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

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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 in to 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 fulfil the demands of the population.

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).

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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

Table 1 Example of ecosystem services' indicators (de Groot *et al.* 2010)

Ecosystem Services	Ecological Process	Generated Services	Performance
Food-provisioning	Food availability	Total or average stocks in kg/ha	Productivity in kcal/ha/year
Water-provisioning	Water availability	Water supply in m^3/ha	Maximum consumption of water (m^3/ha/year)

a great response in the ecosystem (Groffman *et al.* 2006). In the perspective of regional development, the use of the concept of thresholds on environmental carrying capacity aims to study the impacts that occur on the environment due to regional development and population growth. Furthermore, this threshold can serve as a basis for limiting growth (Muta'ali 2012).

This, in this research, spatial modelling was done by a quantitative approach with the aim of knowing the threshold status and distribution patterns of carrying capacity in form of a map. Closed system was applied to determine the carrying capacity status which was based solely on the potential of existing resources in the region without taking in to account the flow of material in or out of the system. In this research, water-provisioning ecosystem service was used as a quantitative approach to determine the carrying capacity.

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.

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).

Table 2. Various data sets for water-provisioning carrying capacity modelling

Data	Sources	Spatial Units
Population	Statistics Indonesia 2015	District Administrative (Polygon)
Land Cover	Ministry of Environment 2014	Land Cover (Polygon)
Road	Geospatial Information Agency 2015	Road (Polyline)
Ecosystem Services Index	Ministry of Environment 2015	Ecoregion and Land Cover (Polygon)
Potential Water Supply	Center of Water Resources 2012	River Area (Polygon)

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

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:

Table 3. Population weight scores for each road classes and land cover types (Nengsih, 2015, with adaptation)

Road Classes and Land Cover Types	Weight
Arterial	0.095
Local	0.180
Collector	0.009
Others	0.072
Settlement	0.328
Rice fields	0.095
Dryland fields	0.058
Bushes	0.036
Production forests	0.017
Plantations	0.004
Ponds	0.075

$$D_i = P_{ij} \times KHL \qquad \text{(Eq. 1)}$$

with,

D_i : water demand for domestic uses in grid-*i* (m^3/year),

P_{ij} : population number in grid-*i* of districts *j* (person),

KHL : water demand for worthy life,

KHL : 43.2 m^3/person/year.

43.2 m^3/person/year as the standard for domestic uses accommodates the need for drinking water and household activities, which is 120 liters/person/day.

For the demand of land utilization, there were only three land classes to be calculated. It considered the common place where local people producing foods. These classes were rice fields, plantations, and dryland fields. The equation used to calculate demand of land utilization refers to the formula for calculating water use for paddy per year as follows (Muta'ali 2012):

$$Q_i = A_i \times I \times q \qquad \text{(Eq. 2)}$$

with,

Q_i : water demand for land utilization in grid-*i* (m^3/year),

A_i : area of land cover class in grid-*i* (hectare),

I : crop intensity in percentage for every season per year (%),

q : standard of water use for agriculture (1 litre/second/hectare), and

q : 0.001 m^3/second/hectare × 3600 × 24 × 120 days per season.

In the meantime, for plantations and dryland fields classes, the general ratio over agricultural land (rice fields) was used, i.e. rice fields : plantations : dryland fields = 4 : 1.5 : 1 (Siswanto 2014).

The total water demand for each grid was derived from the sum of domestic and land utilization demand. Here is a formula of the total water demand of each grid:

$$T_i = D_j + Q_i \qquad \text{(Eq. 3)}$$

with,

T_i : total water demand in grid-*i* (m^3/year),

D_i : water demand for domestic uses in grid-*i* (m^3/year), and

Q_i : water demand for land utilization in grid-*i* (m^3/year).

2.4. Supply Calculation

To calculate the potential for water supply, Water Provisioning Ecosystem Services Index (WPESI) was used. This index served as the weight scores to distribute water supply in river area units into the grid. The river area is a working unit for management which consists some catchment areas. The steps taken to calculate potential water supply were:

1. WPESI calculation per grid,
2. WPESI calculation per river area, and
3. the distribution of water supply in the grid system.

The WPESI value was obtained from the analysis by Ministry of Environment. The analysis involved expert judgement process and spatial analysis between ecoregion and land cover.

Firstly, WPESI was recalculated by using the proportion of every land cover polygons in each grid. Weight with the value equal to one was assigned to a grid which only has one class of land. Whereas, for a grid with more than one class of land, weighting was applied by comparing the area of that polygon to the area of the whole grid regarded. WPESI granting for each grid was calculated by the following mathematical equation:

$$WPESI'_{ij} = WPESI_{ij} \times (LC_i / LC) \qquad \text{(Eq. 4)}$$

with,

$WPESI'_{ij}$: WPESI of grid-*i* in the river area-*j* that will be used in weighting,

$WPESI_{ij}$: WPESI of grid-*i* in the river area-*j*,

LC_i : area of land cover in grid-*i* (hectare), and

LC : area of whole grid-*i* (hectare).

From Eq. 4, WPESI for each grid was obtained. Subsequently, these values of WPESI were summed by each district. It was assumed that the total of WPESI and the water supply for each river area are proportional. Thus, water supply for one WPESI can be obtained as follows:

$$1WPESI'_{ij} = W_j / \sum WPESI_j \qquad \text{(Eq. 5)}$$

with,

$1WPESI_j$: water supply of one WSEPI in river area-*j*,

W_j : water supply of river area-*j* (m^3/year),

$\sum WPESI_j$: total WPESI in river area-*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:

$$W_{ij} = 1WPESI_j \times WPESI'_{ij} \qquad \text{(Eq. 6)}$$

with,
W_{ij} : water supply in grid-i of river area-j (m^3/year),
$1WPESI_j$: water supply of one WPESI in river area-j, and
$WPESI'_{ij}$: 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:

$$S_i = W_{ij} - T_i \qquad \text{(Eq. 7)}$$

with,
S_i : the difference of water supply (m^3/year),
W_{ij} : water supply in grid-i of river area-j (m^3/year), and
T_i : total water demand in grid-i (m^3/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:

$$TA_i = (W_i - Q_{i)}) / KHL \qquad \text{(Eq. 8)}$$

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 (m^3/year),
Q_i : water demand for land utilization in grid-i (m^3/year), and
KHL: water demand for worthy life, (m^3/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:

$$ST_i = TA_i - P_i \qquad \text{(Eq. 9)}$$

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).

3. Results

3.1. Water Demand Distribution

Figure 1 shows the distribution of the population in the 5″×5″ grid system as the basis to distribute the demand. The results imply that the population is denser in the urban area, Bandung City and Cimahi City. Figure 2 and Figure 3 respectively are the distributions of water demand on domestic uses and land utilization.

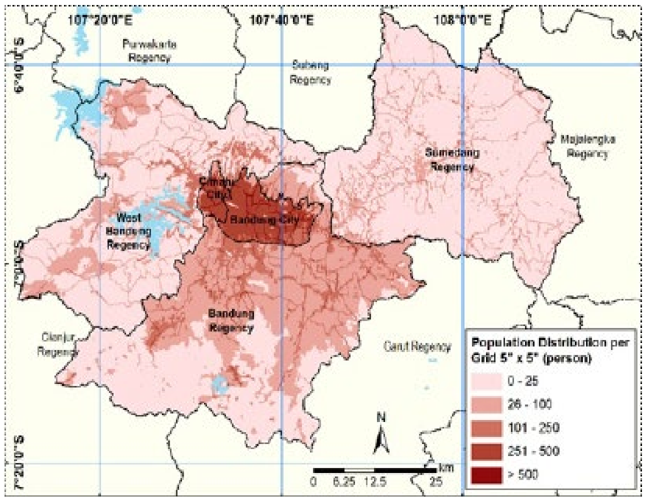

Figure 1. Population distribution in grid system

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).

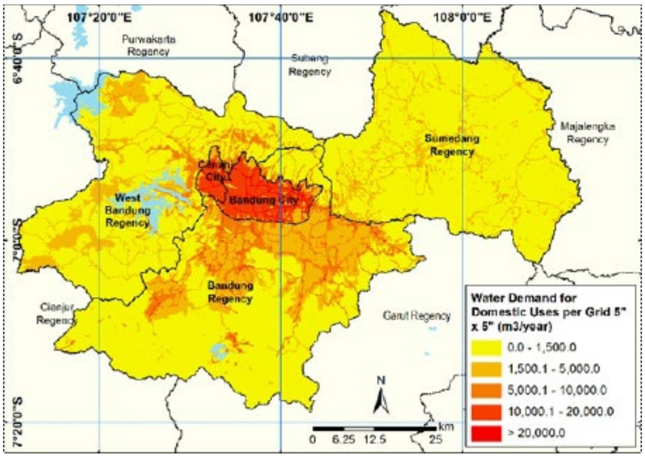

Figure 2. Water demand for domestic uses in grid system

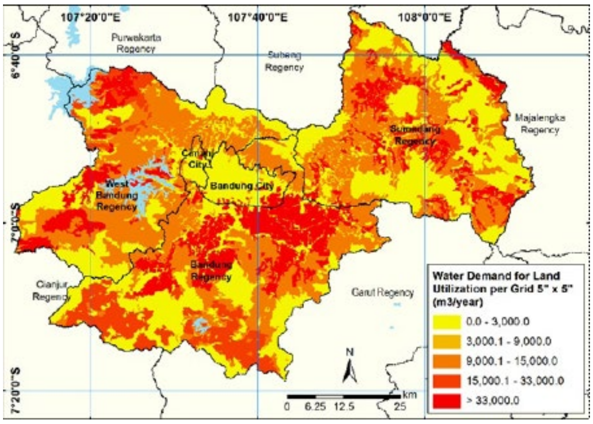

Figure 3. Water demand for land utilization in grid system

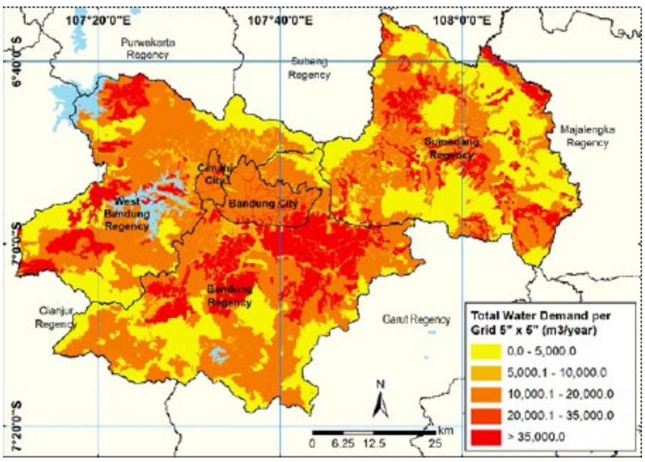

Figure 4. Total water demand in grid system

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).

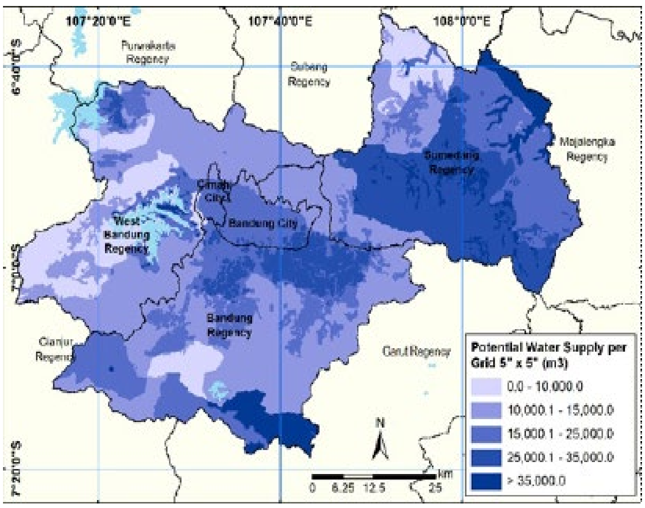

Figure5. Potential water supply in grid system

Table 4. Difference of water supply per district

District	Supply	Demand	Difference
	(million m³)		
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

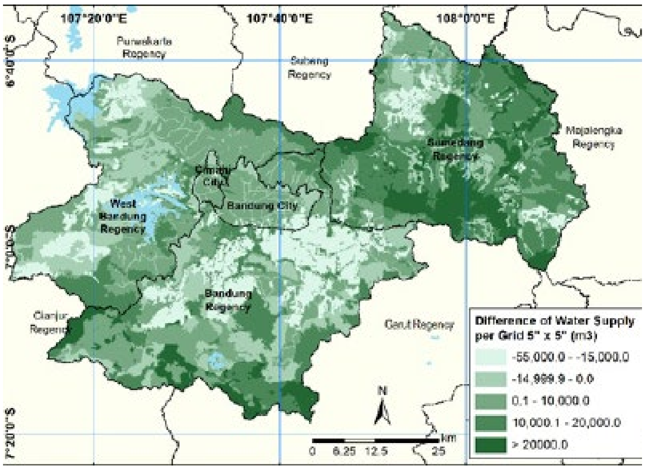

Figure 6. Difference of water supply in grid system

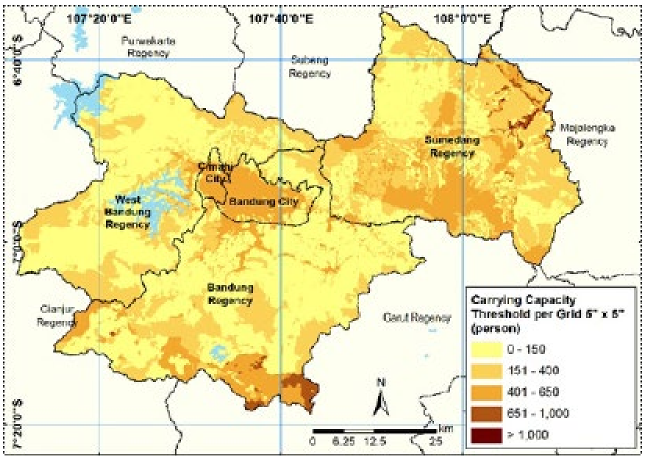

Figure 7. Carrying capacity threshold in grid system

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.

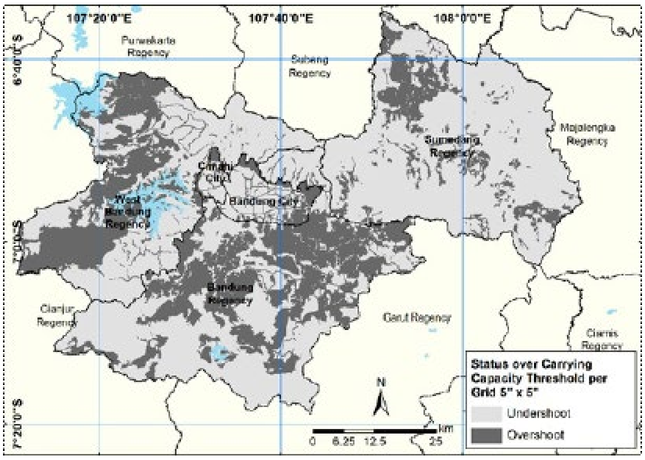

Figure 8. Carrying capacity status in grid system

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

Table 5. Water demands in each district

District	Domestic	Land	Total
	(million m^3)		
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

a wide percentage that still able to support 82.29%, followed by Cimahi City with 68.43% and Bandung City equals to 61.29%. Meanwhile, the area that still can be supported by water-provisioning ecosystem services in West Bandung Regency is 60.51% and Bandung Regency is only 57.34% which is also the smallest in Greater Bandung.

Although Bandung Regency has a surplus water supply, it has the smallest percentage of area that has not passed the threshold of carrying capacity. As for Bandung Regency, its land covers which have higher water demands are situated in numerous immense areas. However, this model is only able to determine the carrying capacity threshold in a closed system concept which is per grid. Further research might be conducted to allow the determination of resources flow.

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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