Estimation of peak runoff impact from land use change using remote sensing and GIS in Keduang sub-watershed

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Abstract. Changes in land use in watersheds and climate change have a dominant influence on watershed hydrology. One of the important aspects of watershed hydrology related to land use change and climate change is runoff. Land use changes in the watershed area from non-built areas to built areas or vegetated areas to non-vegetated areas will increase runoff. Because vegetation helps absorb rainwater optimally into the soil. Thus, rainwater that falls to the ground will become more runoff. For this reason, it is necessary to conduct a study to determine the land use changes and impact on the runoff, as has been done in the Keduang sub-watershed, Wonogiri District, Indonesia. Land use change and peak runoff were estimated using remote sensing and Geographic Information System (GIS). Remotely sensed images from the Landsat satellites were used to develop land use maps of the study area in 2009 and 2020. The peak runoff was computed by the Rational Method. The land use map between 2009 and 2020 shows an increase in built areas and dryland agriculture and a decrease in the vegetated area such as a forest and mix garden. The impact of land use change increases the coefficient runoff value in the study area from 0.22 to 0.24. The results showed that peak runoff for 2009 was 358.73 m$^3$/s and in 2020 was 363.38 m$^3$/s there is an increase of 4.66 m$^3$/s.

1. Introduction
Environmental changes can be associated with natural or human activities [1]. Land use change in watersheds and climate change have a dominant influence on watershed hydrology. Land use in watersheds that ignores land capability and conservation principles will cause the watershed to be damaged or critical [2]. In Indonesia, this phenomenon almost occurs, especially in the upstream and downstream areas due to the increasing population [3]. Due to climate change, an increase in rainfall can cause flooding, or a decrease in rainfall can cause a drought. Drought and flood impact various fields, for example, land use change [4][5]. One of the important aspects of watershed hydrology related to land use change and climate change is runoff. Changes in land use in the watershed from vegetated areas to non-vegetated areas will increase runoff. Because vegetation helps absorb rainwater optimally into the soil. Thus, rainwater that falls to the ground will become more runoff.

Many methods have been developed to estimate peak runoff, both directly and indirectly [6]. Recently, estimation of peak runoff indirectly can be done based on the integration of remote sensing and GIS with a Rational method [1][7]. Estimating runoff using remote sensing and GIS provides quick
results and it is one of the best techniques to estimate runoff spatially [8]. Remote sensing and GIS with satellite imagery can be used to determine the dynamics of land use change [9]–[11]. Land use maps can be used to determine the runoff coefficient. The process of identifying land use change requires spatial and temporal data [12]. The advantages of remote sensing include the speed of providing information, efficiency in time, effort, and cost when compared to direct field surveys [13]. The rational method is practical and easy to apply. This method is suitable for tropical conditions in Indonesia [14].

Currently, many watersheds in Indonesia are in critical condition due to land use change. The Keduang sub-watershed is part of the Solo watershed which is in critical condition. Land use in this sub-watershed is very dynamic. The peak runoff will change with changes in land use. The purpose of this study was to analyze land use changes and their impact on the peak runoff in the Keduang sub-watershed in 2009-2020.

2. Materials and method

2.1. Study area

This research was conducted in Keduang sub-watershed, Wonogiri Regency, Indonesia. This sub-watershed is located between 7°42'29"-7°55'39" S and 111°11'01"-111°24'54" E with an area of 39,379.41 ha as shown in Figure 1.

![Study area](image)

**Figure 1.** Study area.

2.2. Remote sensing and rainfall data

Remote sensing data Landsat 8 path/row 119/065 an acquisition date on August 23rd, 2020, and Landsat 7 an acquisition date on October 20, 2009, have been downloaded from The United States Geological Survey (USGS). Daily rainfall data from 5 rain gauge stations were collected from BMKG, BBWS, and Balitek DAS. The location and name of rain gauge stations are shown in Figure 1.

2.3. Determine land use change

Classification of land use maps from Landsat imagery using Maximum Likelihood Classification (MLC) method. Then, the accuracy assessment is carried out by comparing with field observation data and high-resolution satellite imagery.
2.4. Determine the peak runoff

Peak runoff was estimated using the Rational method in equation (1) [15]. The constant 0.278 is a conversion factor for peak runoff to units (m³/s).

\[ Q = 0.287 \cdot C \cdot I \cdot A \]  

(1)

Where,
- \( Q \): Peak runoff (m³/s)
- \( C \): Runoff coefficient in the watershed
- \( I \): Rain intensity (mm/hour)
- \( A \): Watershed area (km²)

The value runoff coefficient (C) is obtained by equation (2). The value runoff coefficient (C) is based on the type of land use and refers to Table 1 [16].

\[ C = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i} \]  

(2)

Where,
- \( C \): Runoff coefficient
- \( C_i \): Runoff coefficients for various land use
- \( A_i \): Area (km² or ha).

| Type of land use             | Runoff coefficient (C) |
|-----------------------------|------------------------|
| Built area                  | 0.4                    |
| Forest                      | 0.1                    |
| Shrubs                      | 0.3                    |
| Wet paddy field/dry paddy field | 0.21                |
| Dry land                    | 0.3                    |
| Mix garden                  | 0.15                   |

The maximum daily rainfall is calculated using the Thiessen polygon method. Then the rainfall intensity (I) for 2009 and 2020 is calculated using the Mononobe equation (3).

\[ I = \frac{R_{24}}{24} \left( \frac{24}{T_c} \right)^{2/3} \]  

(3)

Where,
- \( I \): Rainfall intensity during the period \( T_c \) (mm/hour)
- \( R_{24} \): Maximum daily rain intensity (mm)
- \( T_c \): Time of concentration (hour)

The rainfall duration must be greater than or equal to the \( T_c \), otherwise, the runoff won’t have time to rise to the maximum value [17]. The \( T_c \) is calculated using Kirpich equation (4) [18].

\[ T_c = 0.01947 L^{0.77} S^{-0.385} \]  

(4)

Where,
- \( T_c \): Time of concentration (minutes)
- \( L \): The channel flow length (meters)
- \( S \): Main channel slope
3. Results and discussion

3.1. Land use change

Analysis of land use change begins with radiometric and atmospheric correction of Landsat imagery. Radiometric correction to correct the pixel value considering the atmospheric disturbance factor as the main source of error. Atmospheric correction to reduce or to eliminate errors recorded by the sensor in the image due to atmospheric influences and to obtain reflectance value [19]. After the land use map classification is complete, then the assessment accuracy process is carried out to determine whether the results of the classification can be used for further analysis. The classified land use map can be used for further analysis if the overall accuracy is above 85% [20].

![Figure 2. Land use map on 2009.](image)

![Figure 3. Land use map on 2020.](image)

![Figure 4. Land use composition.](image)

There are eight land use types delineated from the MLC method. Types of land use include water bodies, built area, forest, shrub, wet paddy field, dry paddy field, dry land, and mix garden. The land use maps that have been classified are shown in Figure 2 as land use 2009, Figure 3 as land use 2020, and the composition shown in Figure 4. The number of sample point’s assessment accuracy is 67 points. The overall accuracy and the kappa coefficient of land use map 2009 are 85.07%, 0.83, and 2020 are
91.04%, 0.90. With these results, the classification results on the land use map can be used for further analysis based on [20]. The assessment accuracy result is shown in Table 2.

**Table 2. Assessment accuracy result.**

| Land use map | Overall accuracy (%) | Kappa |
|--------------|----------------------|-------|
| 2009         | 85.07                | 0.83  |
| 2020         | 91.04                | 0.90  |

During 2009-2020 in the Keduang sub-watershed there was an increase in the built areas, shrubs, dry paddy fields, and dry land 0.6%, 5.0%, 1.3%, and 3.8% respectively. Meanwhile, the decrease occurred in forests, wet paddy fields, and mixed gardens with decreases of 6.0%, 0.9%, and 2.8% respectively. An increase in the built area, decrease agricultural land, and deforestation can indicate an increase in the population [21]. An increase in population will increase the need for food. In the Keduang sub-watershed, the increase in dry land can be intended to increase food production. The utilization of dry land makes it possible to increase food production [22]. The land use change in the Keduang sub-watershed in 2009-2020 is shown in Table 3 and Figure 5.

**Table 3. Land use change in Keduang sub-watershed 2009-2020.**

| Land use type | 2009 ha (%) | 2020 ha (%) | Change ha (%) |
|---------------|-------------|-------------|---------------|
| Cloud         | 289.08      | -           | -             |
| Cloud shadow  | 64.89       | -           | -             |
| Waterbody     | 80.64       | 14.49       | -66.15        |
| Built area    | 5,470.74    | 5,716.44    | 245.70        |
| Forest        | 5,031.63    | 2,661.03    | -2,370.60     |
| Shrub         | 1,954.35    | 3,954.87    | 2,000.52      |
| Wet paddy field| 4,191.75  | 3,841.74    | -350.01       |
| Dry paddy field| 6,476.40 | 6,992.91    | 516.51        |
| Dry land      | 6,491.34    | 7,988.04    | 1,496.70      |
| Mix garden    | 9,688.59    | 8,569.89    | -1,118.70     |
| SUM           | 39,739.41   | 39,739.41   | 0%            |

**Figure 5. Land use change graph 2009-2020.**
3.2. Estimation peak runoff

The first step to estimation peak runoff is the calculation runoff coefficient (C). Based on the area of land use in Table 3, the runoff coefficient value can be determined for 2009 and 2020. Runoff coefficients in 2009 and 2020 are 0.22 and 0.24, respectively. An increase in built area [23], dry land agriculture [24], and a decrease in vegetated areas such as forest area [25] which has a function as a rainfall buffer zone will increase the runoff coefficient. The result of the runoff coefficient calculation is shown in Table 4.

The second step is the calculation of rainfall intensity (I). Rainfall intensity in 2009 and 2020 were 14.47 mm/hour and 13.48 mm/hour, respectively, a decrease of 0.99 mm/hour. The highest maximum daily rainfall and rainfall intensity occurred in 2010 and 2017. The result of the calculations is shown in Table 5. Extreme climate change will affect rainfall. The effect of rainfall intensity on runoff is influenced by the infiltration factor. If the rain intensity exceeds the infiltration capacity, the runoff will increase according to the increase in rainfall intensity [26]. If the soil is saturated, the rain will immediately become a runoff. High rainfall intensity of short duration will increase runoff faster than light rainfall of long duration because there is not enough time for rainwater to infiltrate into the soil [27].

| Table 4. Runoff coefficient analysis. |
|--------------------------------------|
| Land use type | C value | 2009 |  | 2020 |  |
| | | ha | Runoff coefficient | ha | Runoff coefficient | |
| | | | (C) | | (C) |
| Cloud | 0 | 289.08 | 0.00 | - | 0.00 |
| Cloud shadow | 0 | 64.89 | 0.00 | - | 0.00 |
| Waterbody | 0 | 80.64 | 0.00 | 14.49 | 0.00 |
| Built area | 0.4 | 5,470.74 | 0.06 | 5,716.44 | 0.06 |
| Forest | 0.1 | 5,031.63 | 0.01 | 2,661.03 | 0.01 |
| Shrubs | 0.3 | 1,954.35 | 0.01 | 3,954.87 | 0.03 |
| Wet paddy field | 0.21 | 4,191.75 | 0.02 | 3,841.74 | 0.02 |
| Dry paddy field | 0.21 | 6,476.40 | 0.03 | 6,992.91 | 0.04 |
| Dry land | 0.3 | 6,491.34 | 0.05 | 7,988.04 | 0.06 |
| Mix garden | 0.15 | 9,688.59 | 0.04 | 8,569.89 | 0.03 |
| Runoff coefficient | | 22 | 0.22 | | 0.24 |

| Table 5. Rainfall intensity. |
|-----------------------------|
| Year | Annual rainfall (mm/year) | R max (mm/day) | I (mm/hour) |
|-----|---------------------------|---------------|-------------|
| 2009 | 2,019.66 | 99.31 | 14.47 |
| 2010 | 3,359.58 | 180.84 | 26.34 |
| 2011 | 2,997.95 | 115.49 | 16.82 |
| 2012 | 2,698.57 | 147.86 | 21.54 |
| 2013 | 3,399.09 | 139.08 | 20.26 |
| 2014 | 2,064.31 | 135.59 | 19.75 |
| 2015 | 2,171.70 | 95.73 | 13.95 |
| 2016 | 3,447.69 | 131.22 | 19.12 |
| 2017 | 2,561.73 | 155.14 | 22.60 |
| 2018 | 1,735.45 | 120.81 | 17.60 |
| 2019 | 1,473.75 | 85.14 | 12.40 |
| 2020 | 2,279.24 | 92.54 | 13.48 |
The last step is estimation peak runoff. Peak runoff depends on the runoff coefficient, rainfall intensity, and area. The peak runoff in 2009 was 358.73 m$^3$/s and increased by 4.66 m$^3$/s (1.3%) in 2020 to 363.38 m$^3$/s. The results are as shown in Table 6.

Table 6. Rational method result.

| Year | C$^*$ | I (mm/hour) | A (km$^2$) | Q (m$^3$/s) |
|------|-------|-------------|------------|-------------|
| 2009 | 0.22  | 14.47       | 397.39     | 358.73      |
| 2010 | 0.22  | 26.34       | 397.39     | 653.19      |
| 2011 | 0.22  | 16.82       | 397.39     | 417.14      |
| 2012 | 0.22  | 21.54       | 397.39     | 534.06      |
| 2013 | 0.22  | 20.26       | 397.39     | 502.35      |
| 2014 | 0.22  | 19.75       | 397.39     | 489.74      |
| 2015 | 0.24  | 13.95       | 397.39     | 375.92      |
| 2016 | 0.24  | 19.12       | 397.39     | 515.28      |
| 2017 | 0.24  | 22.60       | 397.39     | 609.21      |
| 2018 | 0.24  | 17.60       | 397.39     | 474.41      |
| 2019 | 0.24  | 12.40       | 397.39     | 334.33      |
| 2020 | 0.24  | 13.48       | 397.39     | 363.38      |

Note $^*$: 0.22: based on land use 2009, 0.24: based on land use 2020.

4. Conclusion
Decreasing the forests by 6% during the 2009-2020 period in the Keduang sub-watershed has increased the runoff by 1.3%. Runoff is closely related to land use and climate. Land use change and climate change will exacerbate peak runoff. Land use change must be controlled. It is necessary to formulate efforts to suppress or stop the conversion of forest in the area as an effort to mitigate the impacts of climate change.

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