  

where \( P_n \) is the number of populations in year n, \( P_0 \) is the number of populations from the previous year, and \( r \) is the average of population growth based on data in 2012, by the number of 0.86% [3].

After the number of populations was known, the total amount of basic water needs in Panggang Island was calculated using the formula shown in Equation 3.

\[ T_{wd} = P \times W_r \]  

where \( T_{wd} \) is total of daily water needs (liters/day), \( P \) is population (person), and \( W_r \) is standard of daily water needs (liters/person/day)

Water availability was determined based on the available groundwater storage using the surplus results obtained from the calculation of Thornthwaite Mather’s water balance method [4]. Water surplus (\( S \)) can be determined from precipitation (\( P \)), actual evapotranspiration (\( AE \)), change in water storage (\( \Delta S_T \)), and runoff (\( RO \)) as shown in Equation 4.

\[ S = P - AE + \Delta S_T - RO \]  

With the assumption that rainwater for evapotranspiration needs can fill the entire groundwater and the excess water is counted as a surplus if the availability of groundwater has reached the maximum limit. The process of calculating surplus water availability is carried out sequentially starting from temperature (\( T \)), heat index (\( I \)), potential evapotranspiration (\( PE \)), precipitation (\( P \)), difference in precipitation and potential evapotranspiration (\( P - PE \)), potential accumulation of water loss (\( APWL \)), water storage (\( ST \)), changes in water storage (\( \Delta ST \)), actual evapotranspiration (\( AE \)), deficit, runoff (\( RO \)), and surplus. Calculation of water balance is elaborated on these following steps:

1. Monthly average temperature (\( T \)) calculation.
2. Heat index (\( I \)) calculation using the formula \( I = (T / 5)^{1.514} \).
3. Potential evapotranspiration (\( PE \)) calculation using the average duration of sunlight each month adjusted for latitude and moon.
4. Difference between rainfall and potential evapotranspiration calculation (\( P - PE \)).
5. Potential accumulation of water loss (\( APWL \)) calculation by accumulating the total value (\( P - PE \)) for a year. The APWL value is equal to the accumulation of the previous (\( P - PE \)) if (\( P - PE \)) is negative, and 0 if (\( P - PE \)) is positive.
6. Water savings (\( ST \)) calculation by looking at the APWL value. For \( APWL = 0 \) then \( ST = WHC \) (Water Holding Capacity). For \( APWL \) is negative then \( ST \) can be obtained from the value given by Thornthwaite Mather based on the APWL value per month.
7. Changes in water storage (\( \Delta ST \)) calculation of each month.
8. Actual evapotranspiration (\( AE \)) calculation with the formula if \( P > PE \), then \( AE = PE \) and if \( P < PE \), then \( AE = P + \mid \Delta ST \).  
9. Deficit (\( D \)) calculation with the formula \( D = \mid PE - AE \).
10. Surplus calculation with the formula $S = (P - PE) - \Delta ST$.

Water Holding Capacity (WHC) is the ability of the soil to hold water. Based on the Thornthwaite Mather water balance method, calculation of WHC requires an area value and a percentage of land use, especially bare land and vegetation on Panggang Island. Bare land has a $Sto$ value of 75 mm and vegetation has a $Sto$ value of 250 mm. The value of $Sto$ is one of the parameters in the calculation of water holding capacity, whose value will be included in the water balance.

Runoff calculation was carried out using Potential Runoff Coefficient (PRC). PRC represents amounts of precipitation that runoff the surface during rain, which is determined by land use, soil type, and slope [5]. PRC was calculated using equation 5 [6].

$$C = C_0 + (1 - C_0) \frac{S}{S+S_0}$$ (5)

where $C$ is PRC for slope $S$ (%). While slope coefficient ($S_0$) is subject to only land use, PRC coefficient for a near zero slope ($C_0$) is dependent on both slope and land use. The values of $S_0$ and $C_0$ are shown in table 2, ranging from 0 – 1, where 1 indicates most impassable.

| Land use | Slope (%) | $S_0$ | $C_0$ |
|----------|-----------|-------|-------|
| Vegetation | $< 0.5$ | 0.03 |       |
|           | $0.5 - 5$ | 0.07 | 0.68  |
|           | $5 - 10$  | 0.13 |       |
|           | $> 10$    | 0.25 |       |
| Bare land | $< 0.5$ | 0.33 |       |
|           | $0.5 - 5$ | 0.37 | 0.42  |
|           | $5 - 10$  | 0.43 |       |
|           | $> 10$    | 0.55 |       |
| Built-up  | 0 - 100   | 1    | 1     |
| Water     | 0 - 100   | 1    | 1     |

Slope calculations were carried out using Digital Elevation Model National (DEMNAS) obtained from the Geospatial Information Agency (BIG). DEMNAS is built from several data sources including IFSAR, TERRASAR-X, and ALOS PALSAR data, by adding the stereo-plotting Masspoint data. DEMNAS’ spatial resolution is 0.27-arcsecond using the EGM2008 vertical datum [7]. Spatial analysis is used to calculate the slope of Panggang Island from DEMNAS.

2.2.2. Land carrying capacity. Land carrying capacity analysis is based on a comparison of the amount of residential land availability with minimum space requirements of each individual. The land carrying capacity is an approach that aims to determine the maximum population that can live on Panggang Island. The population size is determined using the number of houses on the island. Analysis of the minimum space requirements of each individual according to the Indonesian National Standard (hereinafter referred to as (SNI 03-1733-2004)) [8] is used to estimate the number of residential units on Panggang Island.

According to the Provincial Regulation of the Special Capital Region of Jakarta Number 1 of 2012 concerning the 2030 Regional Spatial Plan (known as RTRW), the use of the mainland space of Panggang Island is designated as a residential area [9]. The area of the settlement region is obtained through land cover maps with built-up land cover classes.
In accordance with the Minister of Agrarian and Spatial Planning Regulation No. 17 of 2016 [10], 30% of small island land should be allocated as protected areas. For this reason, land potential that can be used as a residential area can be calculated using Equation 6.

\[
Potential \, Residential \, Area \, Land = Area \, of \, the \, Island \times 0.7 \tag{6}
\]

According to (SNI 03-1733-2004) [8], based on space and fresh air requirements, the indoor air circulation at most twice per hour and an average ceiling height of 2.5 meters, the floor area per person is 9.6 m². To calculate the carrying capacity of the island, the approach according to Equation 7 can be used.

\[
Total \, Floor \, Area = Main \, Floor \, Area + Service \, Floor \, Area \tag{7}
\]

Where the value of the main floor area is 9.6 m² multiplied by the number of people per family. Whereas the service floor area is 50% (basic building coefficient) of the main floor area. With the basic building coefficient of 50%, the minimum lots requirement for each family is 2 times the total floor area. Assuming that each family consists of 4 people, the minimum need for lots is 115.2 m². With the addition of public facilities in the form of secondary local road, which is the lowest class of roads, with a width of 5 meters to connect each residential unit, the number of building units per hectare is 60 units, which can accommodate 240 people [11].

3. Result and Discussion

3.1 Water carrying capacity

Figure 2 displays the population projection from 2013 to 2019. The graph shows the population projection in 2019 reaches 4388 inhabitants.

![Figure 2. Population Projection in Panggang Island](image)

Figure 3 visualizes the amount of monthly temperature and figure 4 visualizes the amount of monthly precipitation respectively on Panggang Island in 2019.
The land use is divided into three classes, which are bare land, vegetation, and built land. Figure 5 visualizes the land use map in Panggang Island in 2019.
The water balance results obtained can be seen in Table 3.

**Table 3.** Water balance calculation using Thornthwaite Mather method in Panggang Island in 2019

| Info | T (°C) | I | Unadjusted PE (mm) | PE (mm) | P (mm) | P-PE | APWL | ST | ΔST | AE | D | S (mm) |
|------|--------|---|--------------------|---------|--------|------|------|----|-----|----|---|-------|
| Jan  | 28.6   | 14.1 | 5.1                | 162.2   | 821    | 658.8| 0    | 200| 0   | 162.18 | 0 | 658.82 |
| Feb  | 29.1   | 14.4 | 5.2                | 149.7   | 221    | 71.2 | 0    | 200| 0   | 149.76 | 0 | 71.24  |
| Mar  | 29.3   | 14.5 | 5.2                | 162.2   | 547    | 384.7| 0    | 200| 0   | 162.24 | 0 | 384.76 |
| Apr  | 29.7   | 14.9 | 5.4                | 162.0   | 341    | 179  | 0    | 200| 0   | 162    | 0 | 179    |
| May  | 29.6   | 14.8 | 5.3                | 162.2   | 190    | 27.8 | 0    | 200| 0   | 162.18 | 0 | 27.82  |
| Jun  | 29.3   | 14.6 | 5.2                | 152.8   | 115    | -37.8| -37.9| 165| -35 | 147 | 5.88 | 0      |
| Jul  | 28.3   | 13.9 | 5.                  | 153.0   | 0      | -153 | -190.9| 76 | -89 | 54 | 99 | 0      |
| Aug  | 27.7   | 13.4 | 4.9                | 151.4   | 5      | -146.4| -337.3| 36 | -40 | 16 | 135.41| 0     |
| Sep  | 27.8   | 13.4 | 4.9                | 147.0   | 0      | -147 | -484.3| 17 | -19 | 2  | 145   | 0     |
| Oct  | 28.6   | 14.0 | 5.1                | 160.6   | 15     | -145.6| -629.9| 8  | -9  | 15 | 145.65| 0     |
| Nov  | 29.5   | 14.7 | 5.3                | 163.8   | 152    | -11.7 | -641.7| 8  | 0   | 152 | 11.77 | 0     |
| Dec  | 29.5   | 14.7 | 5.3                | 170.1   | 904    | 733.8| 0    | 200| 192| 170 | 0.13 | 541.87 |
| Total | 171.4 | 1897.2 | 3311               | 1413.8  | 1354.36| 542.84 | 1863.51 |

Figure 6 displays visualization of slope in Panggang Island in percent-rise and figure 7 shows soil types in Panggang Island which dominated by sand.

![Figure 6. Slope map of Panggang Island](image1)

![Figure 7. Soil type map of Panggang Island](image2)

The value of water availability in liters per year is obtained from the calculation of equation 3. Table 4 shows the surplus value from the water balance calculation, the run-off value calculated using equation 5, and the results from the water supply calculation.

**Table 4.** Water supply in liter per year

| S water balance (mm) | Run Off (Liter/Year) | Area (m²) | Water Supply (Liter/Year) |
|----------------------|----------------------|-----------|--------------------------|
| 1,864                | 24,174,364           | 19012.76  | 11,265,214.46            |
Hereafter the value of water requirement in liters per year could be obtained. With a total population of 4388 in 2019, and the minimum water requirement is 60 liters/person/day, the annual water demand on Panggang Island is 96,097,200 liters.

The calculation of the carrying capacity of water was carried out using Equation 1, where the value of the water supply was compared with the value of the water requirements. The result of these calculations is the water carrying capacity index of 0.12. This means that Panggang Island is only able to support as much as 12% of the existing water needs. The map of water carrying capacity in Panggang Island is shown in Figure 8.

![Figure 8. Water carrying capacity map in Panggang Island.](image)

### 3.2. Land carrying capacity

The land part of Panggang Island is used for residential purposes. After the area of the island has been reduced by 30% to allocate protected areas, the remaining area that can be used as a settlement is 9.25 hectare. Table 5 describes the potential area of land, population, and number of buildings that can be accommodated and actual conditions on Panggang Island.

| Land Carrying Capacity | Actual Conditions |
|------------------------|-------------------|
| The potential area of land | 9.25 hectare-land | 9.48 hectare-land |
| Population             | 2221 persons      | 4388 persons      |
| Number of buildings    | 555 units         | 850 units         |

In Table 5, it can be seen that the potential area for residential land, the population, and the number of existing buildings has exceeded the carrying capacity of the land. The difference in potential area of land for settlements is 0.23 ha. The total population in Panggang Island in 2019 is almost twice the number of people that can be accommodated. The index of the carrying capacity of the land reaches 0.98 which means that Panggang Island is able to support 98% of the land needs, but this still shows that Panggang Island has not fully supported the people in it. The map of land carrying capacity in Panggang Island is presented in Figure 9.
3.3. Discussions
Carrying capacity is the ability of the environment to be able to support the life of living things and the balance between the two. The concept of carrying capacity can be seen from two sides; availability and demand. Availability includes the characteristics of the area and its potential of natural resources, while demand includes the needs of living things and the policy of an area. In terms of its own needs, population is highly correlated with the carrying capacity of an area, in this case Panggang Island. The denser the population on the island, the higher the level of demand. This also correlates with land use, where the denser a population, the more land is built up on an island. Panggang Island is located separately from Java Island and the lack of transportation and infrastructure, the fulfillment of needs will be more hampered. If demand cannot be fulfilled, it will become an environmental problem.

Some recommendations that can be given from the results of this study are the application of suitable clean water management technology that can be applied by using the nature and function of the island's natural environment. Besides being useful, it must also be in accordance with the built and social environment on Panggang Island. The technology used should be comprehensible and applicable by the community, and provide benefits according to the predetermined goals of clean water management. Furthermore, the management of clean water quantity which aims to increase the amount of clean water that can be used by residents on Panggang Island includes optimization of rainwater harvesting by catching rainwater from house roofs, which is then collected in rainwater storage tanks. Rainwater storage tanks must be available in every house with a minimum volume of a predetermined tank. Moreover, there is a need for further treatment to prevent the water in the tank from being contaminated by pollutants in the environment so that it does not endanger the health of the people who use the water. The next step that can be done is spatial planning. Spatial planning is something that needs to be considered in order to create a balance between open spaces, residential areas, and the use of facilities and infrastructure needed by residents. Spatial planning for small islands has different characteristic than main islands. For example, if there should not be any settlements on the coastal border, then small islands such as Panggang Island may not be used as settlements. Due to inadequate transportation, water and disposal infrastructure, the fulfillment of needs will be hampered. Small islands are required to be independent more than areas on main islands.

4. Conclusion
The water and land carrying capacity index in Panggang Island are 0.12 and 0.98 respectively. This means that there is a condition where the ecosystem on Panggang Island is unable to support the people who live on it. Recommendations to overcome the problem of the low carrying capacity index on
Panggang Island include efficient clean water management, clean water quantity management, and spatial planning on island.

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