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ENVIRONMENTAL CARRYING CAPACITY ASSESSMENT FOR CROPS IN BENGAWAN SOLO WATERSHED, INDONESIA: A SPATIAL APPROACH

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Abstract: Sustainable crop production is needed to balance the demand for food in highly populated areas. Bengawan Solo watershed is a rice crop production region in Java Island, Indonesia. However, due to extensive land use change, the area become one of the 15 critical watersheds for restoration, according to the Indonesia Ministry of Environment and Forestry. This condition will affect the carrying capacity of the area to produce food. This study aims to analyze the carrying capacity for crop production upstream of the Bengawan Solo watershed. Water and land carrying capacity were determined based on the regulation from Indonesia Ministry of Environment 17/2009. Food demand and availability were assessed considering population number and crop productivity. Finally, the carrying capacity of each sub-watershed was analyzed using a spatial approach and was linked to its food availability and demand. Our results show that most of the sub-watersheds were in deficit and that the level of food availability is positively related to the degree of carrying capacity. In regards to this condition, therefore, the local government needs to pay more attention to the land use change rate in this area as an effort to maintain the food security status.

Keywords: Carrying capacity, crop, food security, watershed, spatial approach.

Introduction

Food availability in a particular area is determined by climatic conditions and physical characteristics, known as agroecology (Widiyanto, 2019). Nowadays, food crop production is challenged by climate change. The change in global climate has triggered various kinds of disasters impacting the water resource sector, such as droughts and floods, especially in food crop production areas (Shi *et al.*, 2020). This condition will, therefore, lead to a lack of food crop availability. The physical characteristics of an area will affect Environmental Carrying Capacity (ECC). The environment's carrying capacity will then affect food availability in the area (Wang, 2022)less attention has been given to how we will sustainably feed 9 billion people in 2050 and beyond. Here, we review the major natural resources that limit food production and discuss possible options, measures, and strategies to sustainably feed a human population of 9 billion in 2050 and beyond. Currently, food production greatly depends on external inputs, e.g., irrigation water and fertilizers, but these approaches are not sustainable. Due to the unbalanced distribution of global natural resources and large regional differences, urbanization expansion causes important areas to face more serious arable land resource shortages. Hence, sustainably feeding 9 billion people in 2050 and beyond remains an immense challenge for humankind, and this challenge requires novel planning and better decision-making tools. Importantly, the measures and strategies employed must be region-/country-specific because of the significant differences in the socioeconomic characteristics and natural environmental carrying capacity in different parts of the world. Considering the impact of unexpected extreme events (e.g., a global pandemic and war. Food demand will increase along with the increasing population. On the other hand, the availability of resources tends to be stable, resulting in unbalanced conditions between the supply and demand of food.

Watershed management strongly supports the agricultural food security program (Gebregziabher *et al.*, 2016). Good watershed management can increase soil infiltration rates and reduce the rate of soil erosion (Teka *et al.*, 2020). This will result in increasing fertility in the agricultural land. In that context, ensuring food security in the watershed region is essential, especially the upstream and downstream. Considering the complexity of disasters, such as drought in the watershed area (Sari, 2023), innovative watershed management is required, especially for water and land resource conservation.

Additionally, the effectiveness of watershed management requires the participation of the watershed's surrounding community (Syafri *et al.*, 2020)affecting the utilization of river basins. The purpose of this study is to analyze (1. Physical and population characteristics that varied in each region would cause different levels of drought or flood vulnerability (Anna *et al.*, 2021; Setyowati *et al.*, 2021)Indonesia. This flooding has caused damage to road infrastructure, disrupted socioeconomic activities of the community, and disturbed road traffic. However, there is no ongoing disaster management to minimize the risk. Mitigation activity is an important component in the disaster management that is needed to minimize the impact of flooding. Spatial analysis and modelling is part of disaster mitigation as it can be used to predict the spatial extent of floods. The purpose of this study is to develop a spatial model of flooding using the rational modification method. The stages in this research include creating flood evaluation model, model validation, and model visualization. This study used secondary data accompanied by field observations. The datasets consist of rainfall data, slope, vegetation cover, soil type, area, surface storage, water infiltration volume, and drainage capacity. All data was then analysed by descriptive quantitative techniques. For the flood modelling, Geographic Information System (GIS. Those physical and human aspect characteristics create differences in adaptation strategies undertaken by farmers. Soil and water conservation are found to be the dominant resilience strategies by farmers, as indicated by Turyahabwe *et al.* (2022)Bulambuli district, Uganda. We used questionnaires, interviews, focused group discussions and field observations to collect the required data, which was analyzed using basic descriptive statistics and logistic regression model. Results indicate that, the dominant climate change resilience strategies adopted in the study were, soil/water conservation (65%.

Bengawan Solo watershed is the largest catchment area in Java Island, Indonesia, having a total area of approximately 16389 km^2 (Marhaento *et al.*, 2021). Since the agricultural area dominates the upper part of Bengawan Solo, protecting this watershed area is critical to ensure food security. According to Indonesia Presidential Decree 15/2018 and the national medium-term development plan 2020-2024, Bengawan Solo is one of the 15 critical watersheds that are priority targeted for restoration and conservation (Idris *et al.*, 2019; Putri *et al.*, 2022) due to intensive deforestation which been lasting for these three decades (Hannum *et al.*, 2020). Bengawan Solo watershed has experienced a high conversion from forest to settlements (by 25%) and agricultural areas (6%) in the observation period from 1994 to 2013 (Marhaento *et al.*, 2017)Indonesia, can be attributed to land use change using the Soil Water Assessment Tool model. A baseline-altered method was used in which the simulation period 1990–2013 was divided into 4 equal periods to represent baseline conditions (1990–1995. In addition to the land conversion, the Bengawan Solo region is prone to floods and landslides (Fariza *et al.*, 2015). In this evaluation, the carrying capacity for rehabilitation planning is highly regarded.

The ability of a region to provide food needs to be assessed so that the food demand in the region can be controlled and the environmental support can be maintained. Several attempts have been made in food system assessment and modeling from the socioeconomic perspective (Noruzi-Ajabshir *et al.*, 2023) and environmental assessment (Zamri *et al.*, 2022). In that case, environmental modeling using a spatial approach is required to provide complete information on carrying capacity variability across a region. Several studies have recognized the importance of carrying capacity assessment (Cuadra & Björklund, 2007; Mamat & Husen, 2021; Qing *et al.*, 2019)and usefulness of, three different analysis methods: (1. However, the analysis using a spatial approach is limited. Since a region's characteristics may vary, further analysis with spatial data (shown in maps) is required to see the spatial pattern. In particular, for the Bengawan Solo area, prior studies have focused on land use change (Marhaento *et al.*, 2021) and land degradation (Hannum *et al.*, 2020; Supangat & Wahyuningrum, 2021). Therefore, the analysis of the crop-carrying capacity in this study area is not covered yet.

This study provides an understanding of the relationship between carrying capacity and food provision using a spatial approach using spatial data and Geographic Information Science (GIS). Thus, the analysis presented in this study will convey valuable inputs to regional planning in managing critical watersheds where great attention is needed, particularly for agricultural sectors. In detail, this study aims to analyze the carrying capacity in the study area and the relationship of carrying capacity with food crop productivity. A spatial analysis will be conducted to evaluate the carrying capacity status for both land and water aspects to achieve the objectives.

Materials and Methods

Study Area

The study was carried out in the upper area of the Bengawan Solo watershed, with a total area of 3,773.99 km². It is located between 110º13'7.16" -110º26 '57.10" East Longitude and 7º26 '33.15" -8º6 '13.81" South Latitude. The region covers several cities, including Surakarta, Boyolali, Sukoharjo, Karanganyar, Wonogiri, Sragen, and Klaten (Figure 1). The whole watershed includes nine sub-watersheds, which are Pepe, Wiroko Temon, Bambang, Dengkeng, Samin, Jlantah Walikun Ds, Keduang, Mungkung, and

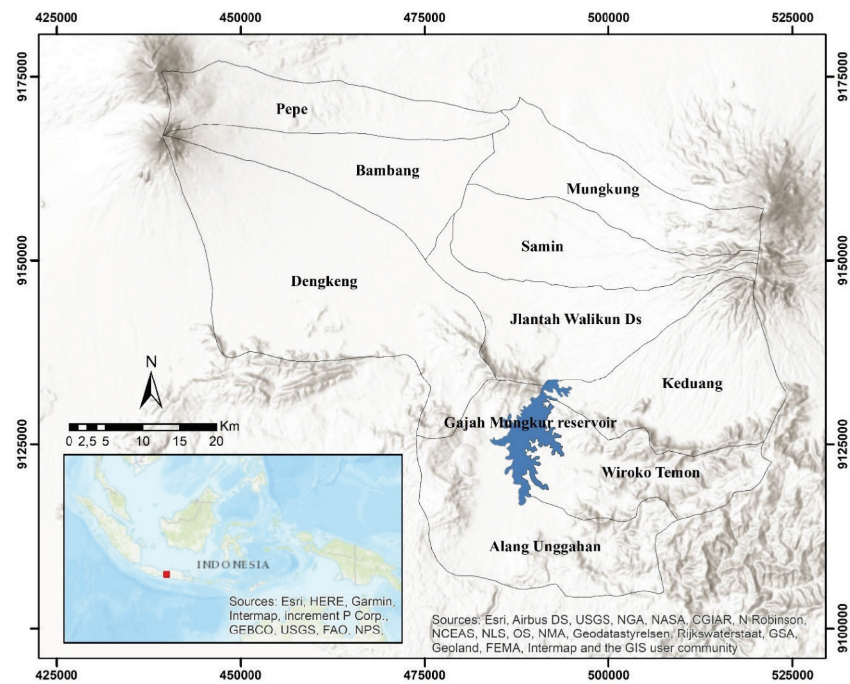

Figure 1: Study area showing the several sub-watersheds in the upper Bengawan Solo watershed

Alang Unggahan. The study area generally has a tropical climate and is dominated by lithosol soil. Most of the area (66.4%) is on a flat slope. The total population in the area covering five administrative regions was 5,328,472 people in 2018.

Annual rainfall in this area is, on average, 2,100 m. The rainy season is between November and April, while the dry season is from May to October. The total potential amount of surface water in the upstream area was 6,593.85 million m^3/year in 2010 (Surakarta Directorate General of Water Resources, 2010). The largest water potential amount is in the Wonigiri region (Keduang sub-watershed), whereas the least is in the Surakarta region (Pepe sub-watershed).

This study collected data from secondary sources from the Department of Regional Statistics. Collected data includes data on cropland (cropland area, crop production, productivity, and price). Other data included for analysis are rainfall and population number.

Several steps were taken for the carrying capacity assessment. To summarize, water carrying capacity was calculated in the first step, followed by the measurement of land carrying capacity. Carrying capacity was measured using guidance from the Indonesia Ministry of Environment (Ministry of Environment, 2009). In the next part, we investigated the relationship between water and land carrying capacity with the food availability status in the area. All steps taken in this study are presented in Figure 2.

Water Carrying Capacity Assessment

Based on the regulation of the Ministry of Environment concerning the carrying capacity measurement guideline (Ministry of Environment, 2009), Water Availability (WA) is calculated as below.

$$C = \sum(Ci \times Ai) / \sum Ai \quad (1),$$

$$R = \sum Ri / m \quad (2),$$

$$WA = 10 \times C \times R \times A \quad (3),$$

where

WA = water availability (m^3/year)
C = weighted runoff coefficient
Ci = runoff coefficient of every land use
Ai = land use area (ha)
R = average annual rainfall (mm/year)
Ri = annual rainfall at the i station
m = number of rainfall observation stations
A = total area (ha)
10 = conversion factor from mm. ha to m^3

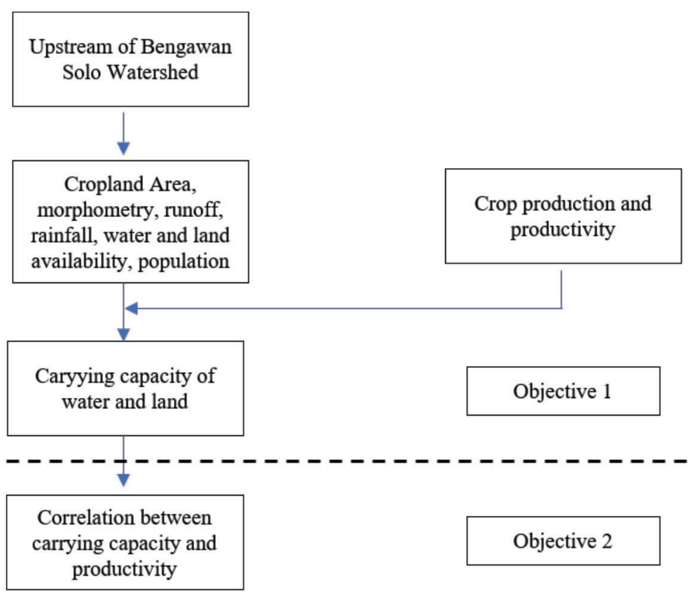

Figure 2: Research flowchart

Table 1 was used to obtain the runoff coefficient of every land use (Ci).

Table 1: Runoff coefficient (Ci) for every land use

Land use/ surface	Ci
city, road, asphalt, tile roof	0.7-0.9
industrial area	0.5-0.9
multi-unit settlements, shops	0.6-0.7
cluster area	0.4-0.6
Villa	0.3-0.5
garden, cemetery	0.1-0.3
coarse soil yard	
slope > 7%	0.25-0.35
slope 2-7%	0.18-0.22
slope < 2%	0.13-0.17
fine soil yard	
slope > 7%	0.15-0.20
slope 2-7%	0.10-0.15
slope < 2%	0.05-0.10
bareland	0.40
pasture	0.35
agricultural cultivation land	0.30
production forest	0.18

Source: Ministry of Environment, (2009)

The next step is calculating Water Demand (WD) using the following formula.

$$WD = N \text{ x } KHLA \quad (4),$$

where

WD = total water requirement (m^3/year)
N = total population
KHLA = water requirement for decent living (1,600 m^3 water/capita/year)

Finally, the water carrying capacity status was obtained from a comparison between WA and WD.

(a) If WA > WD, the carrying capacity of water is surplus.

(b) If WA < WD, the water carrying capacity is in deficit.

Land Carrying Capacity Assessment

Land Availability (LA) was calculated using the following formula.

$$LA = \{(\Sigma(Pi \text{ x } Hi)) / Hb\} \text{ X } (1/Ptvb) \quad (5),$$

where

LA = land availability (ha)
Pi = actual productivity of each type of commodity (unit depends on the commodity)
Hi = unit price for each type of commodity (Rupiah/kg)
Hb = unit price of rice at producer level (Rupiah/kg)
Ptvb = rice productivity (kg/ha)

The next step was assessing Land Demand (LD) using the following equation.

$$LD = N \text{ x } KHLL \quad (6),$$

where

LD = total land requirement equivalent to rice (ha), for Java area 0.25 ha
N = total population (person)
KHLL = the area needed for decent living needs per resident (land needed for decent living divided by local rice productivity). It is provided that (a) land needed for decent living is assumed to be 1 ton of rice/per capita/year, and (b) regions that do not have local rice productivity data can use the average national rice productivity of 2,400 kg/ha/year.

The status of land carrying capacity was then obtained from a comparison between LA and LD (Ministry of Environment, 2009):

(a) If LA > LD, the land's carrying capacity is declared surplus.

(b) If LA < LD, the carrying capacity of the land is declared in deficit.

Relationship between Environmental Carrying Capacity and Food Availability

Environmental Carrying Capacity (ECC) for food is defined as its ability to provide food to meet people's necessities decently. In this study, the status of ECC for food was determined by calculating food availability and demands using the equations below.

$$A = \frac{\Sigma(PixHi)}{Hb} \quad (7),$$

$$FD = N \times KHL \quad (8),$$

where

FA = food availability
FD = food demand
Pi = actual productivity of each type of commodity (unit depends on the commodity)
Hi = unit price for each type of commodity (Rupiah/kg)
Hb = unit price of rice at producer level (Rupiah/kg)
N = number of population
KHL = the need for decent living per population is assumed to be 1,000 kg of rice equivalent/capita/year

In this study, the cropland area of each sub-watershed was determined by the area of LA of each sub-watershed (*see Equation 5).* Then, FA per sub-watershed was equivalent to LA of each sub-watershed (in %) times the total of FA. Finally, to determine the status of food availability in the research area, the classification was used as follows:

(a) FA per sub-watershed > FD per sub-watershed, then food availability is declared surplus.

(b) FA per sub-watershed < FD per sub-watershed, then food availability is declared deficit.

Results and Discussion

Water Carrying Capacity

The determination of water carrying capacity is influenced by WA and WD. In this study, we considered WA on the surface, including nine sub-watersheds. The calculation was carried out to compare the supply and need of water used in daily activities, such as domestic, industrial, agricultural, and services. Based on the calculation, the total availability of water in the Upper Bengawan Solo watershed is 257,766,292.7 m^3/year, while the WD is 10,842,326,400 m^3/year (Table 2). A detailed comparison of WA and the need of each sub-watershed is also presented in Table 2.

According to the Guidelines for Environmental Carrying Capacity in Regional Spatial Planning (Ministry of Environment, 2009), the status of water carrying capacity is

Table 2: Status of water carrying capacity of the upper Bengawan Solo watershed in 2021

Sub-watershed	WA (m^3/year)	WD (m^3/year)	Status
Pepe	20,626,765.90	1,801,336,000	Deficit
Mungkung	31,374,002.40	855,912,000	Deficit
Bambang	28,988,156.20	2,579,590,400	Deficit
Dengkeng	50,106,012.70	3,184,888,000	Deficit
Samin	31,121,240.20	610,187,200	Deficit
Jlantah Walikun DS	31,282,766.20	124,136,000	Deficit
Keduang	26,952,560.0	1,020,800,000	Deficit
Alang Unggahan	23,080,256.60	643,601,600	Deficit
Wiroko Temon	14,234,532.50	21,875,200	Deficit
Total	257,766,292.70	10,842,326,400	

WA: water availability; WD: water demand.

obtained from a comparison between WA and WD. Table 2 shows that WA is less than the WD, indicating that the water carrying capacity status is deficit.

The status of the water-carrying capacity in the study area can be seen in Figure 3. The figure shows that the Dengkeng sub-watershed had the largest WD, while the Wiroko Temon sub-watershed was in the lowest position for water needs. The physical characteristics of the area can explain this condition. From Figure 1, we can see that the topography of the Wiroko Temon sub-watershed is hilly, especially in the eastern part of the area. This situation, therefore, results in low population and low WD.

Land Carrying Capacity

Land carrying capacity is the comparison of its availability and need. The calculation results showed that the LA for food is 121,049.90 ha, while the LD is 1,694,114 ha (Table 3).

Based on Table 3, it can be seen that most of the sub-watershed areas have a lower LA than the demand. It indicates that the carrying capacity status of the land is in deficit status. However, only in the Wiroko Temon sub-watershed was the value of LA much greater than the land requirement, resulting in a surplus status (Figure 4).

Our results show that all sub-watersheds are in deficit water status, while only the Wiroko Temon sub-watershed has surplus land water status. This condition could have relevance to the topographic condition of the area. In particular, the Wiroko Temon sub-watershed has a hilly topography (Figure 1), which causes less population and thus less LD in this area. Another reason for the water and land deficit status in most sub-watersheds is the high WD and LD due to the high population, especially in Surakarta (Pepe sub-watershed) (Rahayu *et al.*, 2019). Moreover, land degradation in the upstream Bengawan Solo also decreases the carrying capacity for crops (Fariza *et al.*, 2015; Supangat & Wahyuningrum, 2021).

Analysis of Food Availability and Demand

As a basic human need, food has a significant meaning and national role. Thus, the lack of food can create economic instability (Suweis *et al.*, 2015). In this study, according to the calculation, all sub-watersheds were in deficit status (Table 4).

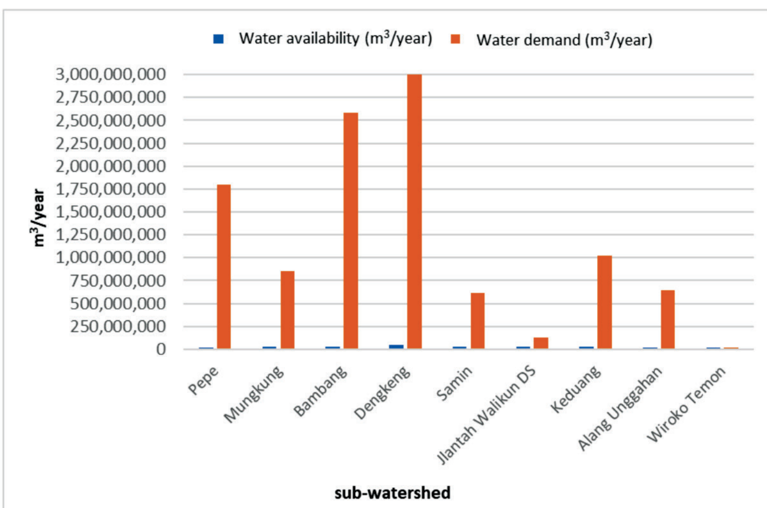

Figure 3: Comparison between water availability and demand in the upper Bengawan Solo watershed

Figure 4: Comparison between land availability and demand

Table 3: Status of land carrying capacity in the upper Bengawan Solo watershed in 2021

Sub-watershed	LA (ha)	LD (ha)	Status
Pepe	11,594.80	281,459	Deficit
Mungkung	2,441.10	133,736	Deficit
Bambang	25,434.60	403,061	Deficit
Dengkeng	5,069.10	497,639	Deficit
Samin	3,403.20	95,342	Deficit
Jlantah Walikun DS	10,592.70	19,396	Deficit
Keduang	23,401.40	159,500	Deficit
Alang Unggahan	29,558.70	100,563	Deficit
Wiroko Temon	9,554.30	3,418	Surplus
Total	121,049.90	1,694,114	

LA: land availability; LD: land demand.

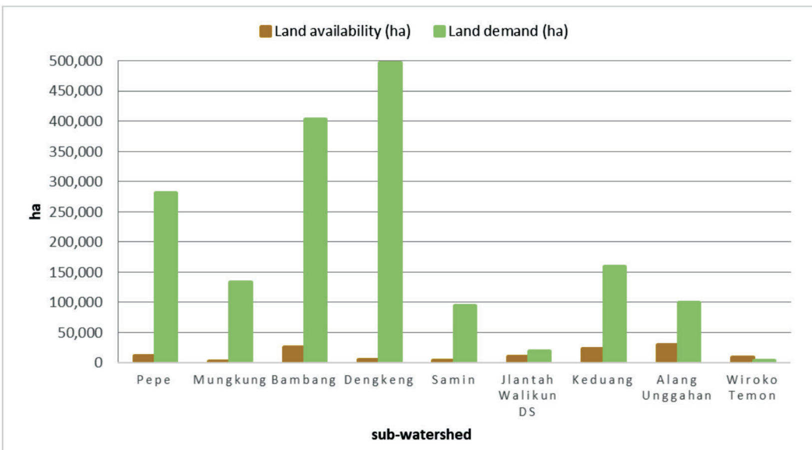

Figure 4: Comparison between land availability and demand

As shown in Table 4, the highest food availability is in Dengkeng at 438,387 kg/year. Meanwhile, the lowest food availability is in Bambang, 111,166 kg/year. The highest food needs are in Dengkeng at 1,990,555,000 kg/year, while the lowest is in the Wiroko Temon at 13,672,000 kg/year.

WA and LA can also be evaluated from the spatial distribution. Figure 5 shows the spatial pattern of water, LA, and corresponding food availability and demand.

As seen in Figure 5, the Bambang sub-watershed had high food demand (Figure 5f). Such a condition, however, was not supported by its food availability (Figure 5e). On the other hand, although there was a high food requirement in Dengkeng (Figure 5f), its carrying capacity for food was also high (Figure 5e).

The level of food availability is highly dependent on the productivity of each commodity, while the need for food is highly dependent on the population. When food crop productivity is high, food availability is also high. Indeed, the larger the population, the higher the need for food. This level of food availability positively correlated with the carrying capacity of water and land (Table 5).

Table 4: Status of food availability and demands in the upper Bengawan Solo watershed

Sub-watershed	FA (kg/year)	FD (kg/year)	Status
Pepe	136,338	1,125,835,000	Deficit
Mungkung	219,872	534,945,000	Deficit
Bambang	111,166	1,612,244,000	Deficit
Dengkeng	438,387	1,990,555,000	Deficit
Samin	186,458	381,367,000	Deficit
Jlantah Walikun DS	302,769	77,585,000	Deficit
Keduang	265,408	638,000,000	Deficit
Alang Unggahan	350,161	402,251,000	Deficit
Wiroko Temon	397,358	13,672,000	Deficit
Total	2,407,917	6,776,454,000	

FA: food availability; FD: food demand.

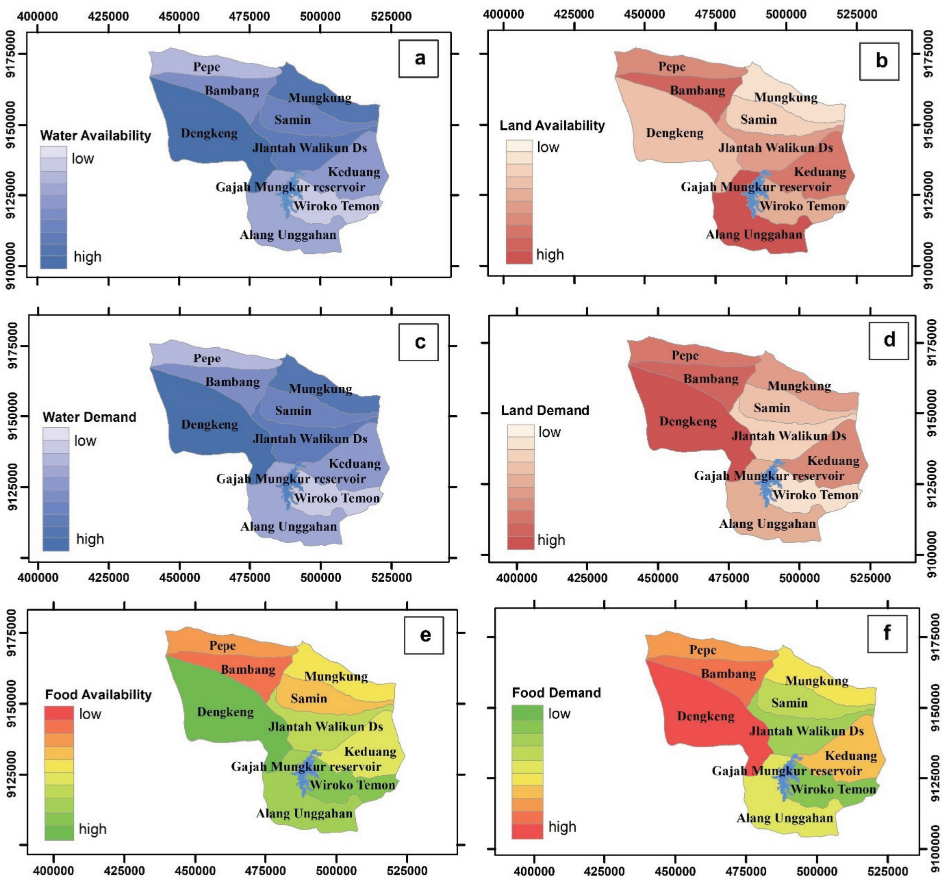

Figure 5: Distribution of (a) water availability, (b) land availability, (c) water demand, (d) land demand, (e) food availability, and f) food demand in the study area

Table 5 shows that the food availability in almost all sub-watersheds positively correlates with the amount of WA and LA. However, in the Bambang Sub-watershed, the large land area is not followed by the high amount of food. From Table 3 and Figure 5(b), we can see that despite the Bambang watershed's high rank of LA, the water is moderately available (Figure 5a), and LD is high (Figure 5d). This makes crops less supported to grow, hence less food available. The relationship between WA, LA, and food availability is presented in Figure 6.

Interestingly, in our findings, the high land and water carrying capacity does not always correlate to the high provision of food. Several reasons could explain this. Other factors also significantly affect a region's food productivity, including land biophysical conditions and land, plant, and farming management practices (Miner *et al.*, 2020). The productivity of food crops is also affected by land area, the number of seeds purchased (Frimawaty *et al.*, 2013) Indonesia. The analysis used modification of Rapfish method by using multidimensional scaling (MDS, and fertilizer used (Mozumdar, 2012).

Based on the results, several efforts are suggested to maintain food availability, including conserving land and water resources, revitalizing conservation supporting infrastructure, monitoring regional spatial planning, implementing and monitoring the Sustainable Food Agricultural Land (LP2B) program, and providing incentives for farmers as a result of the high cost.

In addition, the assessment of the carrying capacity for food is related to the foodshed concept, which describes the geographical interaction between food producers and consumer regions (Świąder *et al.,* 2018; Schreiber *et al.*, 2021)at present, the lack of a coherent methodological framework and research agenda limits the potential to compare different cities and regions as well as to cumulate knowledge. We conduct a review of 42 peer-reviewed publications on foodsheds (identified from a subset of 829 publications. Carrying capacity measures the agroecosystem's ability to provide food, while the foodshed delimitates the location of food that could be supplied (Peters, 2022). Using GIS tools, researchers can efficiently map out potential local foodsheds for population centers. Other than that, food flow for different food producers and distance clusters among products can be evaluated with geocoding data (Świąder *et al.*, 2018). However, additional datasets are required to analyze potential foodsheds, such as transportation networks, socioeconomic conditions, and consumer behavior, which would be interesting to explore in future studies. Further, as food availability and demands can change over time, further research should consider monitoring changes in carrying capacity status.

Table 5: Carrying Capacity of Water, Land, and Food Availability

Sub-watershed	WA (m^3/year)	LA (ha)	FA (kg/year)
Pepe	20,626,765.90	11,594.80	136,338.00
Mungkung	31,374,002.40	2,441.10	219,872.00
Bambang	28,988,156.20	25,434.60	111,166.00
Dengkeng	50,106,012.70	5,069.10	438,387.00
Samin	31,121,240.20	3,403.20	186,458.00
Jlantah Walikun DS	31,282,766.20	10,592.70	302,769.00
Keduang	26,952,560.0	23,401.40	265,408.00
Alang Unggahan	23,080,256.60	29,558.70	350,161.00
Wiroko Temon	14,234,532.50	9,554.30	397,358.00
Total	257,766,292.70	121,049.90	2,407,917.00

WA: water availability; LA: land availability; and FA: food availability

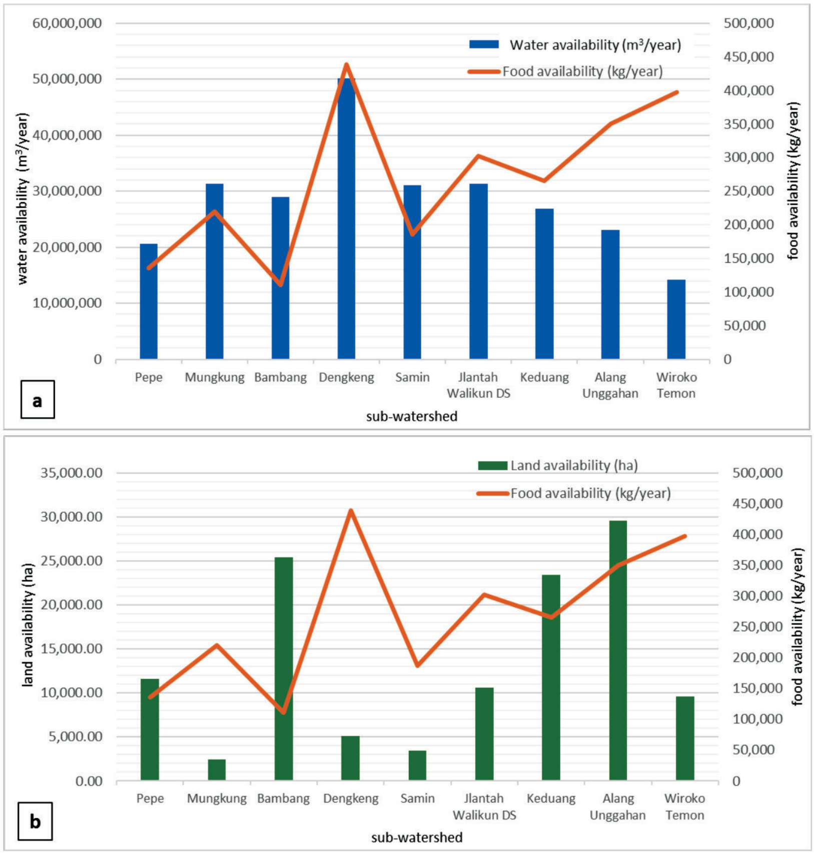

Figure 6: Relationship between (a) water, (b) land, and food availability

Conclusion

Most of the Bengawan Solo watershed's upper area has less WA and LA than the demand, meaning the water and land carrying capacity status is deficient. Our results show an unbalanced condition between food needs and availability. It indicates that the food availability cannot meet the community's needs. Furthermore, assessing carrying capacity using a spatial approach helps understand the variability distribution within the study area. Therefore, based on the results, proper policies addressing regional food security, particularly in the critical watershed region, are highly suggested. Despite the successful attempt to show the spatial variability of carrying capacity status, this study is subject to some limitations. Only rice was considered for the carrying capacity calculation as it is the general staple food in Indonesia. Consideration of other crops, such as maize and sago, is therefore encouraged in other areas of Indonesia. Our study was also merely based on secondary data, which may lead to differences in the actual status at the moment. Therefore, monitoring the carrying capacity status will be helpful to see its trend in the study area. More analysis is also suggested using socioeconomic factors such as transportation lines to see the food flow.

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Conflict of Interest

All authors declared that they have no conflicts of interest.

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