The Mapping of Quantitative Carrying Capacity Using Multi-Scale Grid System (Case Study: Water-Provisioning Ecosystem Services in Greater Bandung, West Java, Indonesia)

Dini Aprilia Norvyani1*, Akhmad Riqqi2, Agung Budi Harto2, Sitarani Safitri2
1 Department of Geodesy and Geomatics Engineering, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Bandung, Indonesia
2 Remote Sensing and Geographical Information Science Research Group, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Bandung, Indonesia

1. Introduction

In Indonesia, carrying capacity assessment is a basis for the environmental planning and management, as has been mandated by Law of the Republic of Indonesia Number 32 Year 2009 on Environmental Protection and Management. This hereby the government to be able to determine the status of carrying capacity by quantifying the threshold of each regional environment. Furthermore, the status needs to be represented spatially for a comprehensive analysis – as carrying capacity has become an important indicator for the government in decision-making. Spatial modelling of carrying capacity is a crucial to ensure the sustainability of land resources exploitation and developmental program.

However, spatial modelling presents an issue caused by the various data with different scales that will be needed to model the carrying capacity. It will take a lot of data types while Indonesia has limitations in the provision of such data. Therefore, there are two mapping methods by Eigenbord et al. (2010) based on the availability of data, among which methods are based on primary data and methods not based on primary data (using approach).

The quantitative approach may have a relatively higher accuracy in mapping so it can display more detailed information for decision making (Mashita 2012). Since carrying capacity can be represented by ecosystem services in the frame of its function in supporting the life of the population in an ecoregion. Therefore the empirical relationship between spatial variables that are considered significant, with the value of ecosystem service indicators, must first be explained in order to make a quantitative approach to the mapping of carrying capacity.

In general, there are three types of indicators used to quantify the types of ecosystem services (de Groot et al. 2010), namely (i) indicators of how processes occur in ecosystems and services, (ii) number of services generated; and (iii) performance indicators that demonstrate the potential of ecosystems to be utilized sustainably. The assessment of these ecosystem services can be quantified through the existing landscape. For example, Table 1 shows the indicators of ecosystem services for food supply services and water supply services.

The carrying capacity status can be determined by its ecosystem services threshold. Simply put, a threshold is an acceptable level. In the context of the environment, the threshold is interpreted as a condition when there is a sudden change in the quality of an ecosystem, property or phenomenon, or when small changes in the environment produce

ABSTRACT

Spatial modelling using multi-scale grid system is adopted to determine the threshold and distribution pattern of regional carrying capacity. Water-provisioning service is used as a quantitative approach. Closed system was applied in which it was based solely on the potential of existing resources in the region without taking into account the flow of material in or out of the system. Steps being taken include the distribution of water demand – of land and domestics – and supply; and the determination of carrying capacity status based on the threshold of water-provisioning services. A grid system with 5°×5° resolution is used to accommodate the various sets and scale, of data. The result shows, 82.29% of Sumedang Regency; 68.43% of Cimahi City; 61.29% of Bandung City; 60.51% of Bandung Barat Regency; and 57.34% of Bandung Regency are still able to fulfill the demands of the population.
2.1. Multi-Scale Grid System

A grid system is a two-dimensional structure, formed by horizontal and vertical lines intersection, which part an area (Riqqi et al. 2011). It can be used to manage various sets of environmental-related spatial data. It is also satisfying to represent continuous geographical phenomena which change gradually, for example, to model greenhouses gases emission. This method is able to describe the phenomenon with diverse patterns by utilizing information that refers to a range of scales (Meentemeyer 1989; Wiens 1989; Hay et al. 200; Riqqi 2008).

The multi-scale grid system applied was developed by Riqqi et al. (2011) which refers to the Indonesian grid system. This grid system uses Sistem Referensi Geospasial Nasional 2013 (SRGI 2013) and geodetic coordinate system. The grid number acts as the identifier of each cell on the multi-scale grid system. Systematic numbering starts from the origin and so on up to the east and north. This grid numbering system starts from a grid of 1° 30’× 1°, derives to the smaller size up to a grid of 5’×5’.

This research used the smallest resolution, which is 5’×5’, i.e. each grid has a size of ± (0.150 × 0.150 km). The time basis applied for this research is in the year of 2015.

2.2. Population Distribution in Grid System

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2. Materials and Methods

In modelling water-provisioning carrying capacity, water demand is distributed by using population distribution with the administrative area as well as the land cover, as the spatial units. Whereas, water supply is modelled with river area and ecoregion as the spatial units (Table 2). Hence, the multi-scale grid system was used in this research to overcome the obstacle within the complexity of data.

Metropolitan Bandung Raya (Greater Bandung) was chosen as the study area of this research. It covers Bandung City, Cimahi City, Bandung Regency, Bandung Barat Regency, and Sumedang Regency. Its population is around 8.5 million people in 2015 (BPS 2015). These areas have been being developed to form a unit of urban area in which the development should be controlled in accordance with each regional carrying capacity.

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2.2. Population Distribution in Grid System

The population distribution model that Nengsih (2015) had created was adopted to distribute the population of every district into the grid system. The distribution is based on the road classes and the land cover types. As in Table 3, every land cover and road has weight to distribute the population.

2.3. Demand Calculation

There were two kinds of water demand to be considered in this research, domestic uses and land utilization. Demand for domestic uses was calculated referring to the Regulation of State Minister of Environment Number 17 Year 2009 on Guidelines for Determination of Environmental Support Capability in Spatial Planning. The equation used is as follows:
\[ D_i = P_j \times KHL \]  
\[ T_i = D_j + Q_i \]  
\[ W_j = \frac{W_{j}}{\sum WPESI_j} \]  
\[ WPESI'_{ij} = WPESI_{ij} \times \left( \frac{LC_i}{LC} \right) \]  
\[ IWPESI'_{ij} = W_j / \sum WPESI_j \]
After obtaining the amount of water supply for one WPESI, the distribution of surface water supply in the grid system was attained with the following equation:

\[ W_{ij} = WPESIJ \times WPESIJ' \]  
(Eq. 6)

with,

\( W_{ij} \): water supply in grid-i of river area-j (m³/year),
\( WPESIJ \): water supply of one WPESI in river area-j, and
\( WPESIJ' \): WPESI of grid-i in the river area-j that will be used in weighting.

2.5. Carrying Capacity Threshold Calculation

Determination of carrying capacity status was done by calculating the difference between water supply and demand; and/or calculating the population threshold. The difference between water supply and demand was achieved by a formula:

\[ S_i = W_{ij} - T_i \]  
(Eq. 7)

with,

\( S_i \): the difference of water supply (m³/year),
\( W_{ij} \): water supply in grid-i of river area-j (m³/year), and
\( T_i \): total water demand in grid-i (m³/year).

Cloud (in Soerjani et al. 1987) illustrates the carrying capacity of the environment by comparison of the amount of resources that can be managed against the total population consumption. This comparison shows that the carrying capacity of the environment is directly proportional to the number of environmental resources and inversely proportional to the amount of consumption of the population. That is, the growth of the population without the increase in the number of resources will cause the carrying capacity of the environment closer to its threshold.

In this study, the carrying capacity threshold was expressed in terms of population and was approached by a comparison of the supply to demand. It was derived from the assumption that threshold is a state when the difference is zero, or when supply is equal to demand.

The carrying capacity threshold of a district is the total of the threshold values of all the grids within that district. Hence, the carrying capacity threshold based on the water-provisioning ecosystem services per grid was calculated by the following equation:

\[ TA_i = \frac{(W_i - Q_i)}{KHL} \]  
(Eq. 8)

with,

\( TA_i \): carrying capacity threshold for water-provisioning ecosystem services in grid-i (person),
\( W_i \): water supply in grid-i of district-j (m³/year),
\( Q_i \): water demand for land utilization in grid-i (m³/year), and
\( KHL \): water demand for worthy life, (m³/person/year).

The carrying capacity status for each district is the total of the carrying capacity status of all the grids from each district. The status of carrying capacity per grid per district was determined by the difference between the population threshold and the existed population in the same district. The equation for determining the status of carrying capacity per grid is as follows:

\[ ST_i = TA_i - P_i \]  
(Eq. 9)

with,

\( ST_i \): carrying capacity threshold status for water-provisioning ecosystem services in grid-i (person),
\( TA_i \): carrying capacity threshold for water-provisioning ecosystem services in grid-i (person), and
\( P_i \): population number in grid-i (person).
The distribution of water demand on domestic uses has the same pattern as population distribution. While, water demand on land utilization shows higher demands spread over the regencies area, rather than the urban. Highest water demand for land utilization is located in the northern area of Bandung Regency. Hereinafter, both demands for domestic and land utilization were added and resulted in the total demand of water in the study area (Figure 4).

### 3.2. Water Supply Distribution

In modelling carrying capacity based on water-provisioning ecosystem services, WPESI was distributed according to the river area. It was because the existed data of potential water-supply was based on river area. Furthermore, the total WPESI per river area was used to calculate the water supply value for one WPESI (Eq. 5).

After obtaining the value of 1WPESI, water supply in the grid system was distributed by the WPESI value of each grid. The visualization of the distribution of water supply in the grid system is shown in Figure 5.

From the distribution in Figure 5, higher potential water supply is located in the eastern part of West Bandung Regency which covers Saguling Reservoir; the northern part of Bandung Regency; and most of Sumedang Regency. Highest potential water supply found in the centre and north-eastern of Sumedang Regency which is traversed by many streams.

### 3.3. Carrying Capacity Threshold Distribution

The status of water-provisioning carrying capacity was analysed based on the difference between water supply and demand, and based on population thresholds. The difference was obtained through a subtraction between the potential water supply and the water demand within a region. The difference of water supply per district can be seen in Table 4.

Negative water difference shows that the demand for water of a region is greater than its supply so that the environment of the region is no longer able to support the water demand of the people on it. Based on Table 4, it is found that Bandung City and West Bandung Regency – have experienced water deficit. However, visually, a high deficit in water-provisioning is located in some areas of Bandung Regency (Figure 6).

Furthermore, to determine the carrying capacity status, the population threshold (Figure 7) was set aside by existed population in the same region (Eq. 9).
The distribution of carrying capacity status is shown in Figure 8. Visually, Bandung Regency and West Bandung Regency have overshot the threshold of carrying capacity almost all over its area. In addition, the northern part of Bandung City and Cimahi City; and less part of Sumedang Regency, have also passed its threshold.

4. Discussion

The multi-scale grid system used in this study has a resolution of 5"×5". This resolution was chosen because it allows for more detailed analysis of information, meaning that the smaller grid resolution allows non-neglected objects with small areas. When the grid is rougher or has a larger resolution value (for example, the 30"×30" grid resolution is greater than 5"×5"), the detail of the information on the map is decreasing. In other words, when generalizations need to be made, the difference between modelling results and the resulting population is not as significant as the use of larger-resolution grids.

The biggest water deficit was experienced by Bandung City and West Bandung Regency. Shown by Table 5, Bandung City and Cimahi City have larger water demand in domestic uses rather than in land utilization. While, for Bandung Regency, West Bandung Regency, and Sumedang Regency, land utilization demands more water-provisioning.

Referring to Table 4, both cities have a relatively small water supply compared to their high water demands. Most of the water demands in Bandung City is allocated for domestic uses since Bandung City has the highest population density among Greater Bandung region. Meanwhile, West Bandung Regency spends the most of its supply to fulfil the demand of land utilization at its western area. Bandung Regency has a distribution of the supply from small to high (seen from the gradation of colour), one of which is influenced by the larger area compared to Bandung City and Cimahi City. In addition, land cover types that more varied than in the city causes the value of the difference of one district spread over the region.

Multi-scale grid system enables the threshold to be calculated and distributed spatially. Moreover, based on comparisons between the areas that still have an undershoot status over the area of its district respectively, a percentage of the area which is still capable to support water demands, can be found. The result (Table 6) shows that Sumedang Regency has

| District     | Supply     | Demand    | Difference |
|--------------|------------|-----------|------------|
| Bandung Regency | 1,423.965 | 1,388.756 | 35.209     |
| West Bandung Regency | 741.879  | 796.125   | -54.246    |
| Bandung City   | 145.275    | 150.742   | -5.467     |
| Cimahi City    | 34.884     | 32.137    | 2.748      |
| Sumedang Regency | 1,504.597 | 860.897   | 643.700    |

Table 4. Difference of water supply per district

Figure 6. Difference of water supply in grid system

Figure 7. Carrying capacity threshold in grid system

Figure 8. Carrying capacity status in grid system
Table 5. Water demands in each district

| District            | Domestic (million m³) | Land (million m³) | Total (million m³) |
|---------------------|-----------------------|-------------------|--------------------|
| Bandung Regency     | 149.383               | 1,239.373         | 1,388.756          |
| West Bandung Regency| 69.814                | 726.311           | 796.125            |
| Bandung City        | 106.683               | 44.059            | 150.742            |
| Cimahi City         | 25.025                | 7.112             | 32.137             |
| Sumedang Regency    | 48.811                | 812.087           | 860.897            |

Table 6. Percentage of supporting areas per district

| District            | Supporting Area (1,000 ha) | District Area (1,000 ha) | Percentage (%) |
|---------------------|-----------------------------|-------------------------|----------------|
| Bandung Regency     | 99.006                      | 172.675                 | 57.34          |
| West Bandung Regency| 78.404                      | 129.579                 | 60.51          |
| Bandung City        | 10.568                      | 17.242                  | 61.29          |
| Cimahi City         | 3.054                       | 4.464                   | 68.43          |
| Sumedang Regency    | 128.654                     | 156.338                 | 82.29          |

Through the resulting spatial model, the distribution patterns of the environmental regions – that have overshot its carrying capacity threshold – can be identified easily, visually. This is an advantage, as opposed to the usual tabular-based calculations that are only able to show the overall environmental capacity for each district. Spatial modelling that utilizes a multi-scale grid system allows the analysis to be more detailed – according to the grid resolution used – although the data used is smaller in scale.

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