Integrating Remote Sensing (RS) and Geographic Information System (GIS) for Carbon Sequestration Monitoring in Tropical Watershed

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Abstract. The watershed has many functions related to ecosystem protection. The existence of vegetation in the watershed can absorb some carbon from the atmosphere through photosynthesis. In fact, this carbon sequestration potential is declining due to vegetated land conversion phenomena. Therefore, monitoring carbon sequestration in this area needs to be done. However, it faces a problem due to the large size of the watershed area in a tropical region, so carbon sequestration cannot be measured by field-measurement. By combining RS and GIS, the carbon sequestration in a large watershed can be measured frequently to solve the problem. This research aims to analyze the dynamic change of carbon sequestration in Upper Bengawan Solo from 2000 until 2020. In this research, carbon sequestration was modelled using the Net Primary Productivity (NPP). NPP was measured by using the CASA method used Landsat Imagery and Meteorological Data from Meteorological Agency of Indonesia (BMKG). The results show that the carbon sequestration in Upper Bengawan Solo over 20 years decreased. The most significant decrease happens in the sub-urban area surrounding the urban area in Surakarta city. It indicates an environmental change in this watershed due to physical or human interference during this period. Meanwhile, by using RS and GIS, the spatial distribution of carbon sequestration change can be known, so it can be used to pinpoint the location which needs prior attention based on the higher level of these changes. This research implies that combining RS and GIS can help carbon sequestration monitoring be quicker and cost-limited.

1 Introduction

A watershed is an area of land drained by a distinct stream or river system and is usually separated from other watersheds by the crest of hills or mountains. The watershed plays an essential role related to ecological services [1]. One of the important functions is becoming an area which has the potential to absorb some carbon from the atmosphere [2, 3]. The existence of vegetated areas such as forests, agricultural land, and shrubs that spread in all watersheds, especially in the upper area, can absorb some carbon from the atmosphere

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through the photosynthesis process. Furthermore, it can mitigate the risk of global warming by minimizing the amount of carbon in the atmosphere.

On the other hand, the carbon sequestration function in the watershed is threatened by two phenomena. The first phenomenon is decreasing vegetation due to human intervention [4–7]. The vegetated area in the watershed was converted into built-up land for human settlement and industrial activities. It happens in the downstream area and spreads in the upstream area. The need for residential areas for human life is becoming a primary factor in this land conversion. Conversion of the vegetated area can change the ecological services, so the ability of the watershed to absorb some carbon will decrease.

This phenomenon also happens in Upper Bengawan Solo Watershed. During ten years, there has been a 40% decrease in the vegetated area based on previous research. Forest areas in 2014 had a size of 50,914 hectares which declined to about 30,894 hectares during ten years from 2004 to 2014. The others vegetated area in Upper Bengawan Solo Watershed that declined during this period was dry agricultural land. During ten years, dry agricultural land decreased by around 151,776 hectares [8].

The second phenomenon threatening the watershed's ecological function is increasing land degradation. Increasing land degradation indicates that there is much-buried land without vegetation. It happens due to over-exploitation and mismanagement of the land. Land degradation will affect the decreased soil quality, so it can inhibit plant growth and the photosynthesis process. Moreover, it also decreases the potential of land to absorb some carbon from the atmosphere.

Land degradation phenomenon also happens in Upper Bengawan Solo Watershed. Based on the local government data, until now, there are 3,402 hectares of land in this watershed area classified as very degraded land and 59,844 hectares classified as degraded land. The rate of soil erosion in this area is also classified as high soil erosion with the existence of gully erosion in the steep slopes area. Based on the erosion model modelled by [9], 60 per cent of Upper Bengawan Solo Watershed land was classified as a high erosion hazard.

Therefore, it needs to monitor the dynamic change in watersheds regularly, the land conversion and degradation phenomena, and the carbon sequestration potential. However, it faces a problem due to the large size of tropical watersheds, especially in Indonesia. It is difficult to frequently monitor carbon sequestration in a large area by using field measurements. It needs a high cost and a long time to do.

In this research, we tried to solve this problem by integrating GIS and remote sensing to monitor carbon sequestration in Upper Bengawan Solo Watershed. By using RS and GIS, carbon sequestration can be modelled in large watershed areas in actual time at a low cost. Carbon sequestration modelling with integration between RS and GIS can be modelled by using CASA Method. The CASA method can measure vegetation productivity through photosynthesis, so it can be used to model carbon sequestration. Photosynthesis can determine a vegetated ecosystem's ability to absorb carbon from the atmosphere [10–12]. Ecosystem productivity modelling for estimating dynamic carbon uptake has been developed mainly by utilizing remote sensing data. Several models have been developed, such as the Carnegie–Ames–Stanford Approach (CASA) [13], the GLObal Production Efficiency Model or GLO-PEM [14], GLO-PEM 2 [15] and Vegetation Photosynthesis Model (VPM) [16]. All of these methods were developed to assess carbon uptake in forest areas.

In Indonesia, a study about carbon balance still discusses the potential of carbon storage in the forest area. Research by [17–20] conducted in the forests of Kalimantan, Sumatra, Sulawesi and Papua showed that the value of carbon absorption in Indonesia's tropical forest areas is high yearly. However, this research was conducted in forest areas that experienced little land use change. Research on carbon uptake in areas with high dynamics of land use change, especially in watershed areas, is rarely carried out. Therefore, this research focused on studying the dynamic change of carbon sequestration in the watershed area.

2 Method

2.1 Study area

The research area is located in the Upper Bengawan Solo Watershed (DAS). The Upper Bengawan Solo Watershed is a sub-section of one of the largest watersheds on the island of Java, namely the Bengawan Solo Watershed. The Bengawan Solo River, which flows into the Bengawan Solo watershed, is the longest river on the island of Java, which originates in the southern region of Java Island in the Sewu Mountains and empties into the Java Sea near the city of Surabaya. The total length of the Bengawan Solo River is around 600 km, with a catchment area of 16,100 km^2.

The Upper Bengawan Solo Watershed is part of the Bengawan Solo Watershed, located upstream of the Bengawan Solo River. This watershed system extends upstream in the Sewu Mountains in Wonogiri and Gunungkidul Regencies to the Solo-Klaten Basin region. Administratively, the Bengawan Solo Hulu watershed is in three provinces, namely D.I. Yogyakarta. East Java Province and Central Java Province are divided into ten regencies: Sleman, Gunungkidul, Klaten, Boyolali, Karanganyar, Sukoharjo, Wonogiri, Pacitan, Magetan, and Surakarta City. The existence of the Upper Solo Bengawan Watershed can be seen in **Fig. 1**.

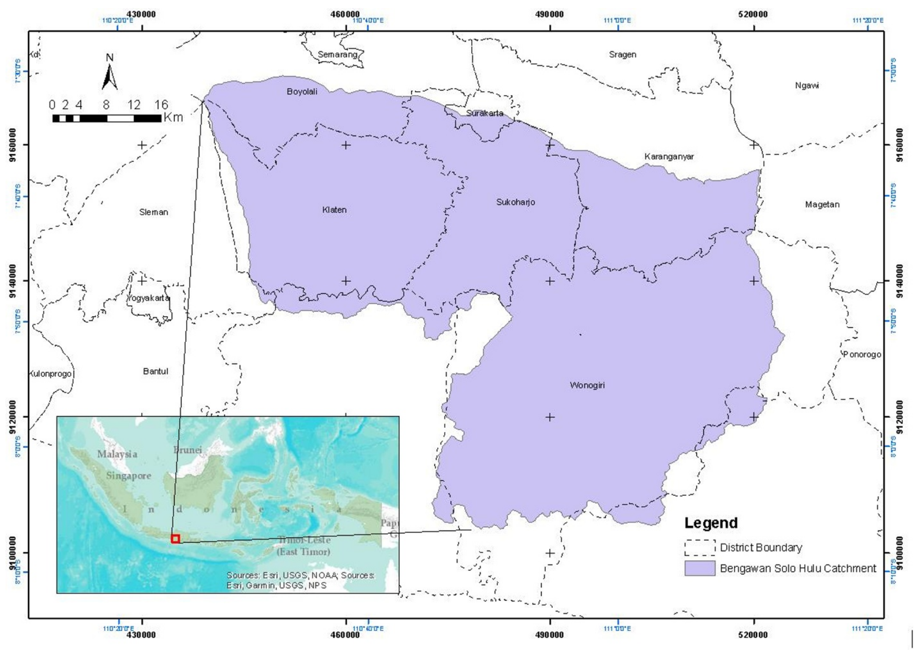

Fig. 1. Location of upper Bengawan Solo Watershed

The astronomical location of the Upper Bengawan Solo Watershed is at coordinates 6°49' – 8°08' LS and 110°18' - 112°45' East Longitude. The Serang and Progo Watersheds border the geographical location of the Bengawan Solo Upper Watershed to the west, the Brantas Watershed to the east, the Grindulu Watershed and Lorong Watershed to the south, and the Kali Madiun Watershed to the north. The total area of the Bengawan Solo Upper Watershed ranges from 3,308 km^2, divided into eight main sub-watersheds: Kapang Sub-watershed, Alang Sub-watershed, Nguntungan Sub-watershed, Remnant Sub-watershed, Temon Sub-watershed, Wuryantoro Sub-watershed, Tirtomoyo Sub-watershed, and Upper Solo Watershed.

2.2 Data collecting

The data needed to model NPP values are meteorological conditions and imagery. The climate parameters used in this research are monthly average temperature, humidity, solar radiation, evaporation, and rainfall from 1985 – 2020. The data obtained for these climate parameters can be seen in **Table 1**.

Table 1. Source of meteorological data

No.	Data	Source
1.	Monthly Temperature	NASA https://power.larc.nasa.gov/
2.	Monthly Air Moisture	
3.	Monthly Precipitation	
4.	Monthly Solar Radiance	BMKG Indonesia https://dataonline.bmkg.go.id/home
5.	Monthly Evaporation	Modellig with Penman Method

The images used in this study are Landsat 7 ETM+ imagery to model the 2000 NPP values and Landsat 8 OLI imagery to model the 2020 NPP values. Landsat 7 ETM+ and 8 OLI imagery were obtained from the USGS through the website https://earthexplorer.usgs.gov/. The Landsat imagery used has a spatial resolution of 30 meters which is used to model the NDVI value as the basis for calculating the NPP value.

2.3 Data analysis

The 2000 Landsat 7 ETM+ imagery and the 2020 Landsat 8 OLI imagery were analyzed to produce a greenish index value or NDVI. NDVI can be calculated by utilizing the reflection of objects in the red (R) and near-infrared (NIR) channels. The equation used to calculate the NDVI value is as follows.

$$NDVI = \frac{NIR-R}{NIR+R} \tag{1}$$

Furthermore, the research area's NPP values in 2000 and 2020 were modelled using the Carnegie–Ames–Stanford Approach (CASA) [12]. The CASA method is used to estimate ecosystem productivity through the process of photosynthesis. Photosynthesis is the process of making food by plants by utilizing carbon dioxide from the atmosphere. The value generated from the CASA method is the net primary productivity (NPP) value. NPP describes the net carbon dioxide uptake potential carried out by vegetation during the photosynthesis process.

NPP can be calculated by considering the value of Gross Primary Productivity (GPP) and Consumption of Autotrophic Respiration (Rd) at a specific time and space. The formulation used is as follows.

$$NPP_{(bulan)}(x,t) = GPP(x,t) - Rd(x,t) \tag{2}$$

GPP values can be modelled by utilizing light energy utilization value (Ɛ), solar radiation (SOL), and Fractional absorption of photosynthetically active radiation (FPAR). The formulation used is as follows.

$$GPP(x,t) = \varepsilon \times SOL \times FPAR(x,t) \times 0.5 \tag{3}$$

The FPAR value can be approximated by the transformation value of the NDVI vegetation index through the formulation:

$$\begin{aligned} &FPAR = 0 && NDVI < 0.123 \\ &FPAR = \{1.164 \times NDVI - 0.04393\} && NDVI > 0.123 \end{aligned} \tag{4}$$

The value of Ɛ is modelled by calculating the value of the effect of temperature on the utilization of light energy (TƐ), the effect of humidity on the utilization of light energy (WƐ), and the maximum utilization of light energy in each type of ecosystem (Ɛmax). The formulation used is as follows.

$$\varepsilon(x,t) = T\varepsilon\,(x,t) \times W\varepsilon\,(x,t) \times \varepsilon_{max} \quad (5)$$

The following formulation can modulate the Rd value using temperature data and GPP values .

$$Rd = \frac{7.825+1.145T}{100} \times GPP \quad (6)$$

The value of the NPP modelling results can be converted from the value of C to CO2 with the following formulation [21]:

$$\text{Total } CO_2 \text{ Sequestration} = \text{NPP value} \times (44 \text{ g } CO_2/12 \text{ g c}) \quad (7)$$

3 Result and discussion

3.1 Vegetation index (NDVI) change during 2000 – 2020

Observation of the distribution of vegetated land in the Upper Bengawan Solo Watershed was carried out based on the NDVI values of the two years of image recording, namely 2000 and 2020. The NDVI value is an index used to identify vegetation distribution, which is modelled using remote sensing imagery on the red and near-infrared (NIR) channels. One of the images that have both channels and is easy to obtain is the Landsat 7 ETM+ and 8 OLI images. This image will also be used to analyze the distribution of vegetated land based on the modelling results with NDVI.

The results of processing NDVI values in the study area are shown in **Fig. 2**, where there are five classes of colour distribution. The first class with an NDVI value < -0.32 is assumed to be a waterbody appearance; the second class with a value range of -0.31 – 0.32 is assumed to be non-vegetated land; the third class with a value range of 0.33 – 0.55 is assumed to be low-density vegetated land; the fourth class with a value range of 0.56 – 0.78 is assumed to be vegetated land with medium density; and the fifth class with a value range of 0.78 – 1 is assumed to be land with a high density of vegetation [22].

Based on **Fig. 2** it can be seen that the Bengawan Solo Upper Watershed in the 2000 – 2020 range is still dominated by non-developed land. In 2000 the vegetated land with medium and high density was still spread out in all research areas. Non-vegetated land is only spread in the central part of the north side, to be precise, in the urban area of Surakarta and the city expansion area, namely in Sukoharjo Regency. Meanwhile, in 2020 there was a significant change where almost all areas in the Upper Solo Bengawan watershed were dominated by non-vegetated and low-density vegetated land. Vegetated land with medium and high density is only spread on the west side, on the slopes of Mount Merapi and on the east side, on Mount Lawu. This condition indicates that there has been a reduction in vegetated land in the study area, thereby enabling a decrease in the value of carbon absorption. The extent of changes in NDVI values in the study area can be seen in **Table 2**.

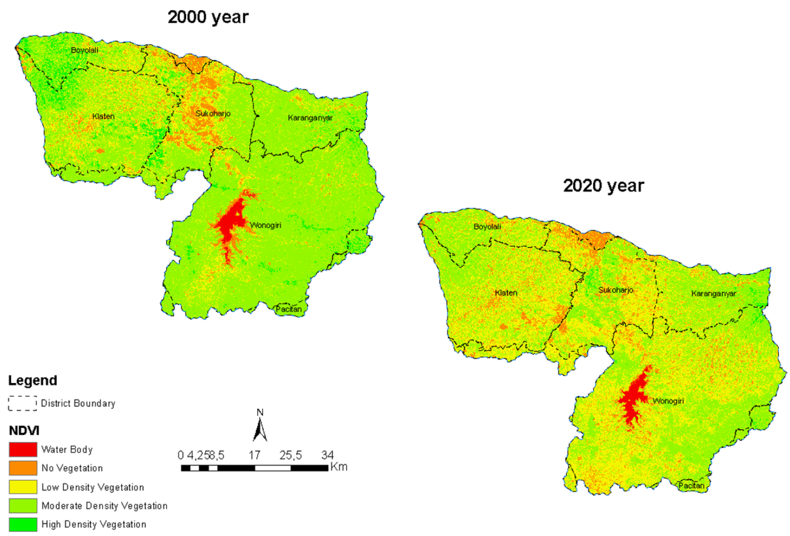

Fig. 2. NDVI Map in upper Bengawan Solo Watershed in 2000 and 2020

Table 2. NDVI change in upper Bengawan Solo Watershed in 2000 and 2020

No	Area	Size (km^2)	
		2000	**2020**
1.	No Vegetation	264.37	409.37
2.	Low-Density Vegetation	49.15	61.92
3.	Moderate Density Vegetation	1.48	2.70
4.	High-Density Vegetation	2993.17	2834.18

3.2 Variation of carbon sequestration value during 2000 – 2020

The value of carbon absorption in an area can be modelled using the value of net productivity through the photosynthesis process known as net primary productivity (NPP). NPP describes the amount of solar radiation energy converted by vegetation into chemical energy to produce food for the vegetation. This process requires a certain amount of carbon to be absorbed from the atmosphere around the vegetation. The modelling results show that the average annual net productivity (NPP) value in the study area is 717.19 gC/m2/year. This value is relatively small when compared to the average NPP value in other areas of tropical forest areas in Indonesia, such as in the forest areas of West Kalimantan [17]; Leuser forest area; Berau forest area, East Kalimantan; Papua Forest areas [18]; and the forest area of Sulawesi [19]. A comparison of the value of net primary productivity (NPP) in various tropical forest areas and research areas can be seen in **Table 3**. It is very reasonable if look at the condition of the built-up land in the Bengawan Solo Hulu watershed in 2020, which is getting wider to suppress the vegetated land in this watershed.

Table 3 shows that the NPP's value in the Upper Bengawan Solo Watershed area and the forest shows a relatively significant difference, even though all locations are in tropical climate areas. The difference in NPP values between the two areas is due to differences in density and types of vegetation [17, 23–25]. This condition can be seen in the study's results, where the distribution of the highest NPP values in the study area was spread over forest and agricultural land. However, the area of forest in the Upper Bengawan Solo Watershed, which only exists on the slopes of Mount Merapi in the western and the slopes of Mount Lawu in the eastern, causes the NPP value to tending still to be low if averaged in the Bengawan Solo

Upstream Watershed unit. The condition of vegetation density, which tends to be low compared to other tropical forest areas, is the leading cause of the lower NPP value in the study area. In addition, another factor that causes the low NPP value in the Upper Bengawan Solo Watershed is the condition of vegetation on vegetated land, especially around residential areas, which tends to be homogeneous or consist of only one type. Generally, the condition of a homogeneous vegetated land will have the same NPP value for each vegetation, so the variation in values will not be too significant. In contrast, NPP values in vegetated land, which tend to be heterogeneous, will have significant variation so that the ability of ecosystems to absorb carbon will also be large [23, 24].

Table 3. Comparison of NPP value with other areas in tropical climate zone

No	Study Area	NPP Value (gC/m^2/year)	Source
1.	Ketapang, Kalimantan Barat	13,200	[17]
2.	Leuser, Aceh	8,950,000	[18]
3.	Berau, Kalimantan Timur	10,300,000	
4.	Kamulo Doso, Papua New Guinea	10,120,000	
5.	Merang, Sumatera Selatan	10,790,000	
6.	Sulawesi	8,400	[19]

NPP values in the Bengawan Solo watershed show spatial patterns related to land cover conditions. The highest NPP values, from 1000 – 1601 gC/m2/year, are spread over forest land cover on the west side of Mount Merapi and the east side of Mount Lawu. In addition, high NPP values are also found in agricultural land in the form of paddy fields in the central part, to be precise, in the Klaten and Sukoharjo Regencies and moor fields on the south side, to be precise, in the Wonogiri Regency area. Meanwhile, in areas with a high density of built-up land, high NPP values are only found in a small area in the form of city parks or the path of a river border and also a reservoir or lake border. The spatial distribution of NPP values in the Upper Bengawan Solo Watershed can be seen in **Fig. 3**.

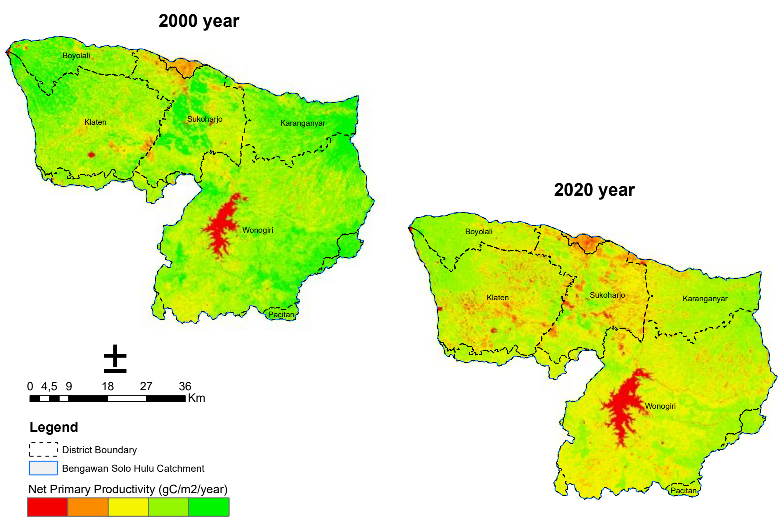

Fig. 3. NPP value map in upper Bengawan Solo Watershed in 2000 and 2020

The value of NPP in the Upper Bengawan Solo watershed not only varies spatially but is also very dynamic over time. The NPP value or the ability of ecosystems to absorb carbon is very dynamic due to natural factors due to changes in climatic conditions [23, 26] and non-natural factors due to human activities [25, 27, 28]. The influence of human activities on land, especially land use conversion, can affect the ability of ecosystems to absorb carbon. This condition can be seen in the study area, where changes in the area of built-up land cause changes in the value of the NPP.

The NPP value in the study area decreased significantly from 2000 to 2020. Overall, the average NPP value in the Upper Solo Watershed has decreased by 240 gC/m2/year. Decreasing NPP value is due to the decrease in the area of vegetated land in the study area. The changes in NPP values in each area in the Upper Bengawan Solo Watershed can be seen in **Fig. 4**.

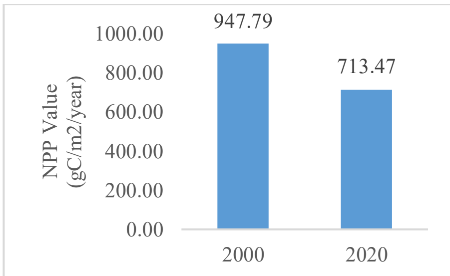

Fig. 4. Comparison of NPP value in upper Bengawan Solo Watershed during 2000 – 2020

The reduction in the value of NPP in the Upper Bengawan Solo Watershed needs to be a concern given that there is a target to achieve carbon emission reduction in every region in Indonesia. One of the things that are important to note to maintain the ability of ecosystems to absorb carbon is related to land use management. Limitations on the conversion of built-up land in the Upper Bengawan Solo Watershed should be considered by policymakers to maintain the ability of ecosystems in the Bengawan Solo Watershed to absorb carbon from the atmosphere.

4 Conclusion

The average value of carbon absorption in the Upper Solo Bengawan watershed has decreased by 25%. The decline occurred almost evenly in all areas, especially in the urban area of Surakarta and the surrounding areas, such as Sukoharjo Regency, Klaten Regency and Karanganyar Regency. The highest carbon absorption value in 2020 is on the west side, to be precise, on the slopes of Mount Merapi and to the east, to be precise, on Mount Lawu slopes. The cause of the decrease in the average value of carbon uptake is the phenomenon of reduced vegetation canopy cover, characterized by a decrease in the NDVI value in the study area in the 2000 – 2020 range. Other factors that cause a decrease in the average value of carbon sequestration have not been studied in this study, so it is necessary to have future research. Future research can link changes in the value of carbon absorption with the phenomenon of land use change, urban sprawl, and an increase in the rate of built-up land.

This research is funded by Universitas Muhammadiyah Surakarta through the "Hibah Integrasi Tridharma (HIT)" in 2021, which the Center of Research and Innovation of Universitas Muhammadiyah Surakarta manages.

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