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Direct Runoff Estimation using SCS-CN method in Lake Toba Catchment, North Sumatra, Indonesia

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Abstract

Lake Toba is the second largest lake located in Sumatra Island, Indonesia. The lake has been an important drinking source for 82% of people living in the catchment. The intense agricultural activities in Toba Catchment produce fertilizers, pesticides, and nutrient rich wastes that threaten the lake quality through direct runoff process. Estimating direct runoff is essential in predicting lake Toba degradation. There is lack of simpler and straightforward method to calculate direct runoff in Toba Catchment. In this study, direct runoff was estimated by using Soil Conservation Service- Curve Number (SCS-CN). It is a method where a single parameter called Curve Number (CN) is used to represent multiple variables of soil conditions. The method is further improved by slope adjustment.

The aim in this study is to estimate direct runoff for 2001-2017 as well as analyzing on how land use change affect CN and direct runoff value. λ coefficient in this method needs to be modified as frequently used coefficients 0.2 and 0.05 were resulted in underestimation of direct runoff.

To determine CN in this study, TRMM precipitation data, ESA land use map, LPDAAC hydrologic soil group map, and ASTER-GDEM elevation map were used. TRMM precipitation data were processed to derive antecedent 5-day precipitation for Antecedent Soil Moisture Conditions (AMC). The results show that $\lambda=0.005$ is the most appropriate coefficient in case of Toba Catchment and this is lower compared to most of the coefficient values used in previous studies. In an urbanized area, direct runoff value seems to have low correlation with CN and more sensitive to precipitation change. In contrast, in forest area with no land use change, direct runoff depends on the CN / soil conditions compared to the precipitation. Meanwhile overall direct runoff is mostly determined by AMC.

Keywords: direct runoff, SCS-CN, Lake Toba, Antecedent Soil Moisture Conditions (AMC), Toba Catchment, curve number, land use change, precipitation,

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Chapter 1. Introduction

1.1. Research Background

Lake Toba (Danau Toba) is the largest lake in Indonesia as well as the largest caldera-type lake in the world. The crater shape was estimated to result from eruption process that occurred three times: 1 Mya, 0.8 Mya, and the latest 0.074 Mya (Chesner and Rose, 1991). One of this lake's water inflow originated from about 123 relatively small rivers which flow from the hills facing toward the lake. The only outflow of this lake is Asahan River which flows to Porsea, the southeast region of the lake and along this river, three dams and two hydroelectric power stations were constructed and most of the generated power is supplied to Kuala Tanjung Aluminum Smelter owned by PT Inalum. This lake is very important drinking water source for 82% people living in the catchment (Sihotang, 2012) and transportation system between mainland and Samosir Island (Siregar, 2010). Lake Toba is one of Indonesia's well-known tourist destinations, attracting frequent visitors from within and outside the country. The drainage basin of Toba sustains local life necessities by supporting agricultural lands, industrial uses, and aquaculture operations (Moedjodo et al., 2003). However, the lake water quality is threatened by number of activities throughout Toba Catchment. Fertilizers, pesticides, and nutrient-rich wastes from agricultural activities threaten the water quality through runoff (Oakley, 2015). Hence runoff estimation in Toba Catchment could be vital in determining lake degradation rate.

Soil Conservation Service-Curve Number (SCS-CN) is a method for predicting direct runoff that has been widely used in earlier studies such as Mishra et al. (2004); Kadam et al. (2012); Bhura et al. (2015); Fadlillah and Widyastuti (2016); and Satheeshkumar et al. (2017). It is a well-known method utilizing precipitation data along with soil, land use, hydrologic conditions, and antecedent moisture. The calculations are directly, intuitively logical and featured in most of the hydrologic computer models in use (Beven, 2012). The main idea of SCS-CN method is assuming that the ratio of direct runoff to potential maximum runoff equal to the ratio of actual soil retention to potential maximum soil retention (Dong et al., 2015). SCS-CN method is proven to be better method which consumes less time and facility to handle extensive data as well as larger environmental area (Satheeshkumar et al., 2017). This study proposed to use improved SCS-CN with an addition of slope adjustment with Huang (2006) formula. The traditional SCS-CN method assumes slope inclination is 5% throughout the basin. However, Figure 22 shows that Toba catchment has varying slopes. Akbari (2015) has proven that Huang (2006) formula improve the spatial variation of CN over the catchment. There are only few direct runoff estimations on Toba Catchment such as Sihotang (2012). Although Sihotang (2012) estimation has high accuracy, the method used is complex and indirect due to dependency on infiltration coefficient. SCS-CN method offers more straightforward estimation of direct runoff. From 2001 to 2009, vegetated area in Toba Catchment has decreased (Sihotang, 2012). This land cover change plays significant role in hydrological processes especially infiltration and surface runoff (Liu et al., 2012). Also, Year 2015 is when the strong El Nino effect occurred particularly in Southeast Asia (Samsuddin et al., 2018). El Nino is the warm phase of El Nino Southern Oscillation (ENSO) which refers to the temperature fluctuations between the atmosphere and the ocean in the east-central Equatorial Pacific (Shi and Wang, 2014). Low direct runoff estimation could indicate drought condition over the catchment as Indonesia is a country that vulnerable to extreme drought s related to ENSO (Aldrian et al., 2006)

1.2. Research Purpose

This study is aimed to estimate direct runoff volume in Toba Catchment from 2001 to 2017 by using improved SCS-CN method. Also, this study analyzes runoff trends by regional and overall in Toba Catchment considering the change in land use.

Chapter 2. Method

2.1. Research Area

Lake Toba (2.88°N 98.52°E- 2.35°N 99.10E°) is the largest lake in Indonesia located in the province of North Sumatra, 176 km from the provincial capital, Medan. The lake stretches from northwest to the southeast at the distance of 87 km and has a width of 27 km. The lake located at 905 m above the sea level and has maximum depth of 505 m. Toba catchment area covers about 3,658 km^2 with lake area accounts for 1,103 km^2 and the rest of area are mostly hilly and mountainous. It belongs to tropical climate zone with average annual precipitation 2607.6 mm/year in the catchment from 2001 to 2017.

2.2. Data

2.2.1. Precipitation

2.2.1.1. Local Rain Gauges

Monthly precipitation data from four stations in Toba Catchment measured by Local Meteorological, Climatological, and Geophysics Agency (BMKG) were cited from Siregar (2010). The data available is from 1993 to 2007.

2.2.1.2. TRMM Rainfall Estimates

Daily precipitation data which is derived from 3B42 Research Version of Tropical Rainfall Measurement Mission (TRMM). The Algorithm applied is the Version 7 TRMM Multi-Satellite Precipitation Analysis. The data available is from January 1998 to present and the horizontal resolution of 0.25°.

2.2.2. Land Use Map

Figs. 2~16 shows annual land use maps of 2001 to 2015 produced by the data of European Space Agency (ESA) with spatial resolution of 300m. They were used to investigate the change in land use. This map was projected to the 1984 World Geodetic System (WGS84) and created by combining data of Advanced Very High-Resolution Radiometer (AVHRR) and PROBA-V sensors. Since the data are available only until 2015, no land use change was assumed for 2015-2017.

2.2.3. Hydrologic Soil Map

Fig. 21 represents globally consistent, gridded dataset of hydrologic soil groups (HSGs) with a geographical resolution of 1/480 decimal degrees or approximately equivalent to 250m. These data have been devoted to support USDA-based curve-number runoff modelling at regional and continental scales. Hydrologic Soil Groups were classified into four groups: A, B, C, and D that corresponds to low, moderately low, moderately high, and high runoff potential. The classification is based on soil texture classes and depth to bedrock.

2.2.4. Elevation Map

The Advanced Space-borne Thermal Emission Radiometer (ASTER) Global Digital Elevation Model Version 2 (ASTER-GDEM V2) was used to investigate the effect of slope on CN. This version was released on mid-October 2011. Fig. 22 shows the elevation data with resolution of

30m and referenced to the 1984 World Geodetic System (WGS84)/1996 Earth Gravitational Model (EGM96) geoid.

2.2.5. Antecedent Soil Moisture Conditions (AMC)

AMC was produced from TRMM precipitation data. The amount of previous 5-day precipitation was used to determine whether soil is dry (AMC I), normal (AMC II), and wet (AMC III). The classification of AMC depending on the seasons can be seen in Table 5.

2.3. Precipitation Validation

Satellite-based Precipitation data provided by TRMM may not be very accurate in some areas. In order to check the validity of the precipitation data, the correlation between TRMM data and local meteorological data from BMKG (Meteorology, Climatology, and Geophysical Agency) were analyzed. The gridded precipitation data from TRMM were compared to precipitation data from each station that overlapped with TRMM grid as shown in Fig. 24.

2.4. Curve Number (CN) Calculation

The initial value of the Curve Number (CN) was determined by referring to a two-dimensional Table by USDA (1986). Land use map by European Space Agency (ESA) has too many types of land use and need to be simplified before used as in Table 2. Land use and hydrologic soil groups raster maps were joined and classified by its curve number by using ArcGIS as shown in Table 3 to produce annual initial CN map with resolution of 300m.

The initial CN value map was then adjusted with slope inclination. As Fig. 22 shows, the slope inclination in Toba Catchment varies and the steep slope in some parts of the catchment could reach 70%. Hence, slope adjustment formula by Huang (2006) is necessary in runoff estimation:

$$CN_B = CN_A \frac{322.79 + 15.63\alpha}{\alpha + 323.52} \tag{1}$$

where CN_B: new CN for moderate soil conditions (Secondary Value), CN_A: CN for moderate soil conditions (Initial Value), α: slope inclination (m/m); $0.14 \leq \alpha \leq 1.4$

Figs. 25~39 shows annual secondary value of CN (Slope-adjusted) in Toba Catchment from 2001 to 2015.

The secondary value was then adjusted with Antecedent Soil Moisture Condition (AMC) of the catchment, which can be defined as the initial moisture condition of the catchment prior to the storm events. There are three conditions considered in AMC: (1) Dry condition (AMC I), (2) Normal condition (AMC II), and (3) Wet condition (AMC III). SCS-CN method expresses this parameter as an index depends on seasonal limits for the total 5-day antecedent precipitation as shown in Table 5. For AMC II, the secondary value was used. For AMC I and III, the secondary value needs to be adjusted with Chow (1988) Formula:

$$CN = \begin{cases} \dfrac{4.2CN_B}{10 - 0.058CN_B} & for\ AMC\ I \\ CN_B & for\ AMC\ II \\ \dfrac{23CN_B}{10 + 0.13CN_B} & for\ AMC\ III \end{cases} \tag{2}$$

where CN: final value of CN, CN_B: secondary value of CN

The product of AMC adjustment is daily CN of Toba Catchment from 2001 to 2017 with resolution of 300m. Average final CN value map for every 6 months were shown in Figs. 40~73.

2.5. Direct Runoff Calculation

Final CN value that already accounts land use, hydrologic soil groups (HSGs), slope and antecedent soil moisture conditions (AMC) can be used to calculate soil maximum retention:

$$S = \frac{25400}{CN} - 254 \tag{3}$$

where *S*: maximum soil retention (mm), *CN*: final curve number. The traditional SCS equation (USDA, 1986) is given by equation (4):

$$q = \begin{cases} 0 & for\ P \leq\ I_a \\ \frac{(P-I_a)^2}{P-I_a+S} & for\ P > I_a \end{cases} \tag{4}$$

where q: direct runoff depth (mm/day), P: precipitation (mm/day), S: potential maximum soil moisture retention after runoff begins (mm/day), Ia: initial abstraction/amount of water before runoff (mm/day) can be described as a function of S as:

$$I_a = \lambda S \tag{5}$$

where λ: coefficient ratio value.

Initial abstraction is the maximum amount of rainfall absorbed into soil without producing runoff. Researchers across the world have concluded that initial abstraction value needs to be calibrated as per regional specific characteristics for better prediction (Ling and Yusop, 2014). It has been generally assumed that λ = 0.20 globally, but more recent research has proven that λ = 0.05 provides better estimation of direct runoff especially in urbanized watershed (Hawkins et al., 2002; Woodward et al., 2003). The further modification of λ value is necessary to obtain optimal results.

2.6. λ Coefficient Calibration

The coefficient ratio value (λ) would be calibrated with Sihotang (2012) results. Sihotang (2012) used empirical equation:

$$q = (1 - I) \times P \tag{6}$$

where *q*: runoff depth (mm), *I*: infiltration coefficient, *P*: precipitation (mm). Infiltration coefficient was determined by considering slope, soil porosity, and land cover.

As Sihotang (2012) results were based on coefficient calibrated based on field measurement, the results should be highly accurate. λ value in this study was calibrated with Sihotang (2012) results. The initial hypothesis of the λ value would be 0.05.

2.7. Regional CN and Direct Runoff Analysis

In this study, four specific areas with different characteristics in terms of land use change were selected at point scale with resolution of 300m. Characteristics and location of each point are shown in Table 6 and Fig.74. The monthly and annual change in CN and runoff for those specific areas were analyzed.

Chapter 3. Results and Discussion

3.1. Precipitation

3.1.1. Precipitation Validation

Figs. 75~79 shows the precipitation data from 2001 to 2007 from TRMM compared with four local meteorological stations by using double mass analysis. In those years, both data correlate with each other although three out of four graphs indicates that TRMM data was underestimated by 15% compared to local station data. Hence it can be inferred that TRMM data was valid to be used though it is a bit underestimated.

3.1.2. Precipitation Trends

Annual precipitation over Toba Catchment is the lowest in year 2015 as shown in Fig. 78. This could be related with strong El Nino effect in 2015 that caused drought in many areas in Southeast Asia (Samsuddin et al., 2018). Fig. 79 indicates that the highest monthly precipitation is in October and the lowest is in June. According to Supari et al (2018), there were wet anomalies in SON (September-October-November) period over northern Sumatra caused by low-level convergence over the equator of strong anti-cyclonic circulation moving towards north from the South Indian Ocean region and a weaker corresponding anti-cyclonic moving towards south from the Bay of Bengal and south-western South China Sea, meanwhile during JJA (June-July-August) period dry condition dominating northern Sumatra especially in El Nino period.

3.2. Parameters Determining CN

3.2.1. Land Use

Figs. 2~16 shows that throughout study period, mixture of cropland and natural vegetation is the dominant land covers in the catchment encompassing 42% of the catchment. Fig. 20 indicates about 1.8% of the catchment underwent land use change from 2001 to 2015 with mostly mixed vegetation and cropland turned to be forest that spread out across the catchment. However, the land use change from forest to cropland especially transition of year 2006 to 2007 (Figs. 7~8) occurred in large-scale but concentrated in southwestern area of the catchment. Meanwhile, urban area especially in the southeast area of the catchment constantly increasing by 50% just in 15 years.

3.2.2. Hydrologic Soil Group (HSG)

Fig. 21 indicates 73% of catchment is dominated by Acrisols which is hydrologic soil type C followed by hydrologic soil type D (27%). Runoff event initiated earlier in this type of soil, hence, suggesting that Toba Catchment has high runoff tendency.

3.2.3. Slope

From Fig. 22, there are some parts of the catchment that has high slope steepness such as western lake shore area that has slope inclination more than 70%. Traditional SCS-CN that assumes 5% slope inclination need to be adjusted with Huang (2006) to provide better results.

3.2.4. Antecedent Soil Moisture Conditions (AMC)

Fig. 23 shows that number of dry or wet days is always above 100 days each year. Number of successive days of dry (AMC I) and wet (AMC III) days could be the indicator of drought and flood events. Therefore, CN determination could be very sensitive to AMC parameters. Year 2004-2005 and 2015 is when the highest dry days and lowest wet days that is corresponding to El Nino period.

3.3. Runoff Coefficient Calibration

3.3.1. Calibration with Sihotang (2012)

As Fig. 81 shows, λ=0.05 does not seem to be appropriate λ value as it resulted in underestimation of runoff and does not show good correlation with Sihotang (2012) results. There are three possible reasons on why the direct runoff estimation with the usage of 0.05 as λ in this study is underestimated. First, precipitation data are also underestimated as shown in Figs. 75~79. Secondly, runoff events start earlier before much water infiltrated into the soil. In that case, λ value should be lower than 0.05. In a study conducted by Ling and Yusop (2015), λ value can be as low as 0.00093 in an area that has similar soil characteristics with this study. Third, the study area could be too big for SCS-CN to be used. Hence, there are errors in some areas along the catchment. A few other possible λ values has been tested to be adjusted with Sihotang (2012) results such as 0.03, 0.01, and 0.005. Fig. 81 shows that the lower λ value has higher correlation with Sihotang and 0.005 is the best λ value that can be used in SCS-CN method in the case of Toba Catchment. Hence, the rainfall-runoff formula in Toba Catchment when the precipitation exceeds initial abstraction can be written as:

$$q = \frac{(P-0.005S)^2}{(P+0.995S)} \tag{7}$$

where q: direct runoff depth (mm/day), P: precipitation (mm/day), S: potential maximum soil moisture retention after runoff begins (mm/day)

3.4. CN Trends

3.4.1. Regional CN Trends

Fig. 82 demonstrates that the significant changes in CN trends was not always affected by land use change. Indeed, there are clear changes of CN values in the year of land use transition for point A, C, and D. At point A, when natural forest changed into farmland in 2007, CN value average is increased from 72.4 to 80.7. While CN is decreased from 83.4 to 75.6 at point C, where reforested cropland occurs. Whereas at point D, when cropland turned into urbanized area in 2014, CN increased from 78.4 to 87.5. However, the unexpected CN value drop occurred in point A from 2004 to 2006. At this point, there is no land use change yet, but it was due to high number of dry soil conditions. Continuous dry soil condition for a lot of days indicate severe drought conditions. This is due to strong El-Nino effects in 2005 that caused drought in several areas in Indonesia (Supari et al., 2018). Point A exhibits the effects of El-Nino on CN values indirectly.

3.4.2. Overall CN Trends

Fig. 87 shows that two lowest points of CN occurs in 2004-2005 and 2015. They correspond to the El-Nino cycles of ENSO that also occurred in similar period (Supari et al., 2018). There is also sudden change of CN in year 2003 which resemble to precipitation pattern (Fig. 79). Fig. 86 shows CN values in September significantly were higher than all other months except for April at confidence level 0.05. However, precipitation of September is significantly higher than April as shown in Fig. 80. High value of CN in April is not caused by amount of precipitation but high number of wet days of AMC. September has low frequency but high magnitude of high precipitation.

3.5. Direct Runoff Trends

3.5.1. Regional Runoff Trends

Fig. 88 indicates that direct runoff can be increased up to 92.3% in Point A with only 11.5 % increase in CN after 2007. Cropland contributes a lot in specific runoff as it covers 18.3% of Toba catchment in 2017. This is supported by the fact that CN changes every year affected direct runoff changes (shown in Fig. 92).

In Fig. 91, Point D is the only one sampling points that does not show correlation between CN changes and direct runoff changes whereas there are significant changes in runoff after land use change. Fig. 93 indicates that point D is more sensitive to rainfall compared to CN/soil conditions. In a study conducted by Yao et al. (2018), runoff risk in urban area varied under different rainfall conditions. After point D turned into urban area, the area became impervious meaning that less variability in infiltration capacity and more vulnerable to runoff when there is storm event. As a result, runoff event became more dependent to the rainfall compared to the soil condition. In this study imperviousness is assumed to be 90% across the catchment urban area. Li et al. (2018) conducted a study where various imperviousness level of urban area is considered, where runoff had the strongest correlation to rainfall rather than vegetation index or antecedent 5-day rainfall. Whereas in point B, direct runoff changes show the highest correlation with CN changes compared to other points and the lowest correlation with precipitation. According to Dong et al. (2015), for most of the large-scale basins, the contribution of land use change is greater than that of precipitation changes. However, land use changes only occurred in 1.8% of Toba Catchment from 2001 to 2015 resulting in land use changes do not have significant impact on overall direct runoff of Toba Catchment.

3.5.2. Overall Runoff Trends

Average Overall runoff in Toba Catchment is $8.17 \times 10^8 m^3$ per year. There is a weak decreasing runoff trends for 2001 to 2017 as shown in Fig. 90. In more specific timescale, four trends can be distinguished: (i) decreasing (2001-2004; 2008-2015) and (ii) increasing (2004-2008; 2015-2017). All years from 2001 to 2017 seemingly agree with the trends' correlation except for year 2003. From Fig. 79, precipitation in year 2003 is 23% higher compared to the year before and after. Therefore, the precipitation anomalies affecting CN and runoff trends.

From Fig. 92, CN changes affect the overall runoff annual changes. AMC trend is more specific factor in CN that indirectly determines overall runoff trends. Number of days with wet soil condition in AMC correlated with direct runoff (r=0.9102). In one of AMC factors, number of wet days per year seems to be highly correlated with direct runoff volume per year as shown in Fig. 99. Whereas number of dry days (AMC I) does not correlated with direct runoff (Fig. 98) although both AMC I and III correlated with CN (Figs. 96~97). Since AMC is determined by amount of precipitation, it can be inferred that precipitation indirectly forms direct runoff trends. Runoff trends could be related to ENSO trends.

For period 2001-2017, direct runoff volume was highest in September (Fig. 89). September has also the highest monthly CN (Fig. 86) but not for precipitation (Fig. 80). Despite having the highest precipitation as shown in Fig. 80, Direct runoff for October is comparatively low compared to September due to CN of October is distinctively lower than September (Fig. 86). This infer that the difference of direct runoff produced each month is depend on CN Value than precipitation value.

Chapter 4. Concluding Remarks

The smaller the coefficient ratio value (λ) used in this study the larger the correlation with Sihotang (2012) direct runoff results. $\lambda=0.005$ is appeared to be the most appropriate value of λ in this study although it is lower than most of the previous studies that assumed the constant is either 0.20 or 0.05. SCS-CN method is applicable to measure runoff in Toba Catchment. However, modification of model can be done by direct calibration of the study area especially for λ value adjustment.

Small changes in CN value cause large changes in direct runoff value. With just 10% increase in CN, the direct runoff volume almost doubled. Observable changes in CN can be seen in an area that experiencing land use changes. However, only 1.8% in Toba Catchment experienced land use changes in the last 15 years. Hence, the increase in overall direct runoff in the catchment due to land use change is not significant.

Direct runoff in urbanized area is sensitive to rainfall compared to soil conditions because of imperviousness of land use. Meanwhile other areas are more sensitive to soil conditions change that represented by CN values. AMC is the largest contributor in determining overall direct runoff in Toba Catchment.

One of the remaining issues in this study is model validation as no previous study nor direct discharge measurement were available for validation. Also, due to the lack of information on imperviousness level in urban area of the catchment, the better runoff characteristics on urban area could not be analyzed.

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Table 1 Data Sources

Data	Source	Spatial Resolution	Observation Interval	Period
Precipitation	TRMM (Tropical Rainfall Measurement Mission)	0.25°	daily	1998.01 ~ 2017.12
	Siregar (2010)		monthly	1993~2007
Land Use / Vegetation	ESA (European Space Agency)	300m	yearly	1992~2015
Soil Map	LP DAAC (Land Process Distributed Active Archive Center)	250m	one-time	2017
Slope Map	ASTER-GDEM	Approx. 30m	one-time	2011

Table 2 Land Use Reclassification

Old Class	New Class
Cropland, rainfed	Paddy Field
Cropland, irrigated or post-flooding	Paddy Field
Mosaic cropland (>50%)/natural vegetation	Other Cropland
Mosaic natural vegetation (>50%)/cropland	Broadleaf Forest
Tree cover, broadleaved, evergreen (>15%)	Broadleaf Forest
Mosaic tree and shrub (>50%)/herbaceous cover	Broadleaf Forest
Mosaic herbaceous cover (>50%)/tree and shrub	Broadleaf Forest
Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	Other
Tree cover, flooded, fresh or brakish water	Broadleaf Forest
Tree cover, flooded, saline water	Broadleaf Forest
Urban Areas	Urban Areas
Water bodies	Water bodies

Table 3 Initial Curve Number Values

Land Use	Hydrologic Soil Group			
	A	B	C	D
Water	100	100	100	100
Urban	77	85	90	92
Broadleaf Forest	36	60	73	79
Paddy Field	67	78	85	89
Other Agricultural Land	67	78	85	89
Other	98	98	98	98

Table 4 Land Use Change of Toba Catchment (%)

Land Use Type	2001	2015
Paddy field/ Cropland	18.17	18.31
Mixture of Cropland & Natural Vegetation	43.65	41.93
Forest (Broadleaved)	30.55	31.53
Sparse Vegetation	5.03	5.15
Urban	0.72	1.06
Water	1.88	2.02

Table 5 Antecedent Soil Moisture Condition (AMC) Seasonal Limits

AMC	Dormant Season (mm)	Growing Season (mm)
I (Dry)	<13	<36
II (Normal)	13~28	36~53
III (Wet)	>28	>53

Table 6 Selected Points' Characteristics in Toba Catchment

Point	Land Use Change	Year of Change	Slope	HSG
A	Natural Forest → Farmland	2007	5.1°	C
B	Forest/Sparse Vegetation (No Land Use Change)	-	4.0°	C
C	Cropland → Forest	2014	18.8°	D
D	Cropland → Urban Area	2014	3.4°	C

Table 7 Average Precipitation (mm) in Toba Catchment

Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	263.7	151.6	169.8	269.2	149.3	204.7	154.2	238.9	382.9	394.6	217.2	265.1
2002	135.4	169.8	199.2	188.6	377.6	108.1	113.7	99.5	316.6	260.2	343.9	165.8
2003	270.0	179.2	305.3	348.3	135.3	196.5	135.9	363.9	341.6	291.8	299.3	179.9
2004	221.3	187.9	306.1	200.8	146.4	87.6	140.8	116.1	408.3	243.6	199.9	182.2
2005	173.9	79.1	159.7	171.3	119.0	120.7	200.0	303.3	132.4	447.7	283.5	309.7
2006	264.6	240.7	154.0	333.2	201.0	199.7	108.5	184.2	312.5	378.0	177.3	294.4
2007	274.2	170.4	199.1	215.7	233.3	138.3	262.3	108.0	268.0	427.7	293.9	174.0
2008	262.4	105.8	362.4	171.3	136.9	127.5	273.6	258.3	353.0	371.6	251.7	316.5
2009	201.1	150.3	378.4	231.9	203.1	119.9	119.4	221.9	305.3	276.1	210.0	190.6
2010	207.8	173.5	231.6	175.5	166.9	234.1	225.0	229.3	237.7	233.9	333.9	212.7
2011	206.2	170.6	300.7	296.2	169.0	124.2	98.0	265.9	217.3	301.5	335.0	319.3
2012	95.3	186.3	246.3	239.2	186.3	103.1	217.6	162.8	254.3	227.6	317.0	272.7
2013	225.8	195.0	125.4	204.1	176.6	120.8	57.9	199.6	221.1	352.9	273.5	296.9
2014	164.2	69.6	118.1	213.1	174.3	108.6	83.7	217.4	203.3	248.9	244.9	280.9
2015	212.0	89.7	162.1	204.1	189.9	109.0	50.4	140.1	198.2	133.4	231.3	238.7
2016	169.5	161.3	178.6	148.9	212.8	189.6	205.5	137.7	287.5	237.8	266.7	264.6
2017	309.5	175.3	195.3	200.9	182.0	111.3	119.6	199.0	334.3	320.2	368.6	303.2
Average	215.1	156.3	223.1	224.3	185.9	141.4	150.9	202.7	280.8	302.8	273.4	251.0

Table 8 Average CN in Toba Catchment

Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	75.21	69.41	68.42	82.56	76.45	80.77	76.52	81.24	89.21	78.24	76.35	72.51
2002	70.72	69.36	72.26	81.82	84.00	76.05	74.35	71.39	89.26	76.96	81.39	71.07
2003	77.71	73.67	73.14	88.55	77.76	75.74	78.52	84.10	86.18	77.66	78.24	73.74
2004	72.71	71.06	79.06	84.43	77.01	73.19	76.36	78.35	81.92	75.39	69.72	73.68
2005	72.58	65.19	68.80	83.07	75.92	73.25	83.86	77.07	79.04	82.63	75.62	78.28
2006	74.19	73.39	70.59	84.17	84.14	83.26	72.52	80.34	88.76	79.54	73.86	75.77
2007	77.07	72.22	72.30	83.35	83.36	82.07	78.76	74.31	86.13	82.97	79.69	70.54
2008	72.99	65.56	82.64	84.12	75.08	80.43	87.13	82.90	86.03	83.08	76.59	77.57
2009	71.68	68.56	81.04	85.64	79.97	78.26	72.47	81.34	86.25	76.03	75.00	72.65
2010	72.48	69.30	75.53	79.94	81.86	81.64	85.26	84.22	86.43	73.58	79.84	76.53
2011	71.72	71.90	81.55	81.36	81.91	77.87	75.12	87.12	84.83	76.32	79.94	76.35
2012	66.56	68.68	75.88	88.05	83.97	74.86	83.15	81.98	83.02	73.87	79.10	78.73
2013	72.29	76.87	67.04	79.24	80.25	77.16	70.57	78.15	85.39	80.41	76.81	78.00
2014	73.15	65.23	64.94	81.85	83.38	73.62	74.43	81.66	84.01	76.11	75.29	75.66
2015	73.63	66.35	68.26	82.36	84.96	77.50	67.30	78.97	80.57	68.50	74.83	74.61
2016	69.66	70.25	71.06	80.50	81.46	80.29	82.54	76.74	85.72	72.40	79.86	76.50
2017	78.75	69.69	70.96	83.89	83.76	73.56	75.58	79.88	85.59	75.91	86.11	77.24
Average	73.12	69.81	73.15	83.23	80.90	77.62	77.32	79.99	85.20	77.04	77.54	75.26

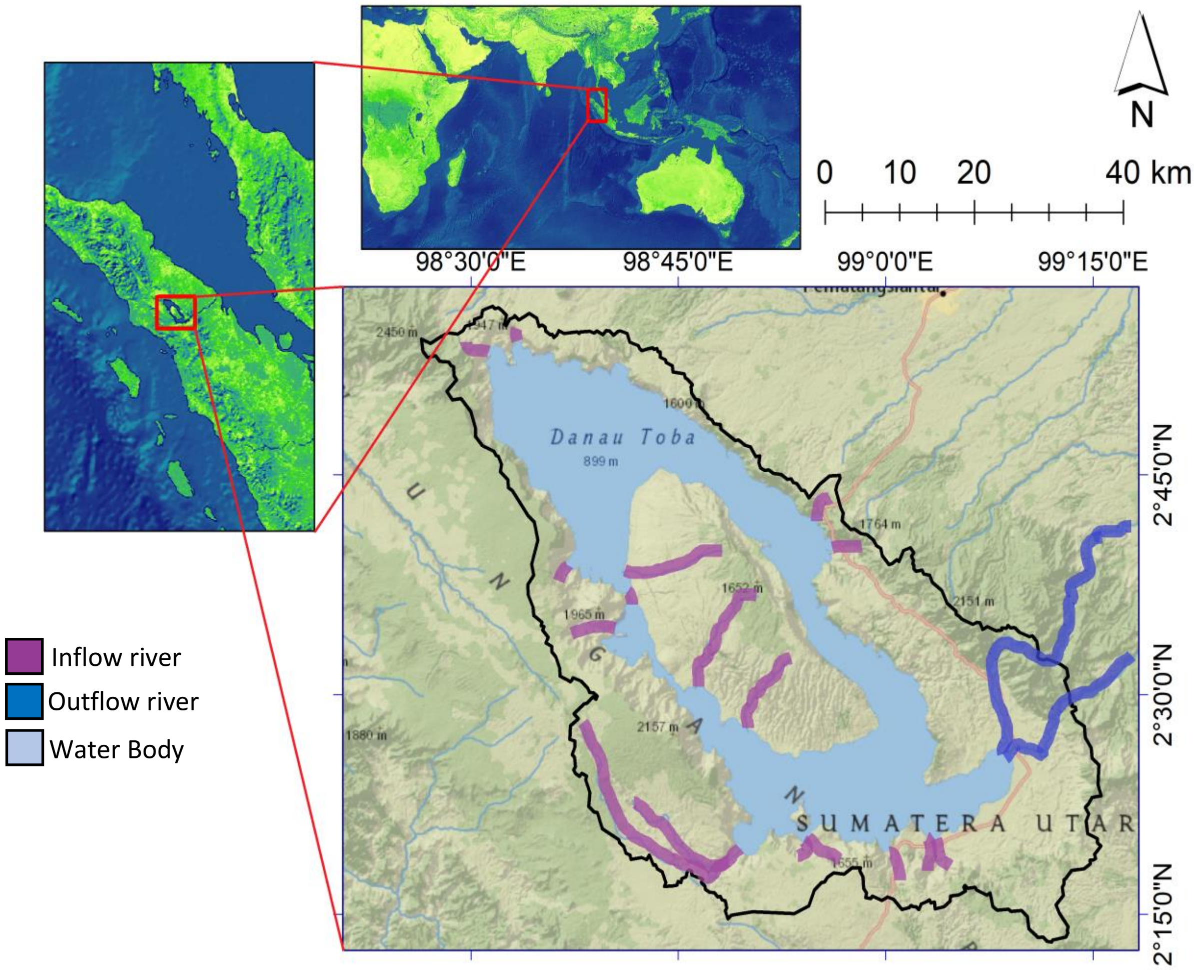

Figure 1 Study Area (Lake Toba, North Sumatra, Indonesia)

Black line indicates watershed boundary

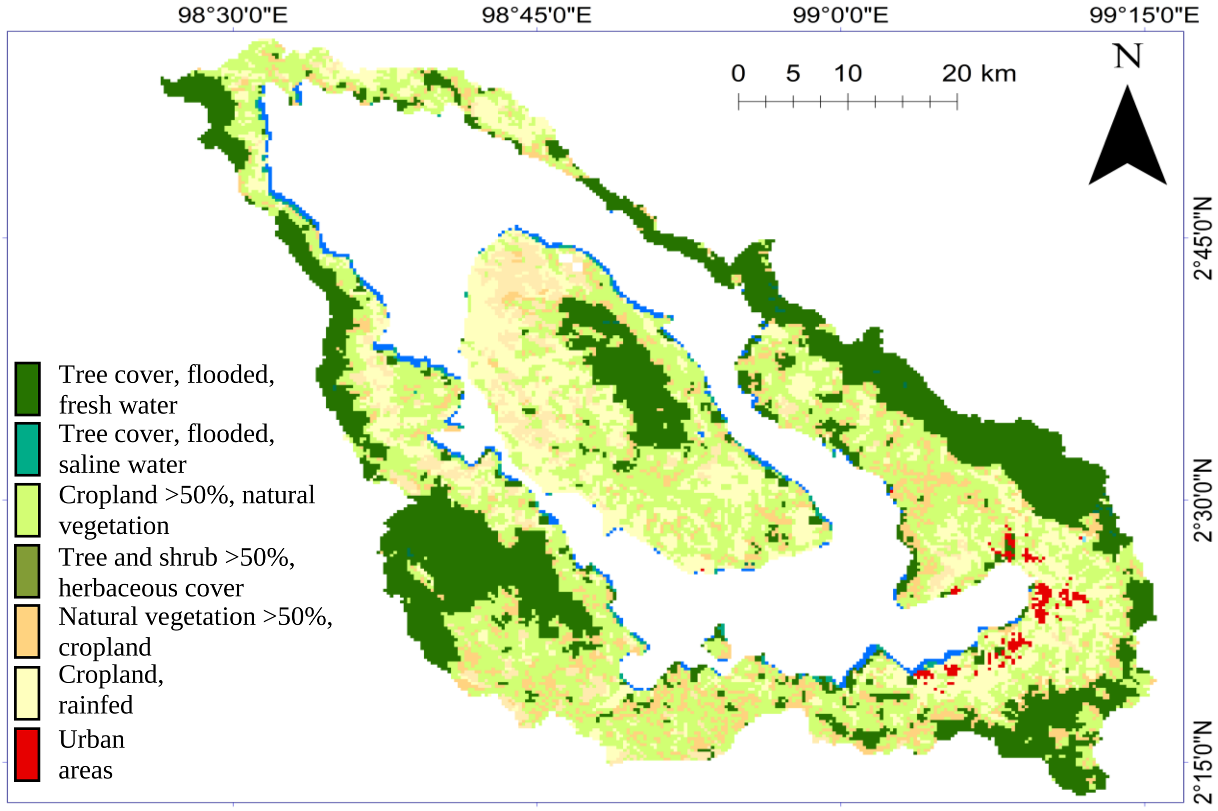

Figure 2 Land Use Map of Toba Catchment 2001

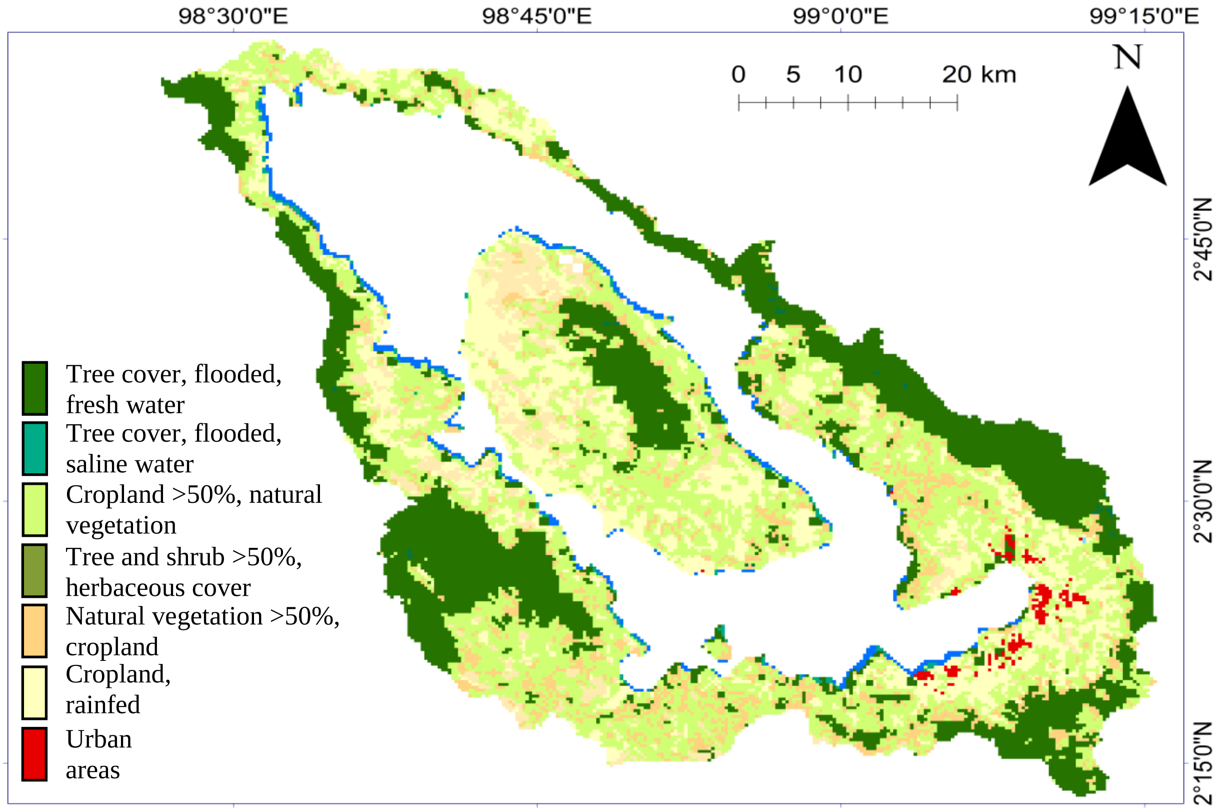

Figure 3 Land Use Map of Toba Catchment in 2002

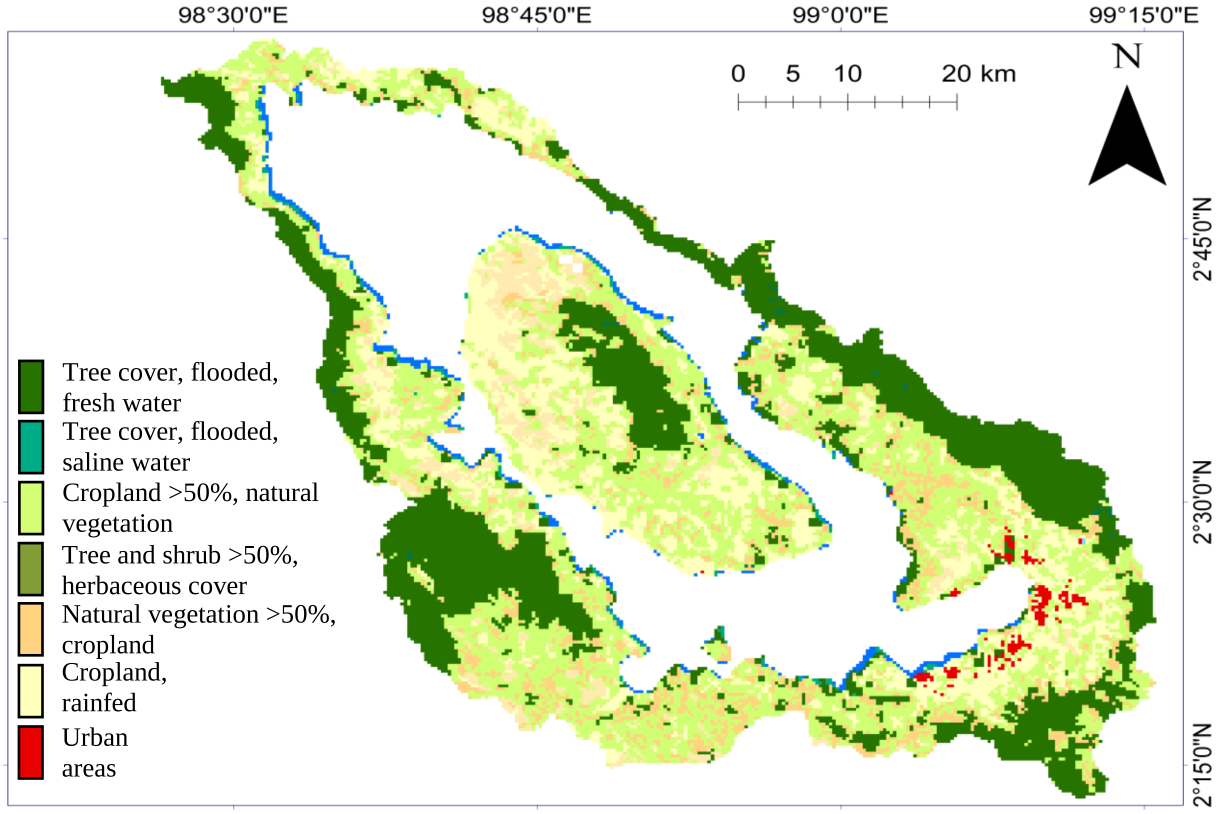

Figure 4 Land Use Map of Toba Catchment in 2003

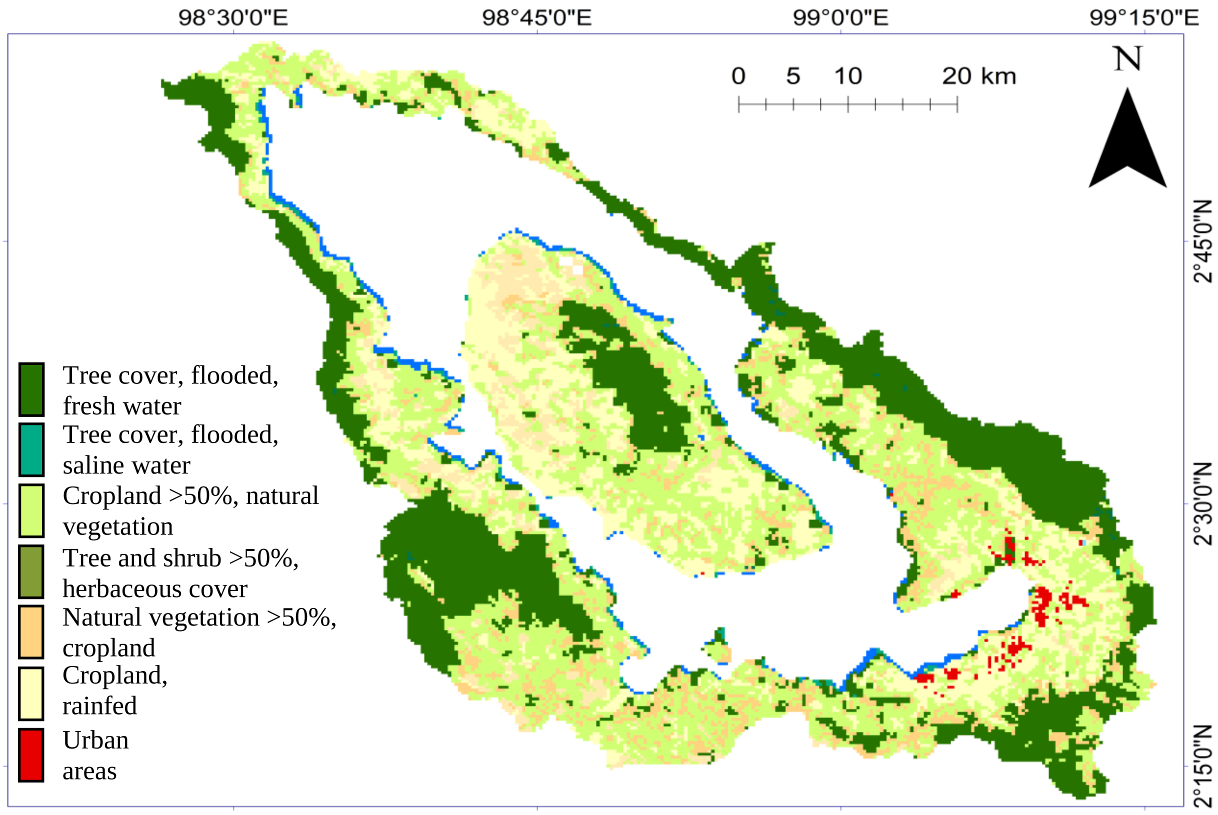

Figure 5 Land Use Map of Toba Catchment in 2004

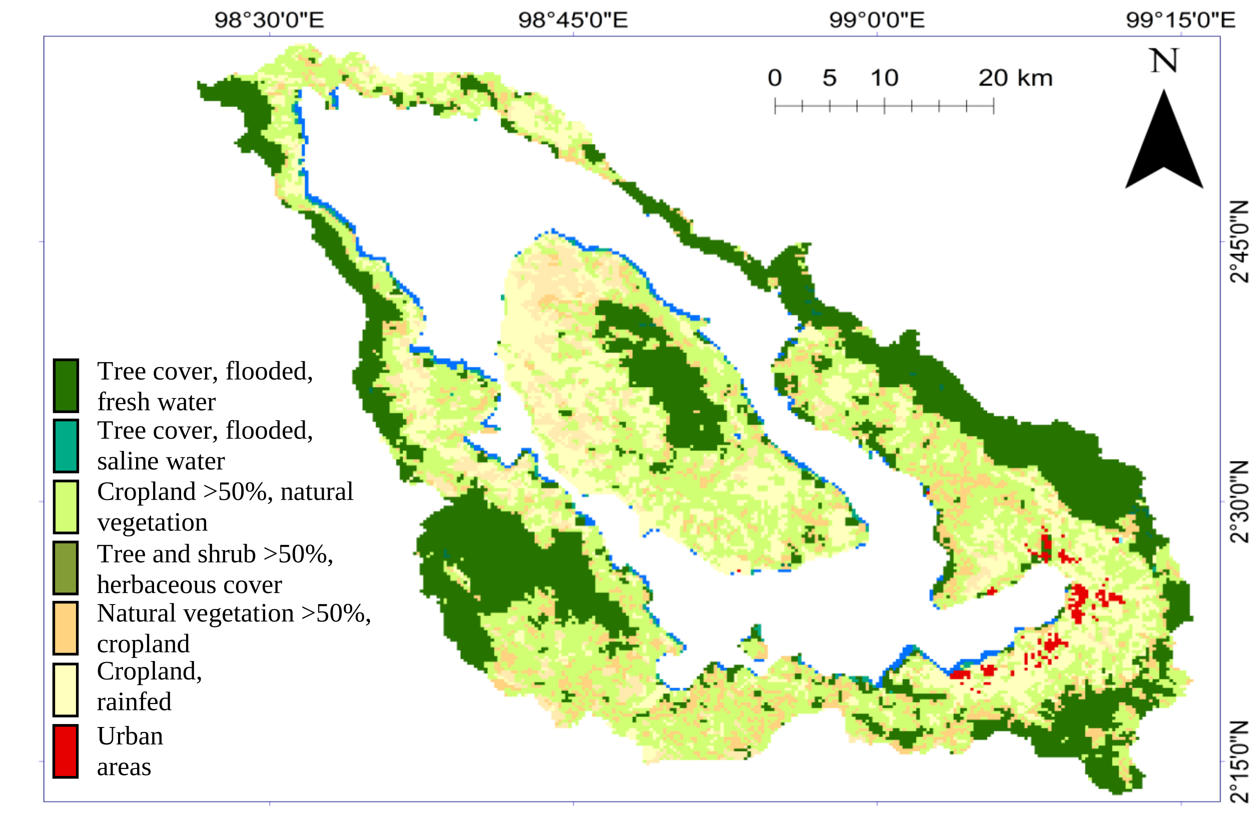

Figure 6 Land Use Map of Toba Catchment in 2005

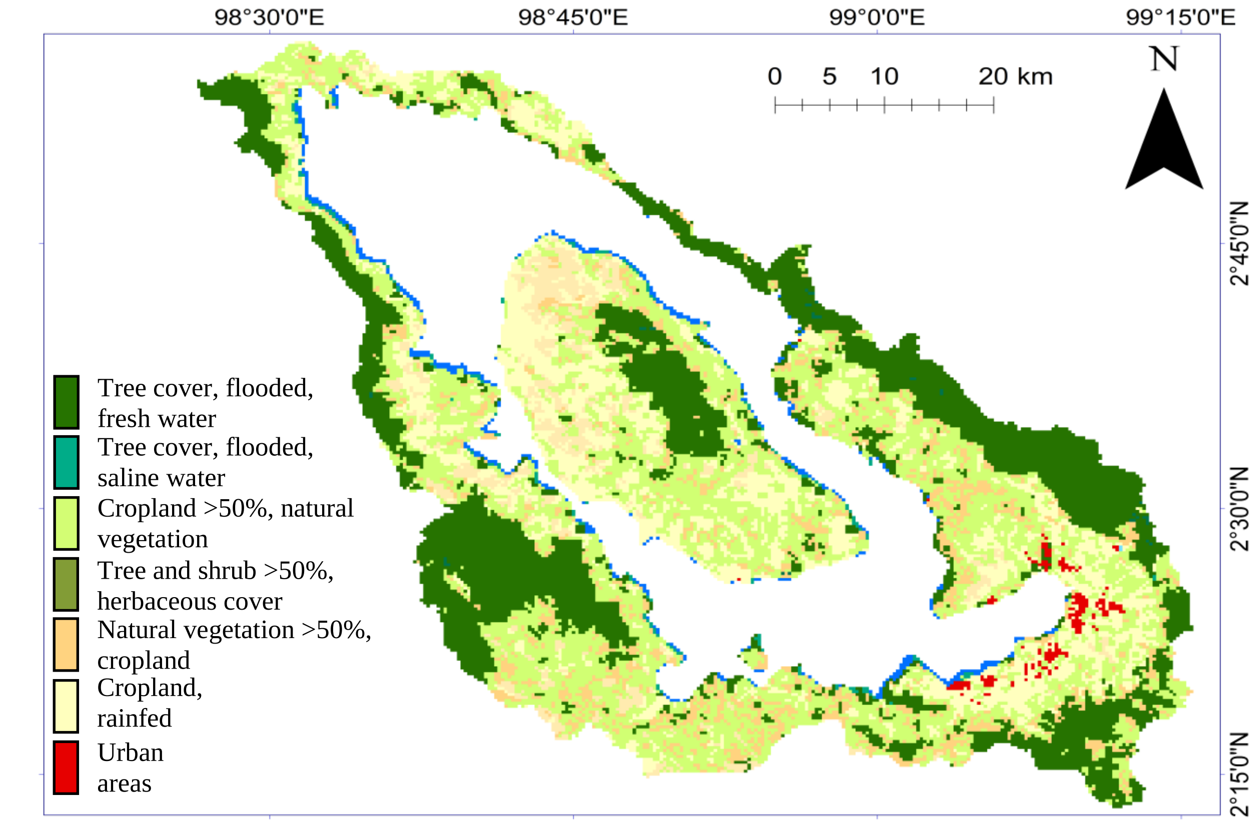

Figure 7 Land Use Map of Toba Catchment in 2006

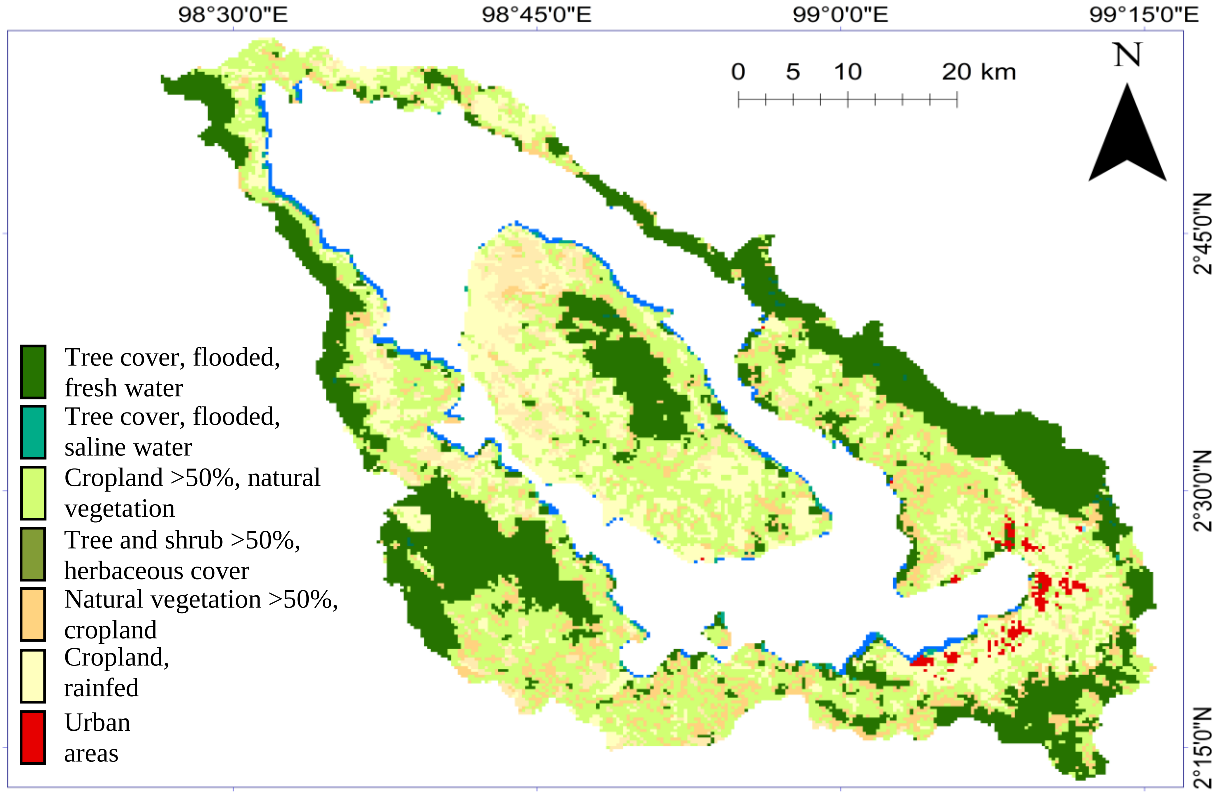

Figure 8 Land Use Map of Toba Catchment in 2007

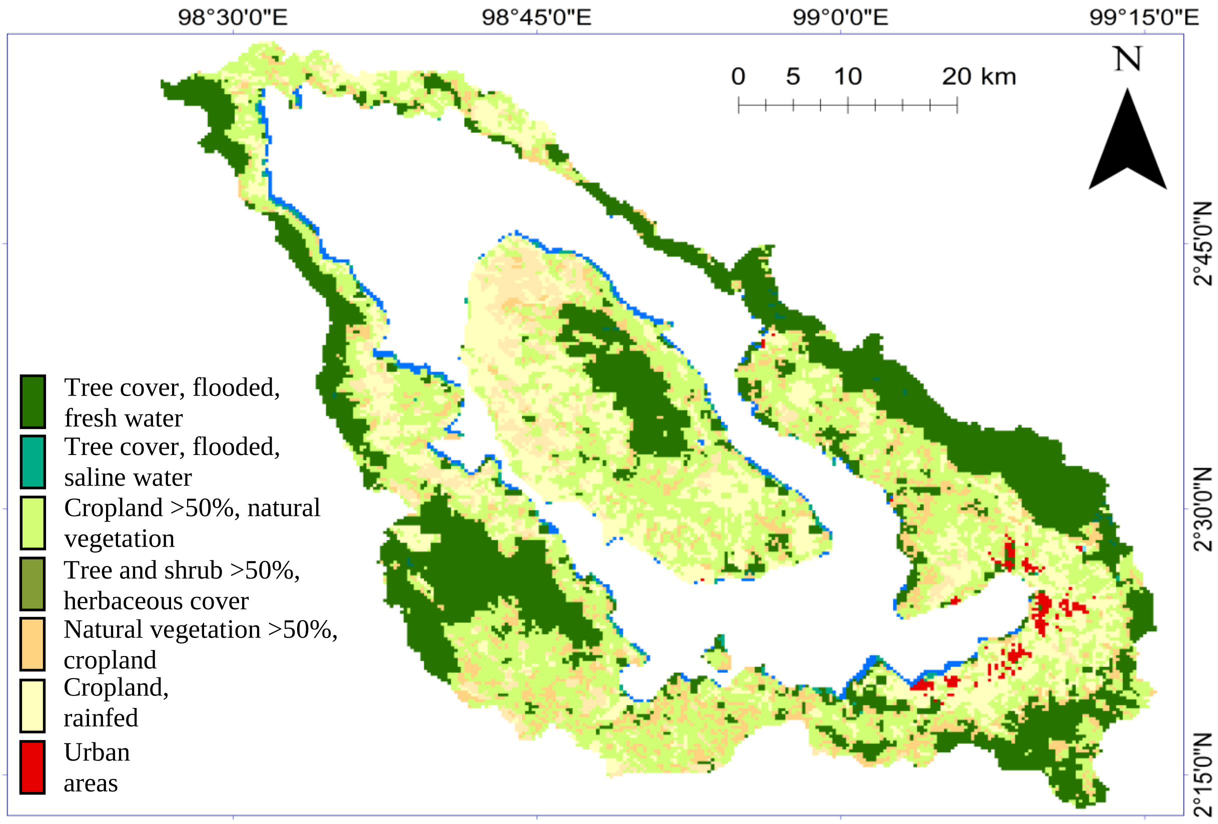

Figure 9 Land Use Map of Toba Catchment in 2008

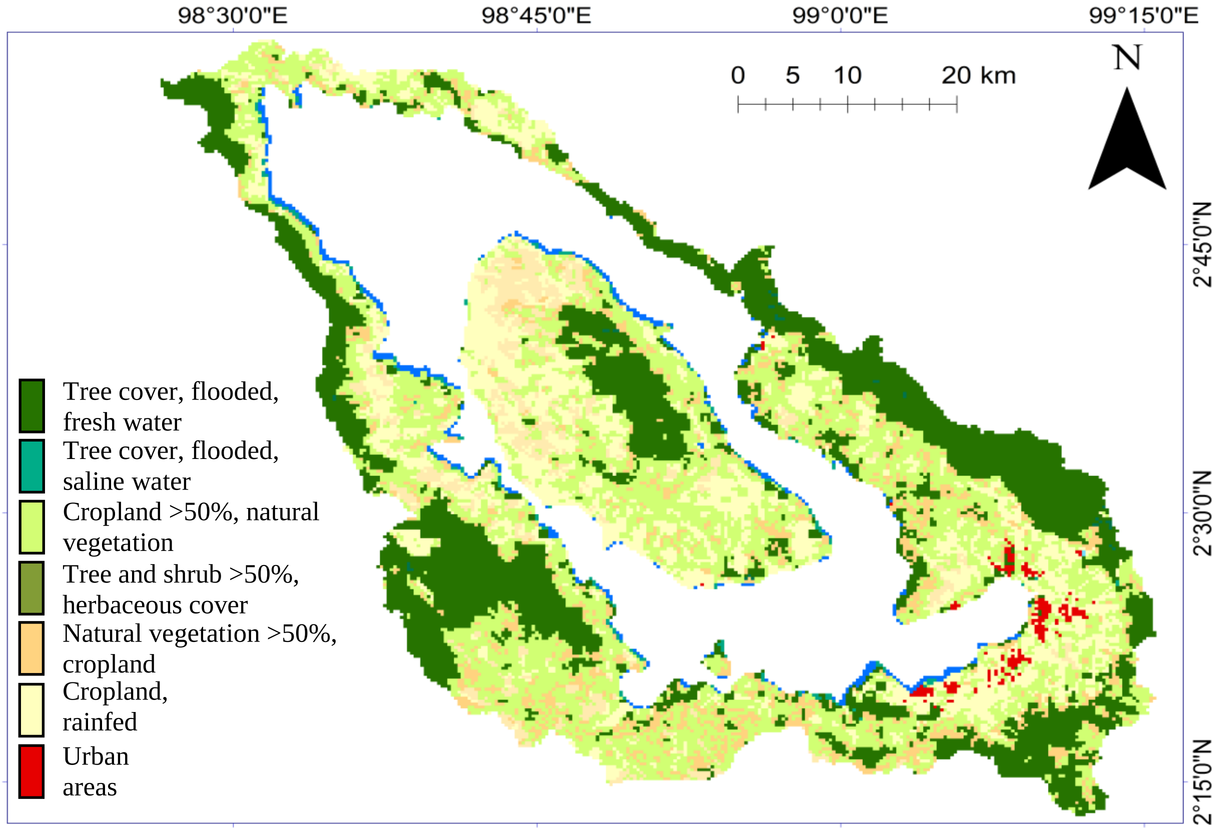

Figure 10 Land Use Map of Toba Catchment in 2009

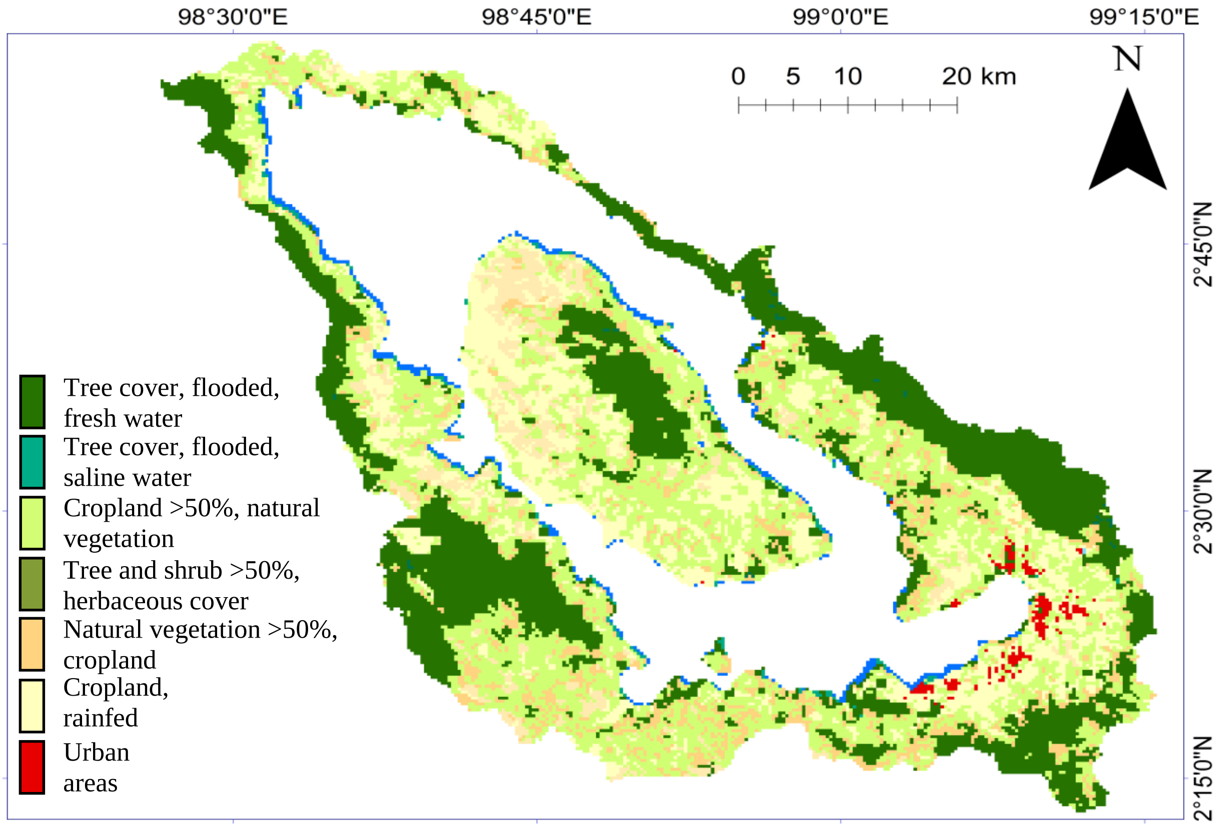

Figure 11 Land Use Map of Toba Catchment in 2010

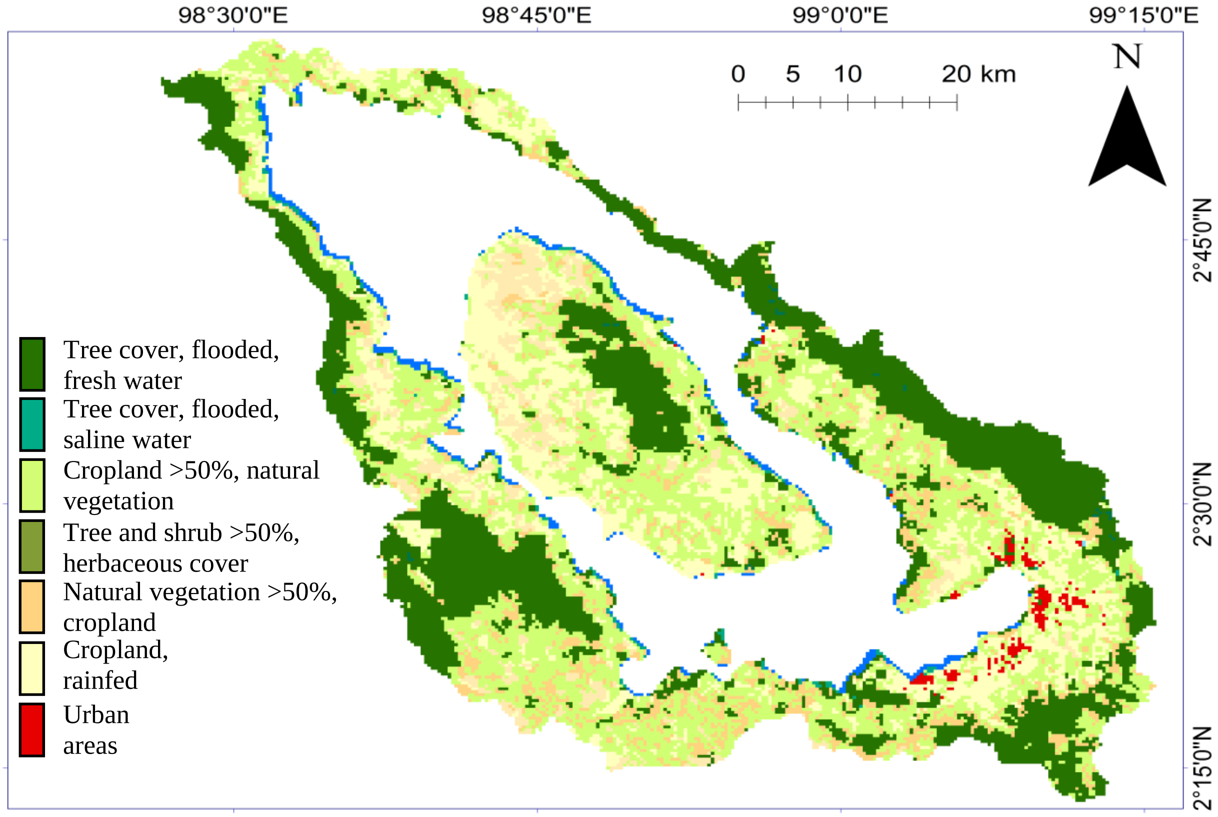

Figure 12 Land Use Map of Toba Catchment in 2011

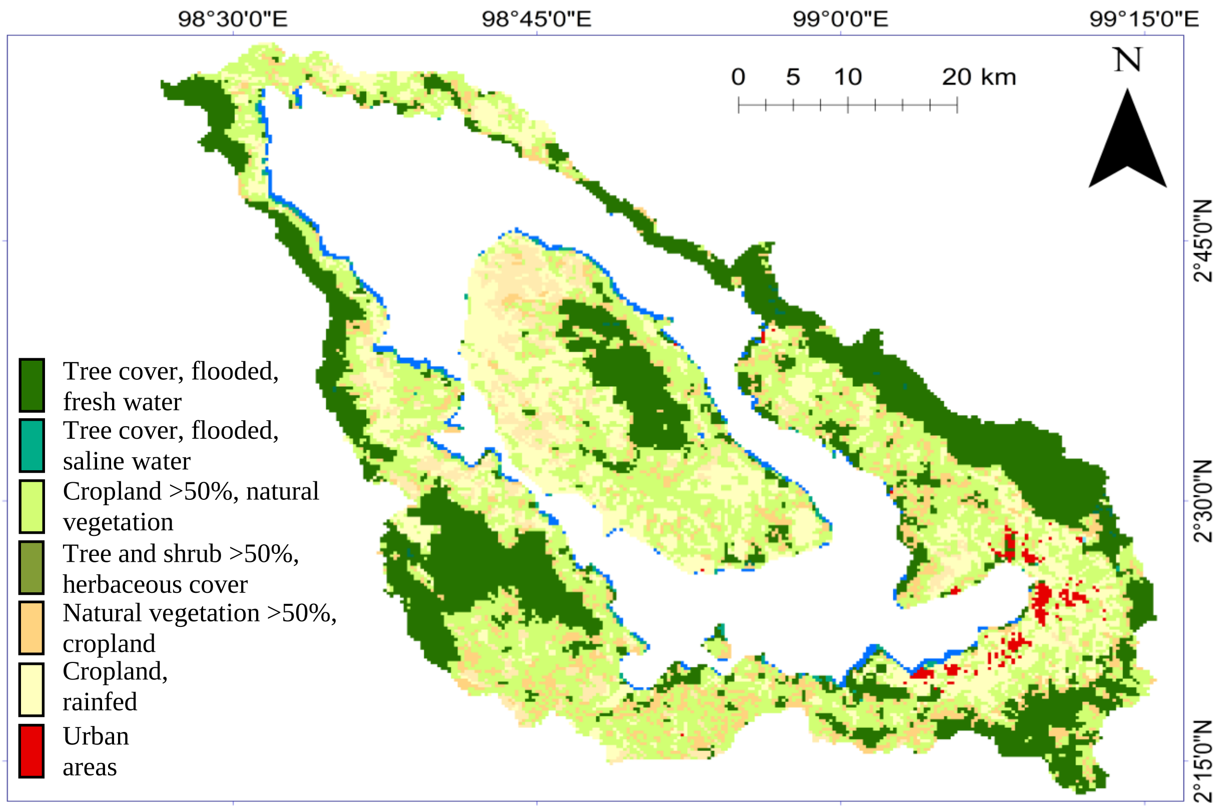

Figure 13 Land Use Map of Toba Catchment in 2012

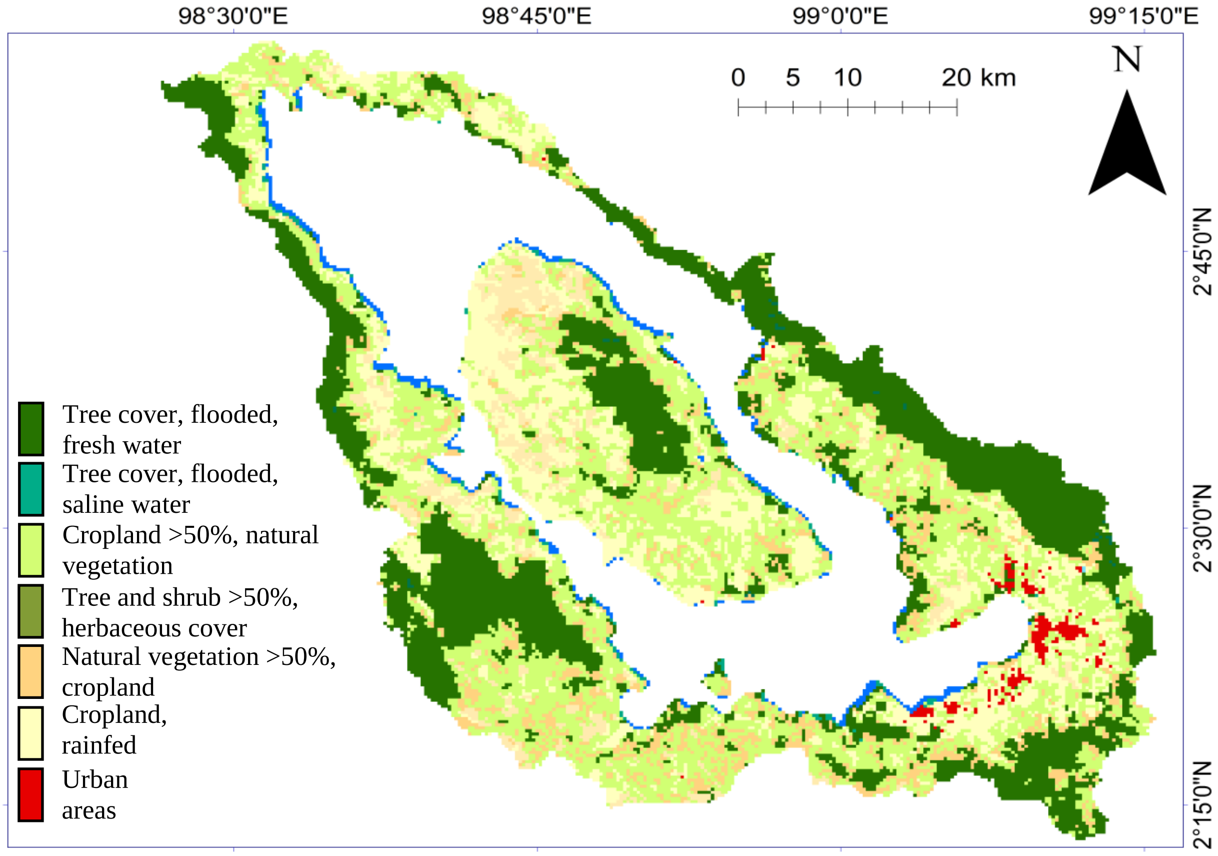

Figure 14 Land Use Map of Toba Catchment in 2013

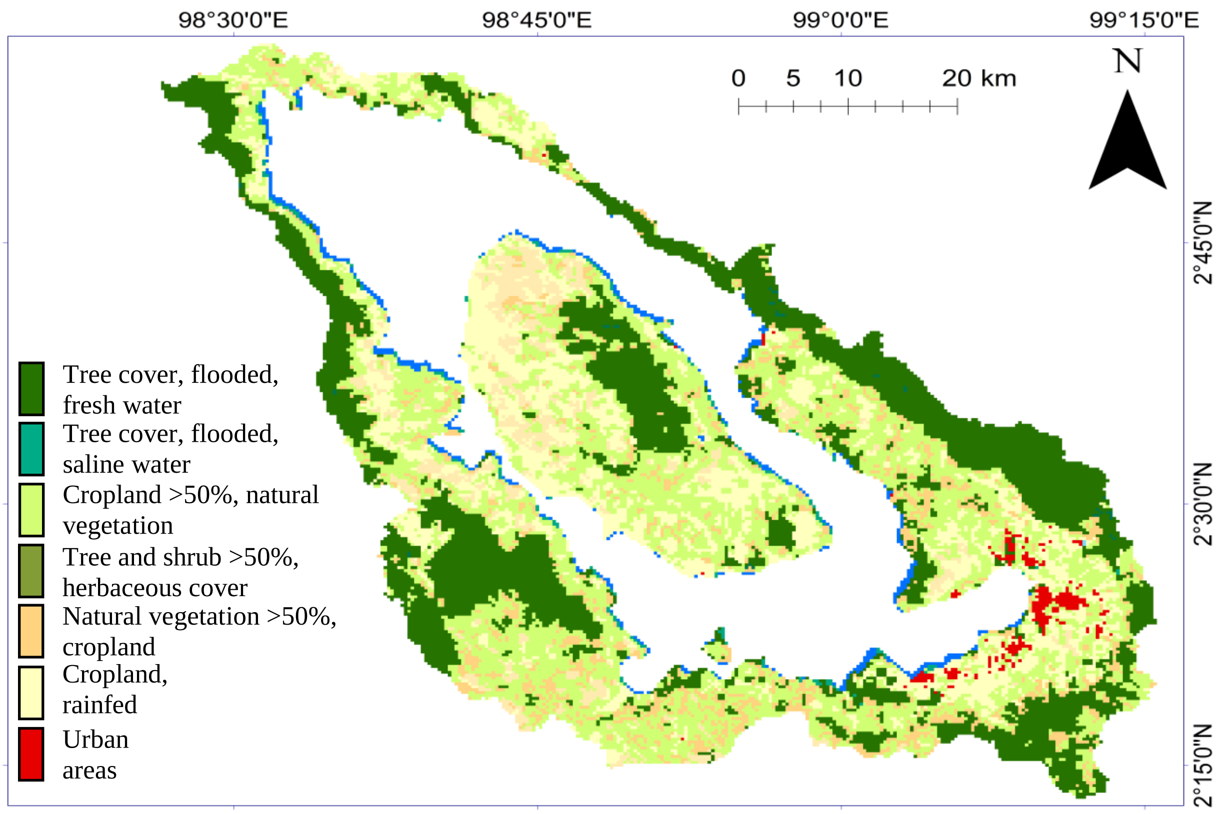

Figure 15 Land Use Map of Toba Catchment in 2014

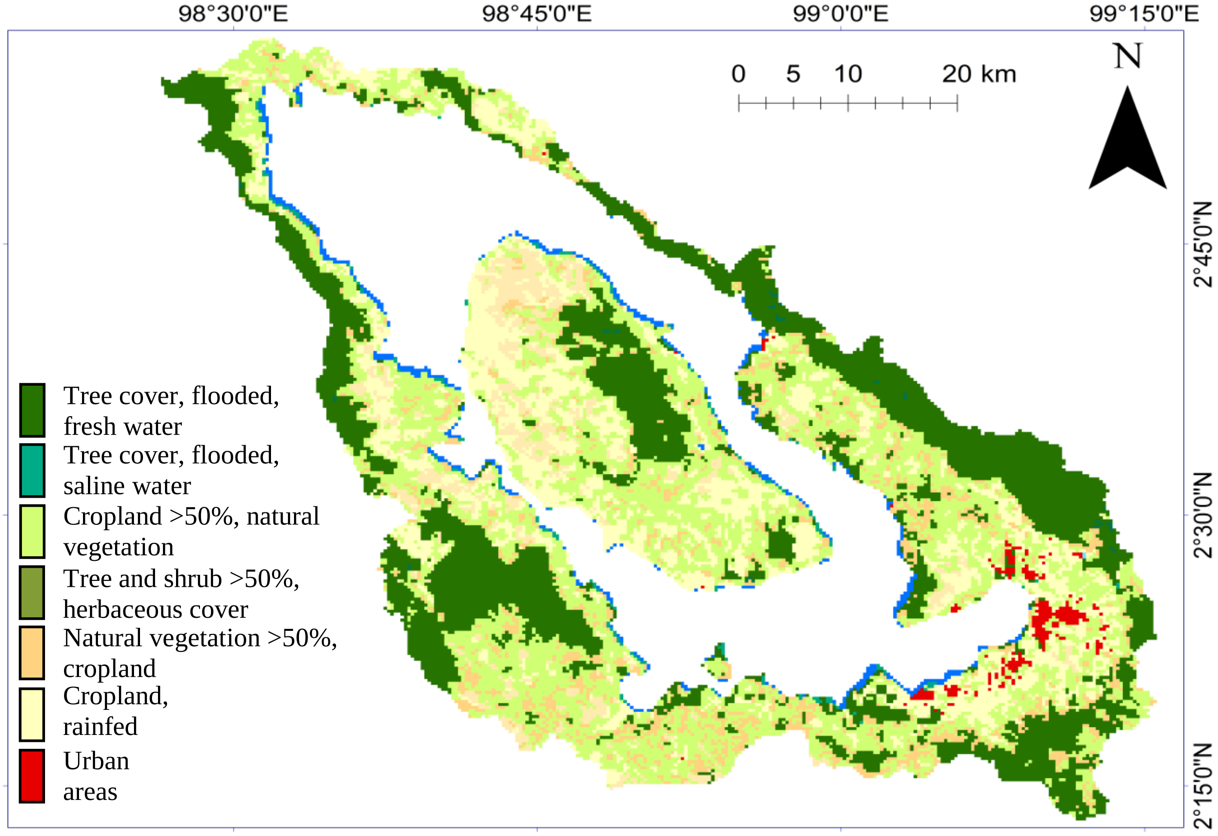

Figure 16 Land Use Map of Toba Catchment in 2015

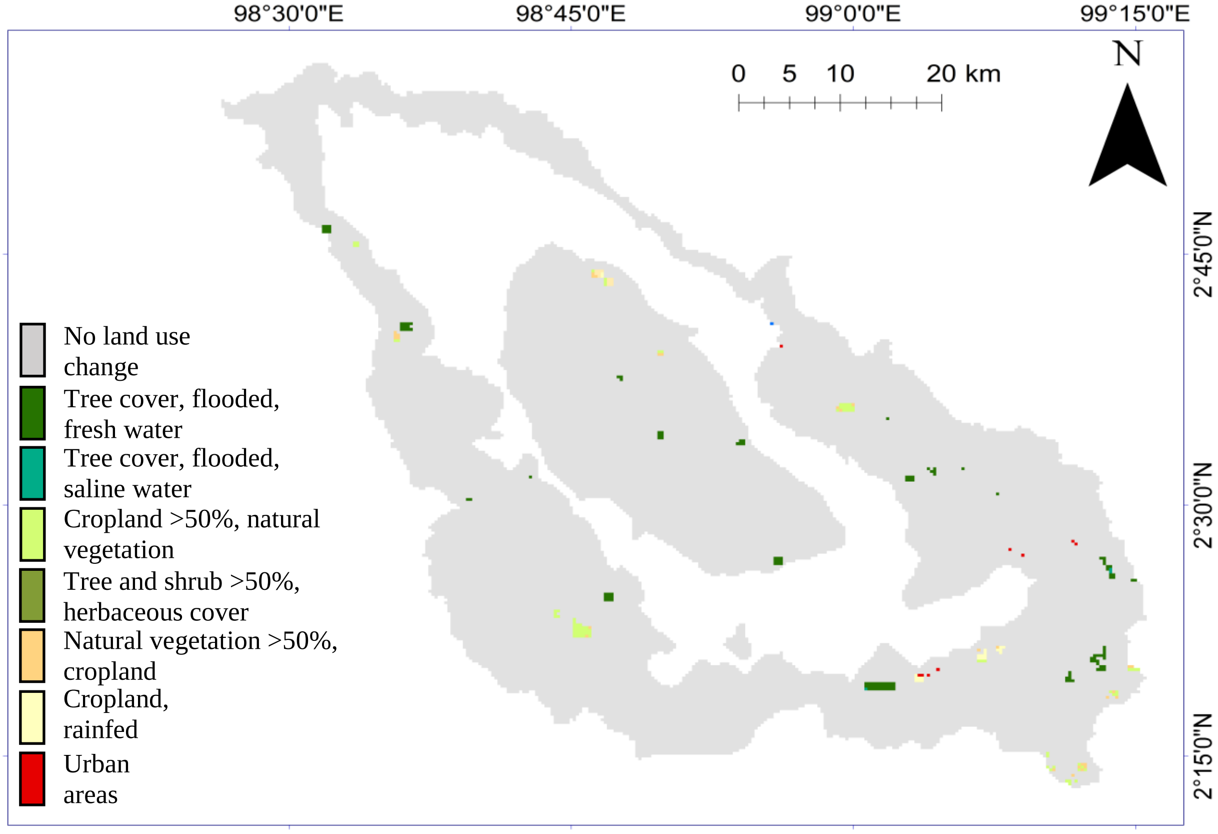

Figure 17 Land Use Change Map of Toba Catchment from 2001 to 2006

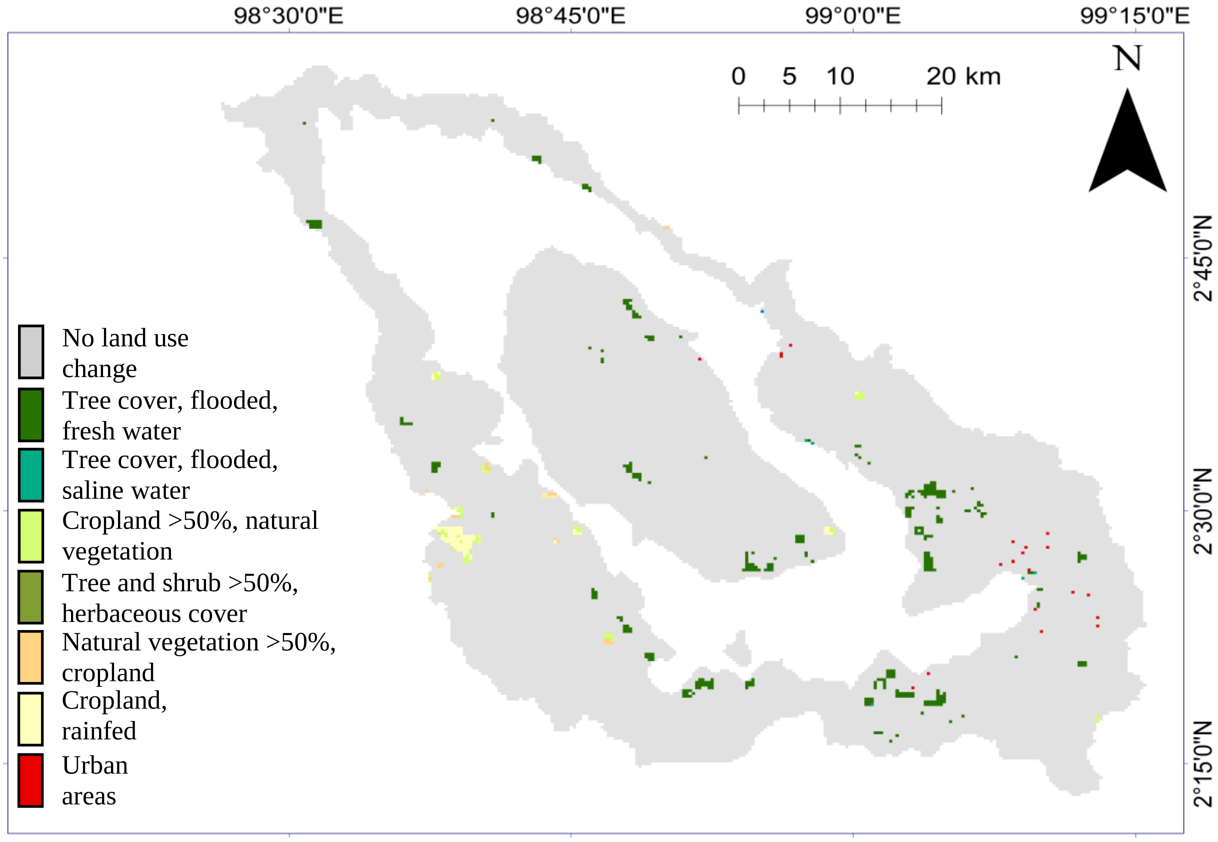

Figure 18 Land Use Change Map of Toba Catchment from 2006 to 2011

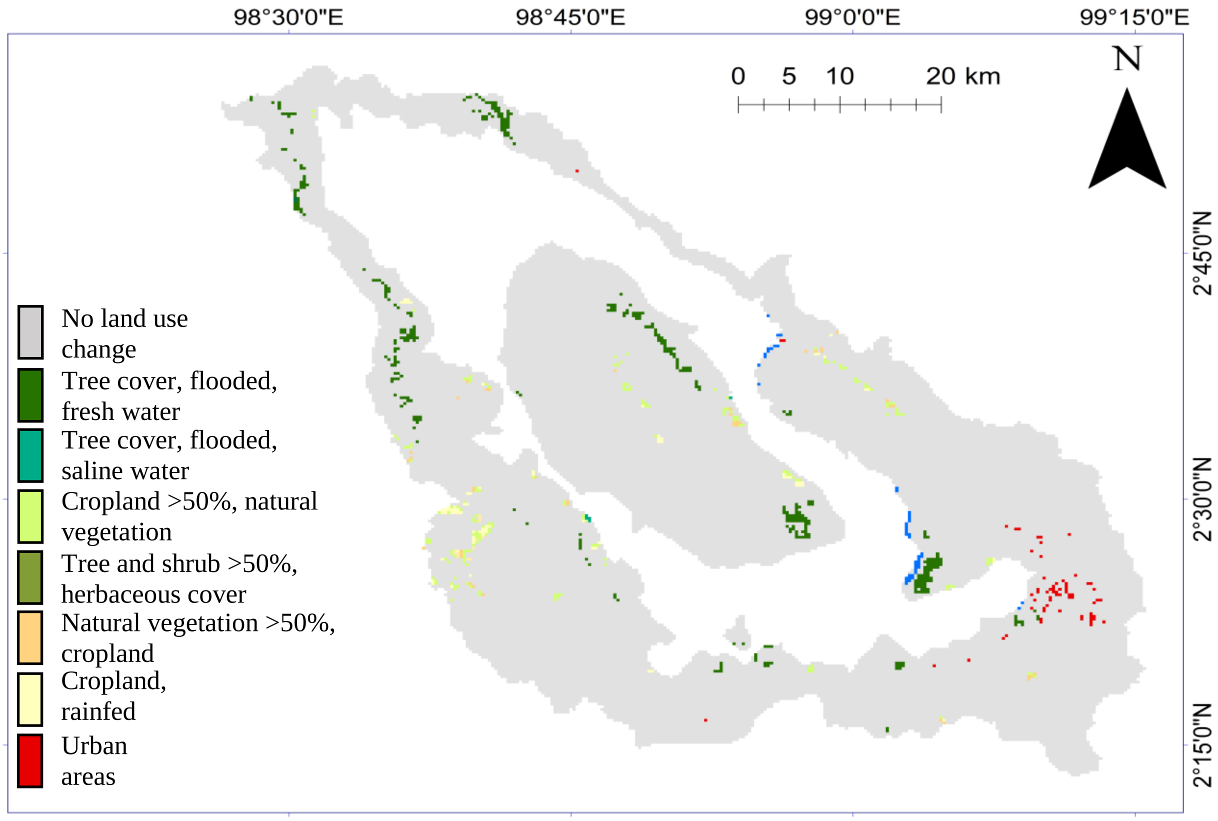

Figure 19 Land Use Change Map of Toba Catchment from 2011 to 2015

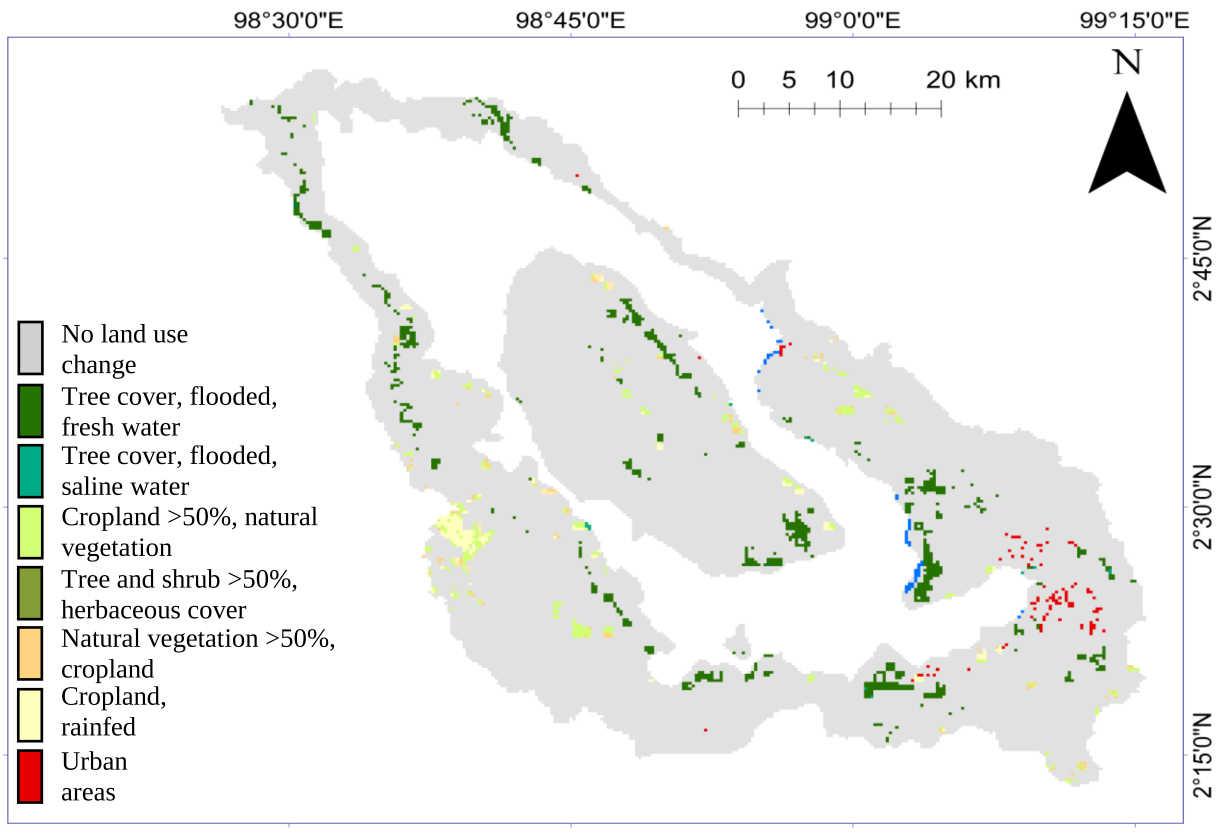

Figure 20 Land Use Change Map of Toba Catchment from 2001 to 2015

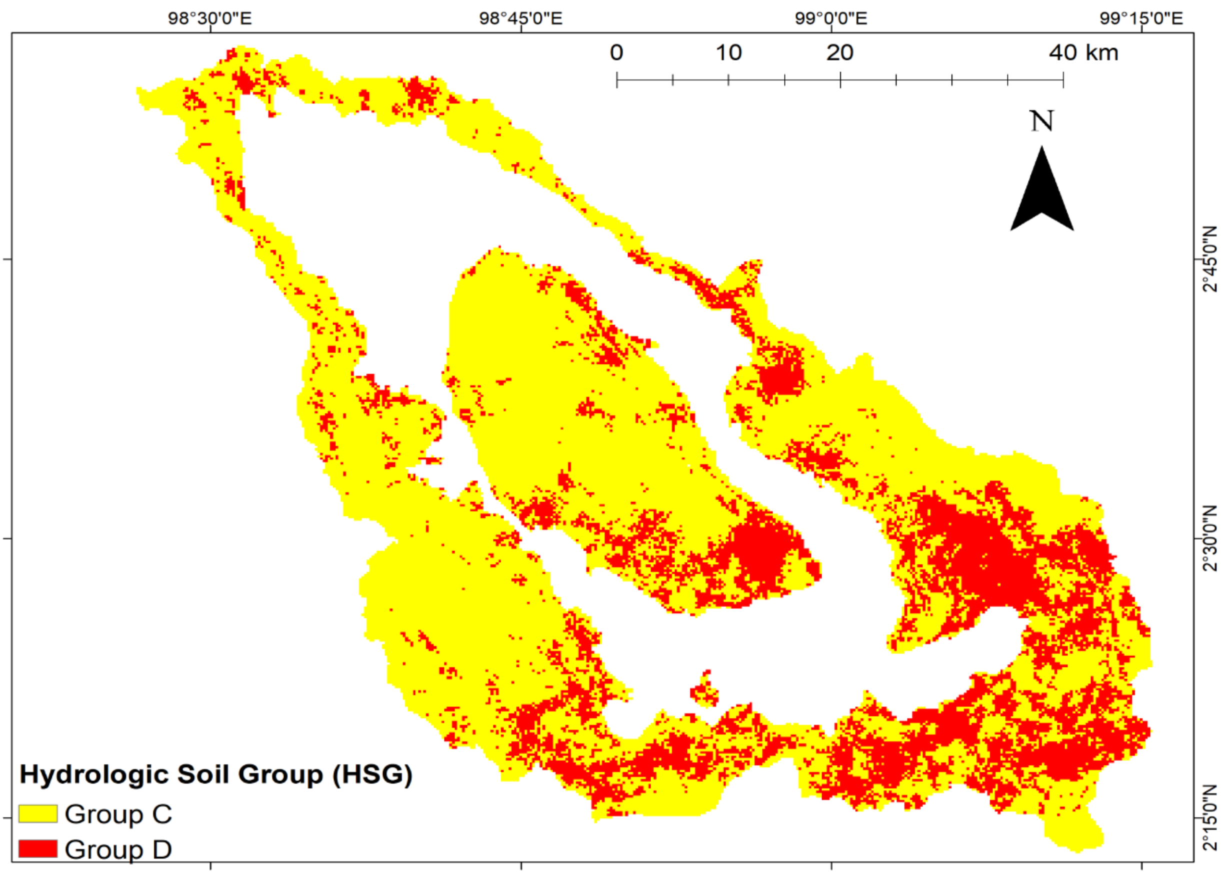

Figure 21 Hydrologic Soil Group (HSG) of Toba Catchment

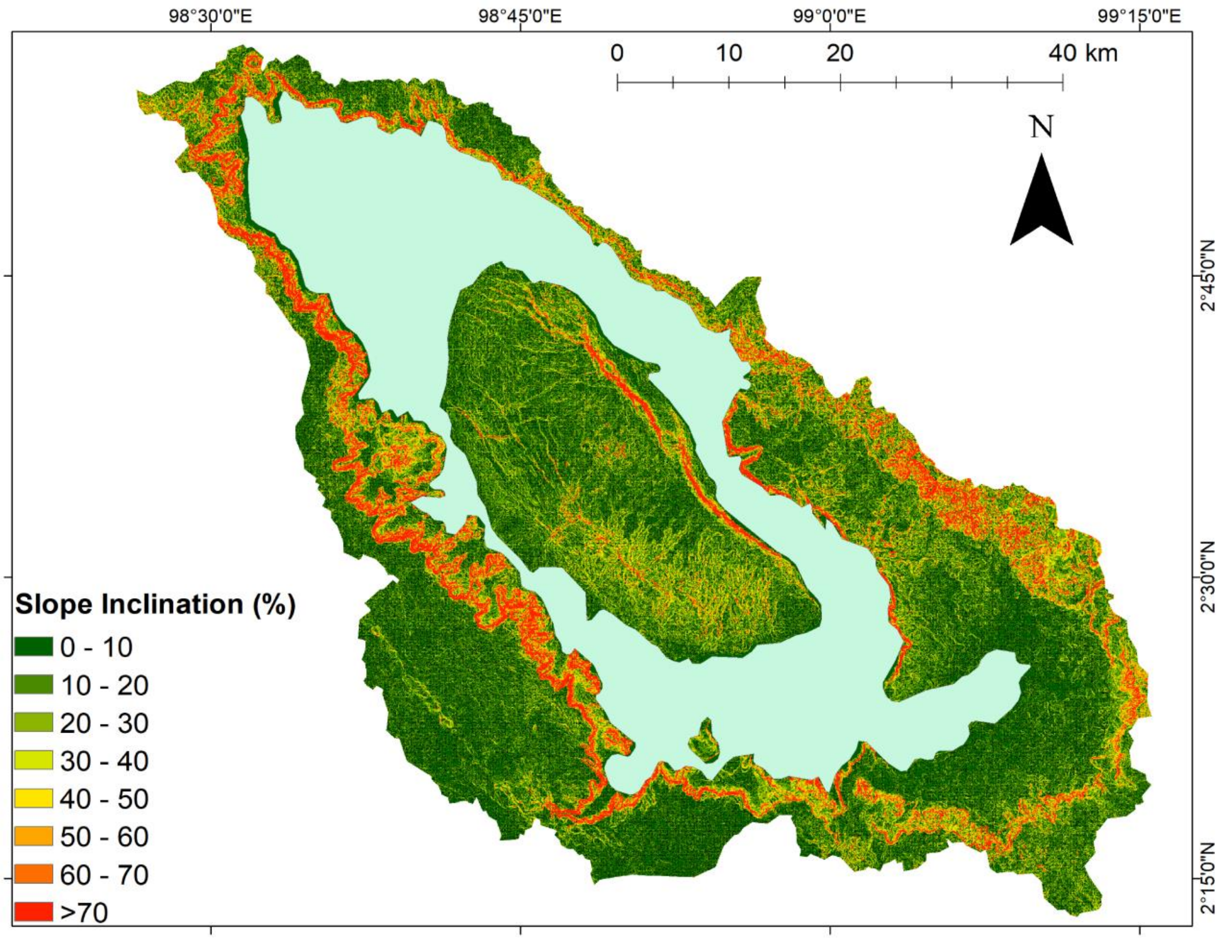

Figure 22 Slope Inclination of Toba Catchment

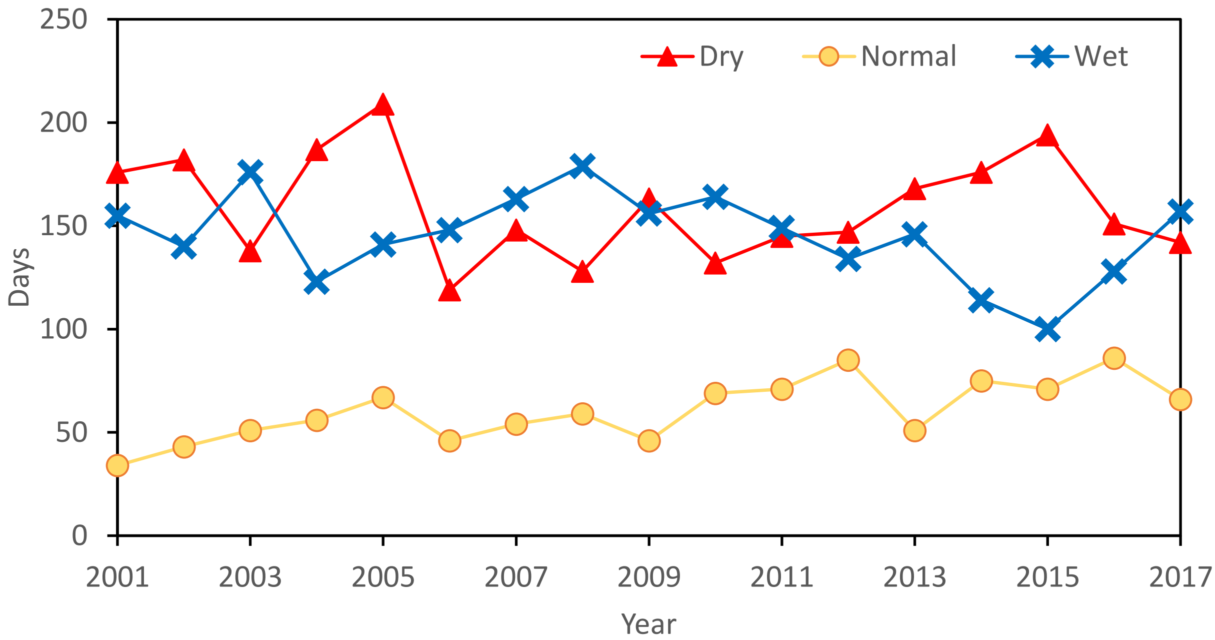

Figure 23 Annual Antecedent Soil Moisture Conditions (AMC) in Toba Catchment

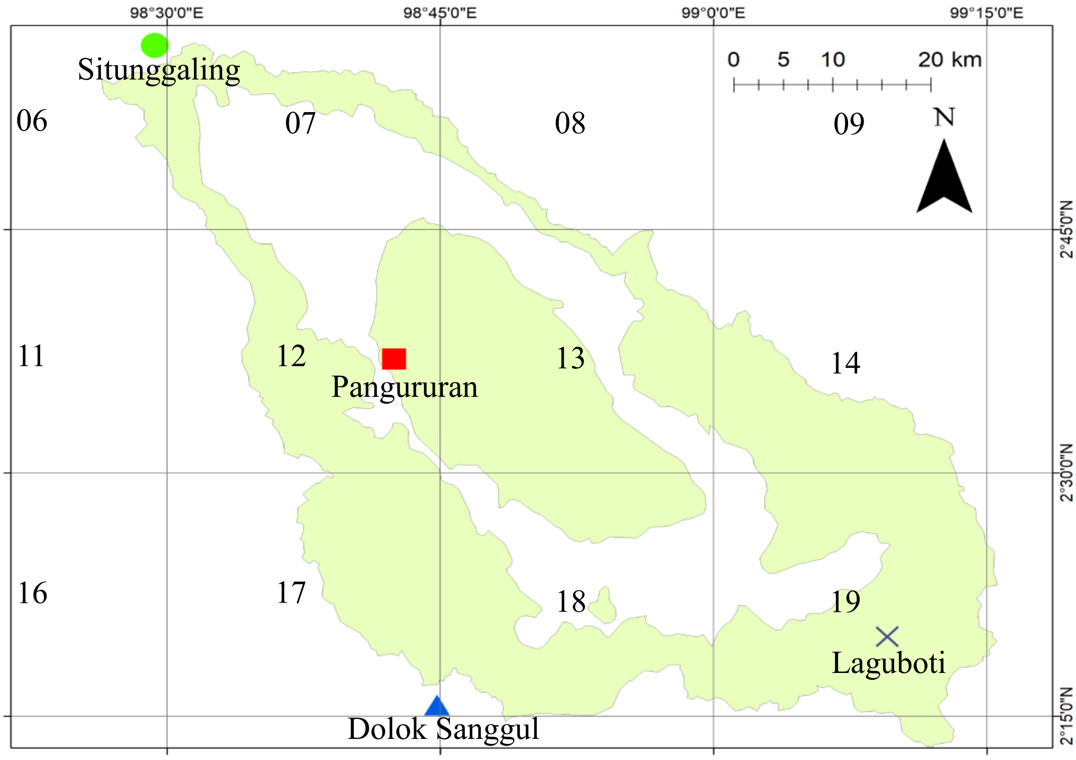

Figure 24 Local Meteorological Stations for Precipitation Validation

Green circles, red square, blue triangle, and cross indicate location of local meteorological stations Situnggaling (Grid 06), Pangururan (Grid 12), Dolok Sanggul (Grid 17), and Laguboti (Grid 19) respectively. Each local meteorological station validated with its respective numbered TRMM 0.25° grid precipitation data.

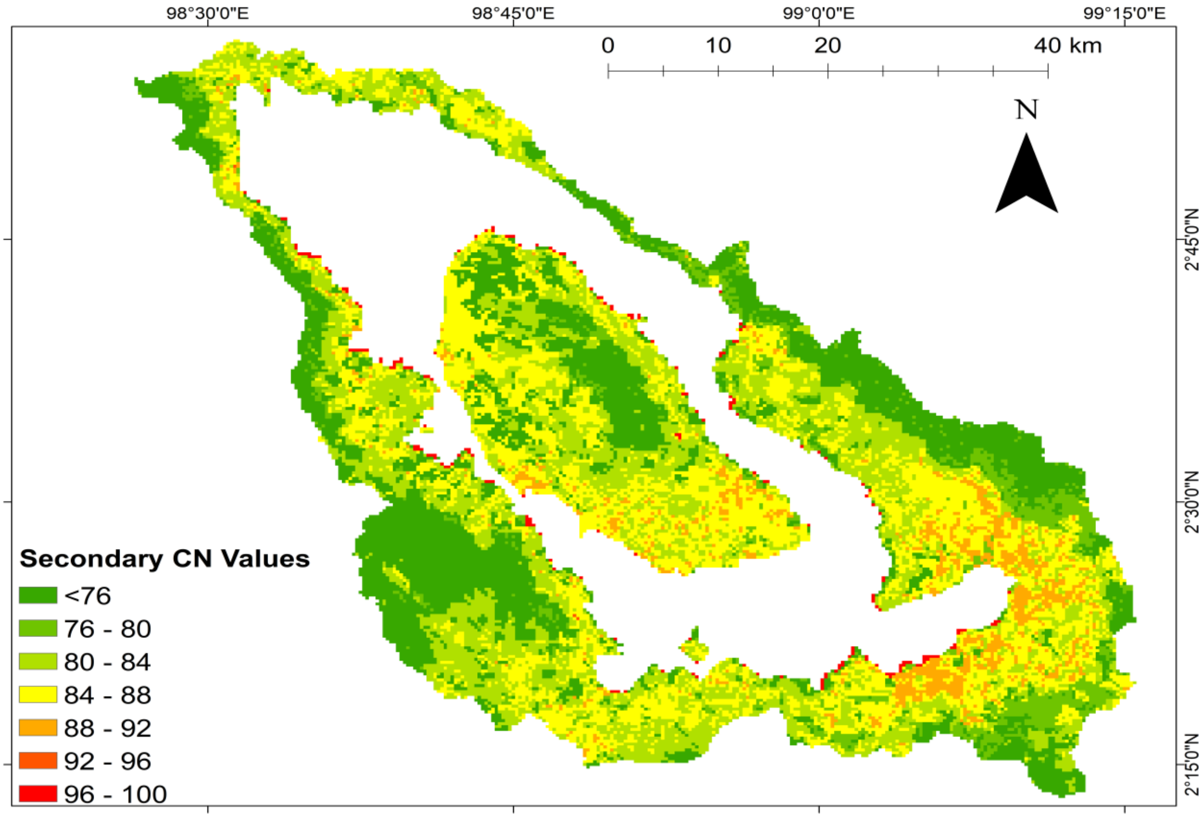

Figure 25 Secondary Curve Number Values of Toba Catchment in 2001

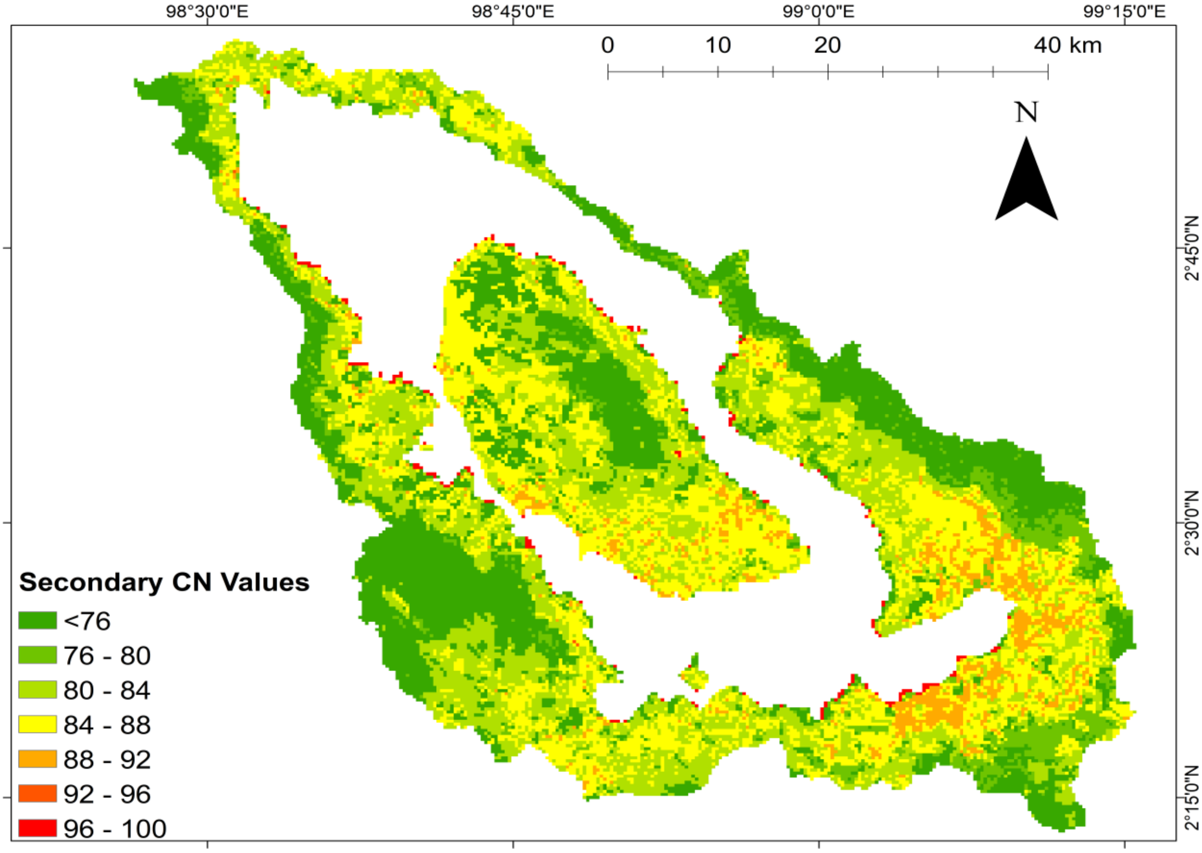

Figure 26 Secondary Curve Number Values of Toba Catchment in 2002

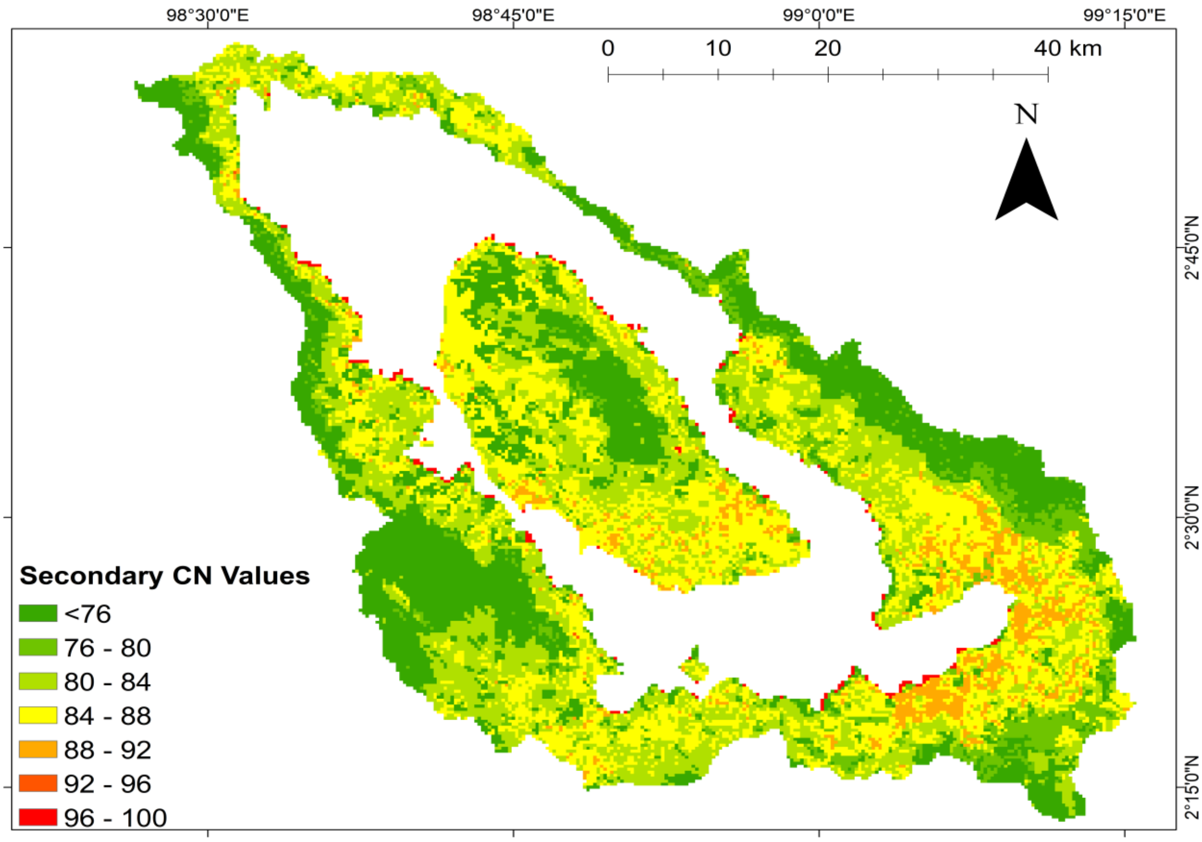

Figure 27 Secondary Curve Number Values of Toba Catchment in 2003

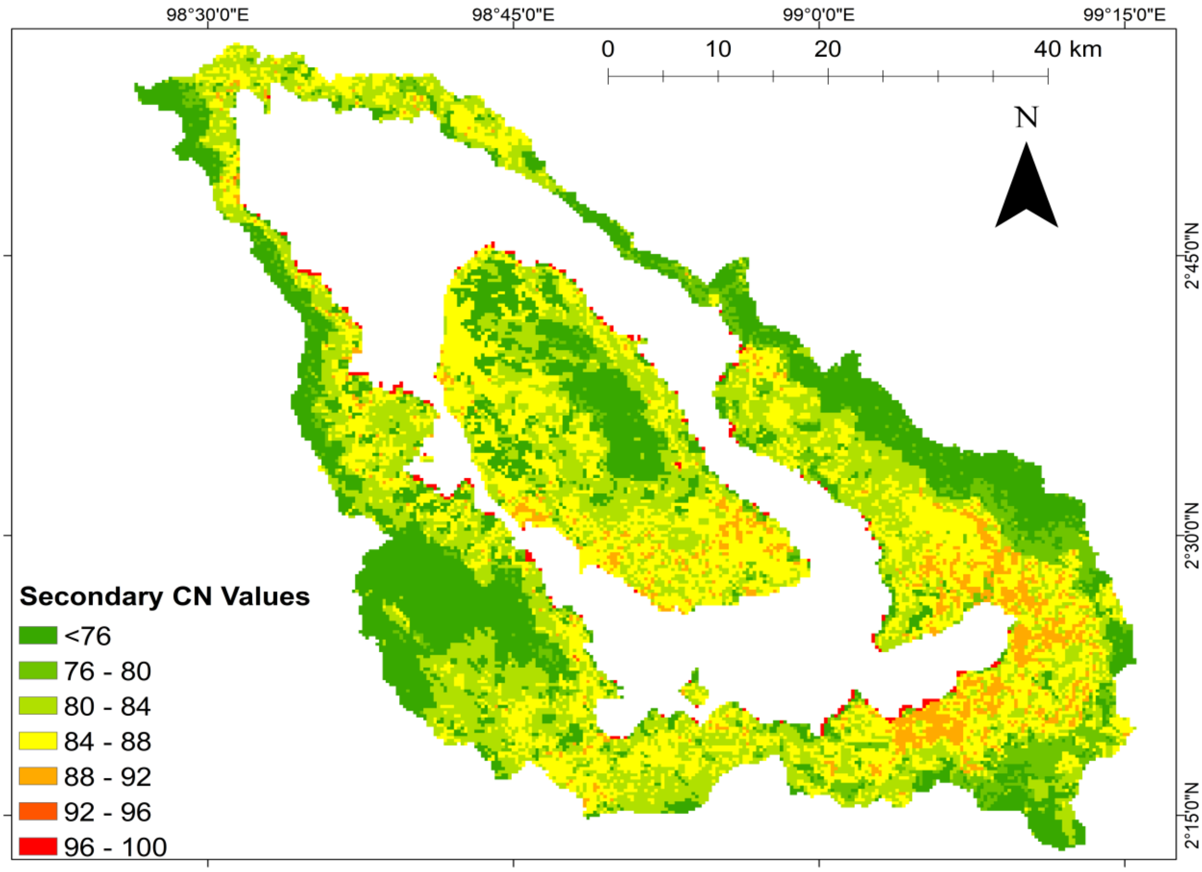

Figure 28 Secondary Curve Number Values of Toba Catchment in 2004

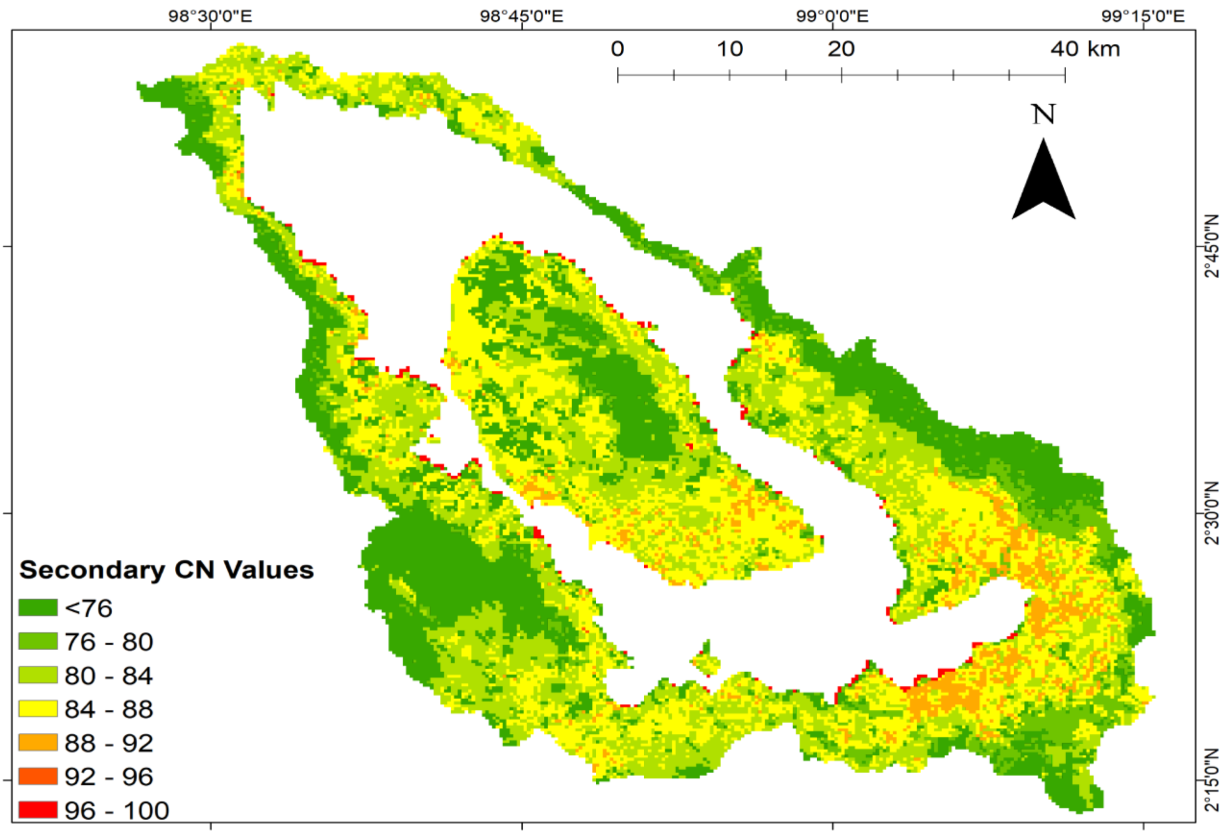

Figure 29 Secondary Curve Number Values of Toba Catchment in 2005

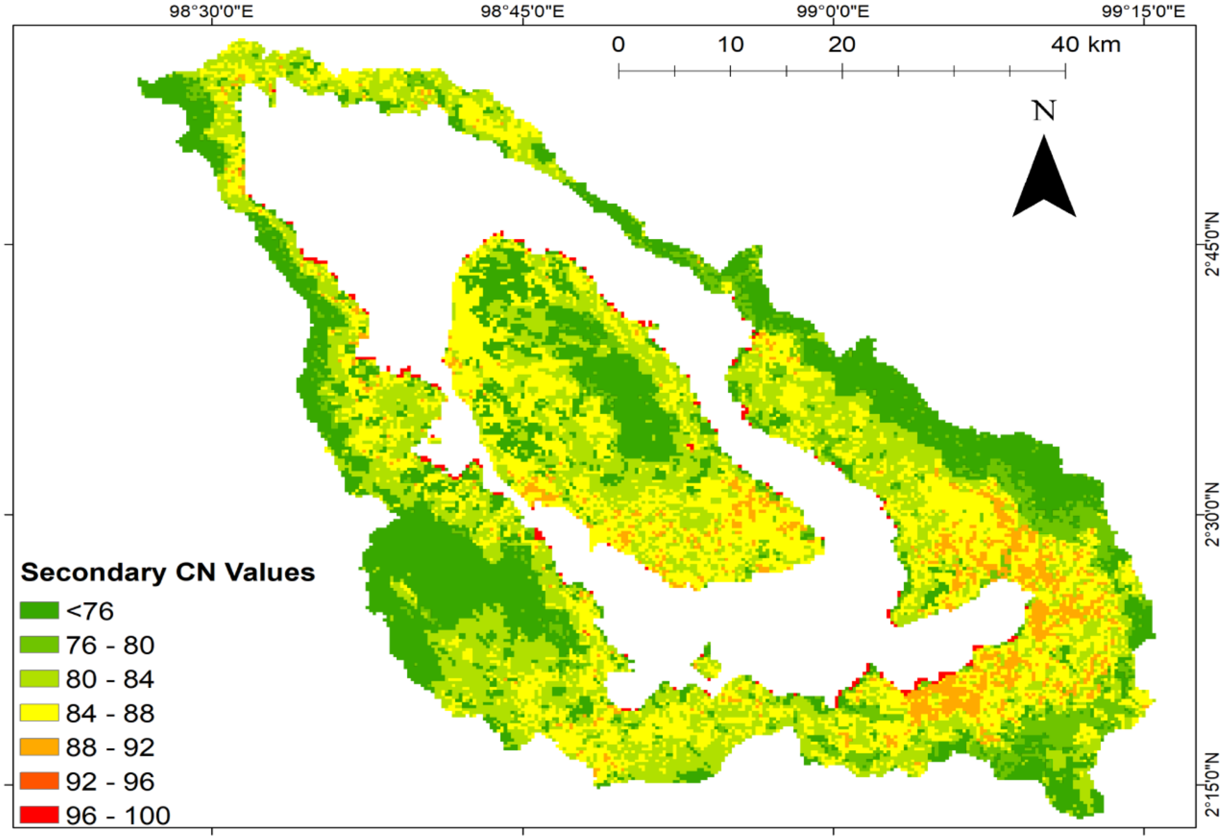

Figure 30 Secondary Curve Number Values of Toba Catchment in 2006

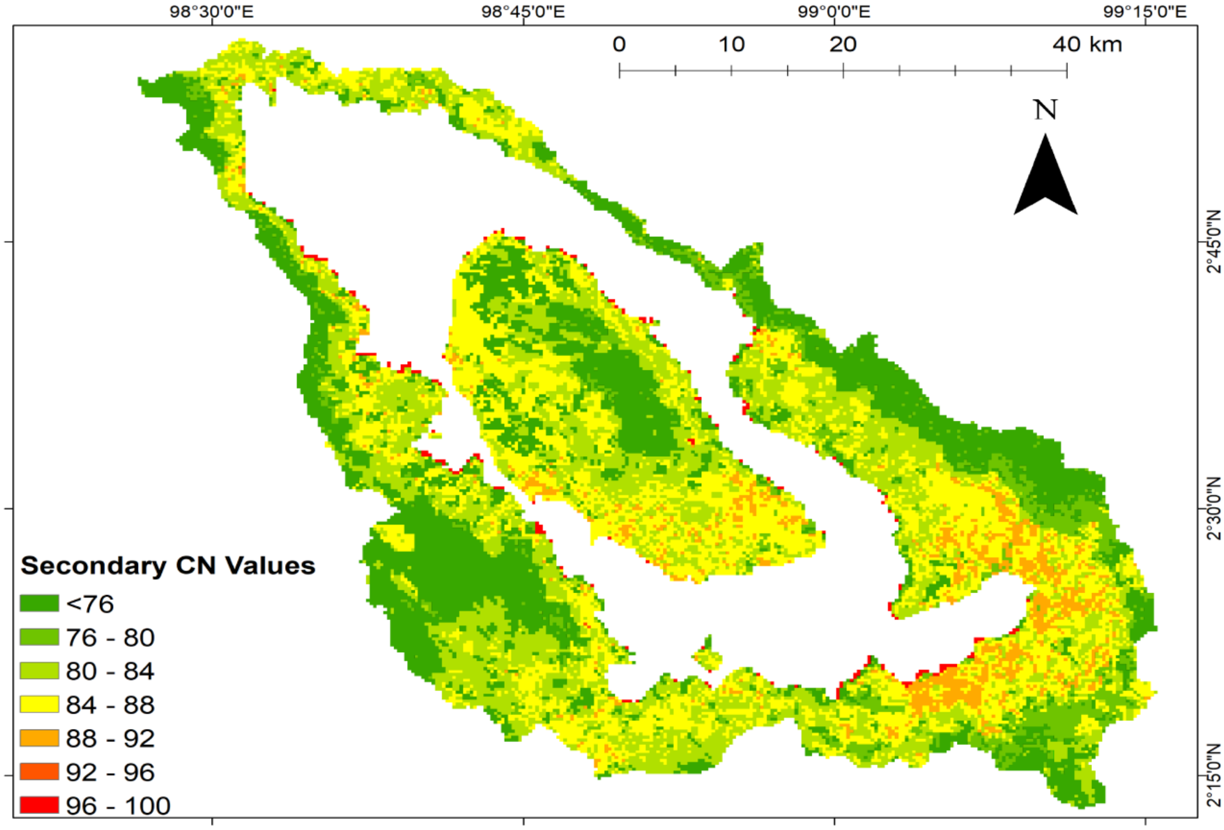

Figure 31 Secondary Curve Number Values of Toba Catchment in 2007

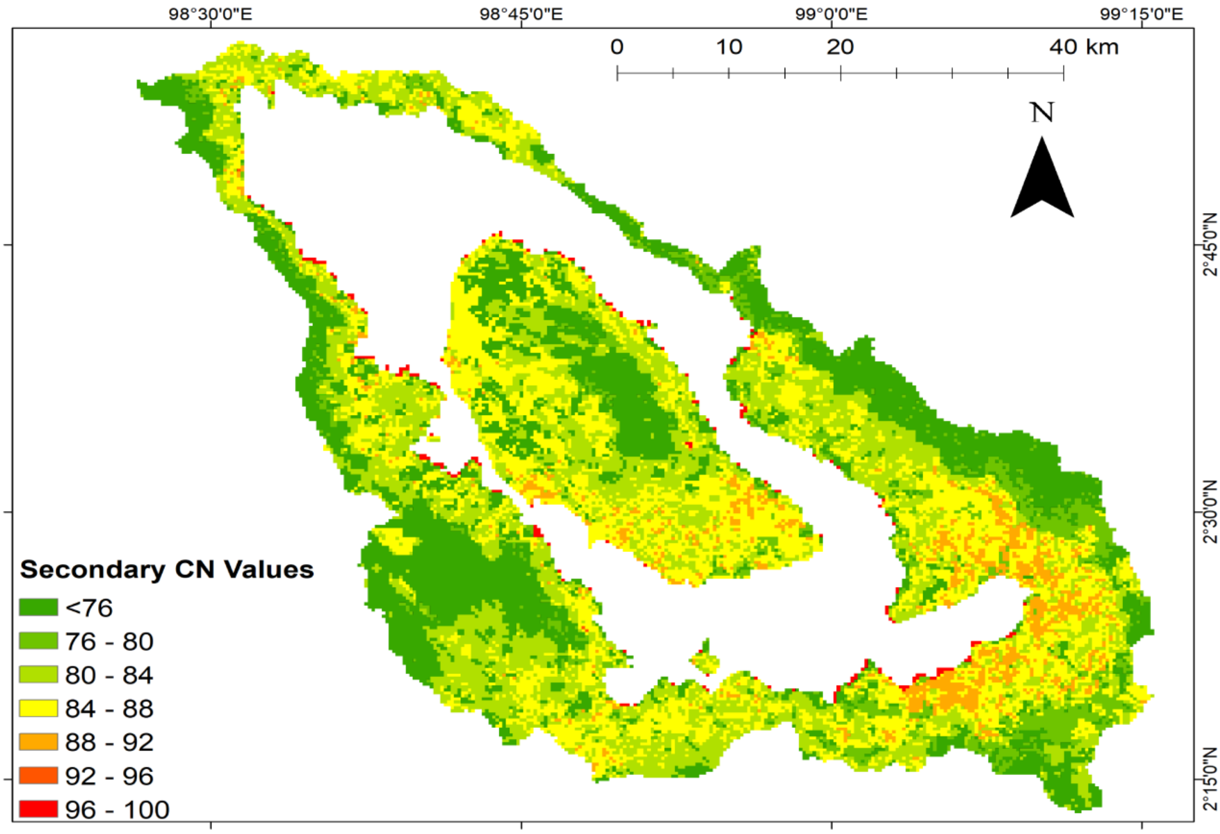

Figure 32 Secondary Curve Number Values of Toba Catchment in 2008

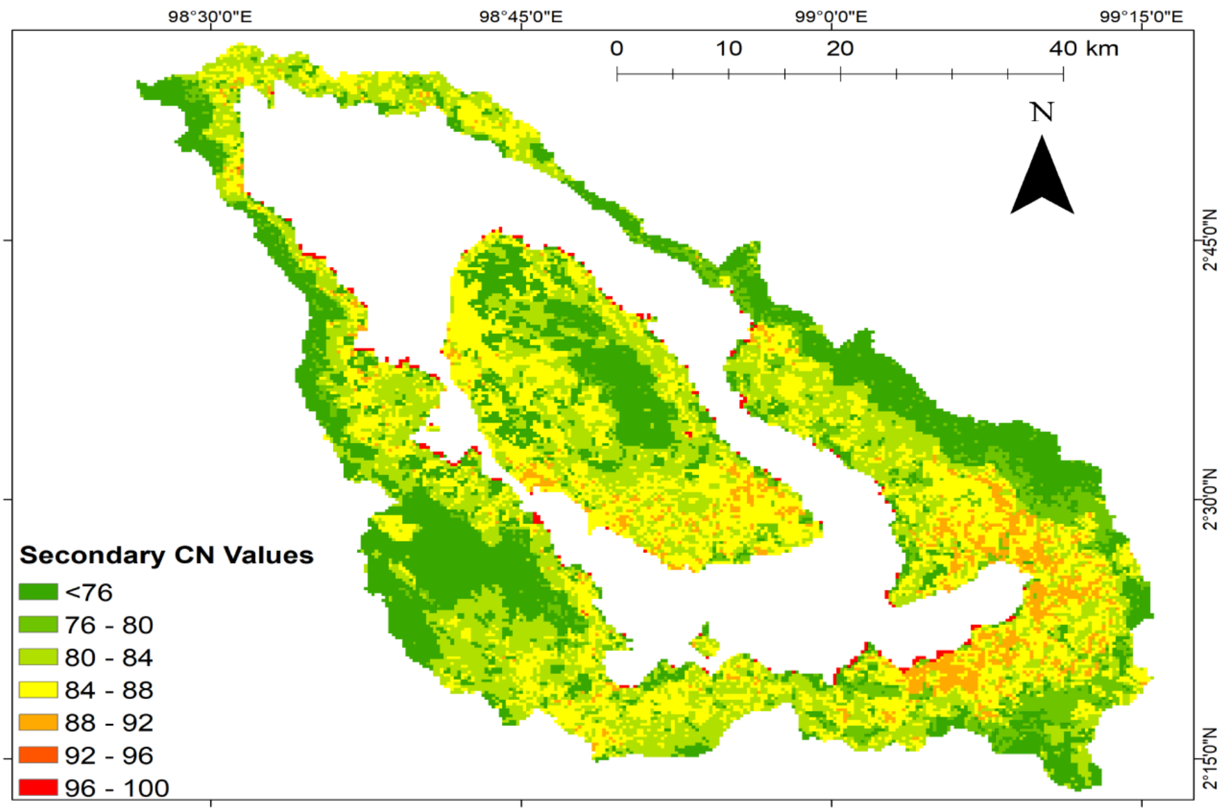

Figure 33 Secondary Curve Number Values of Toba Catchment in 2009

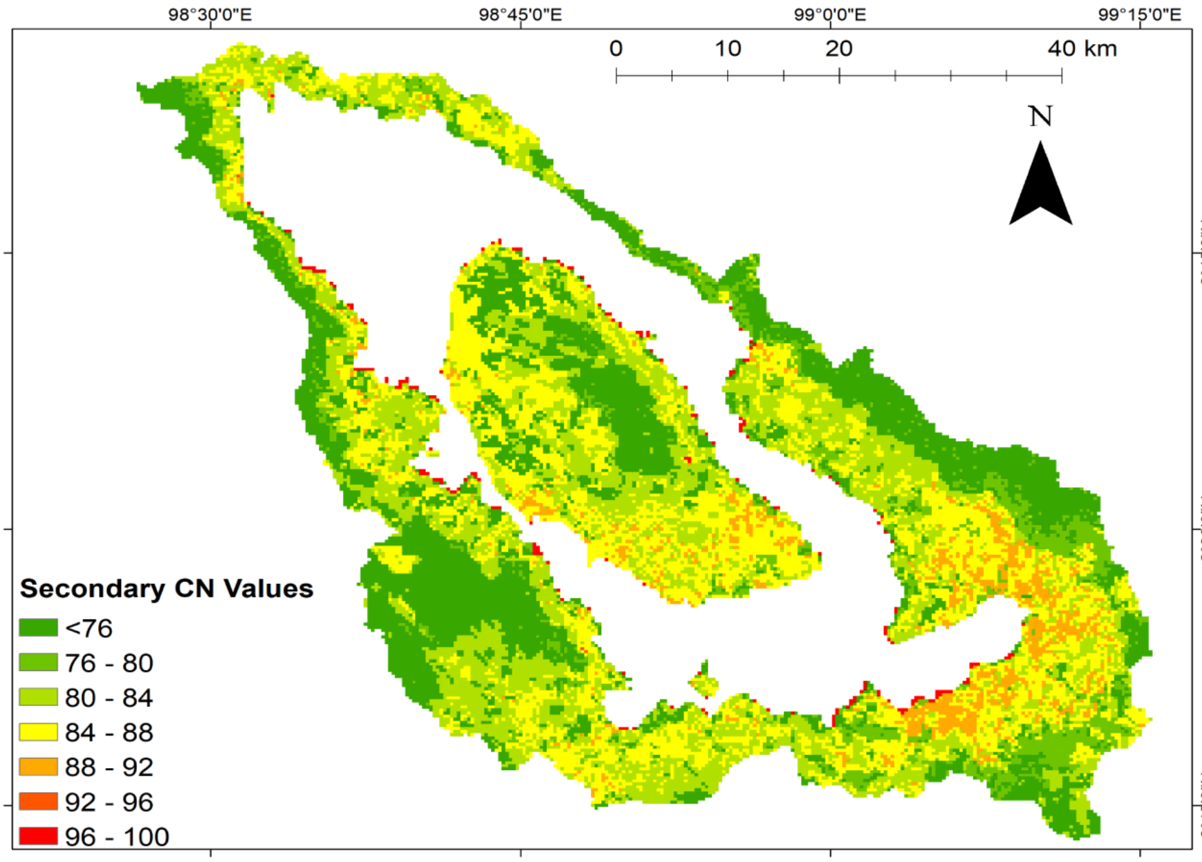

Figure 34 Secondary Curve Number Values of Toba Catchment in 2010

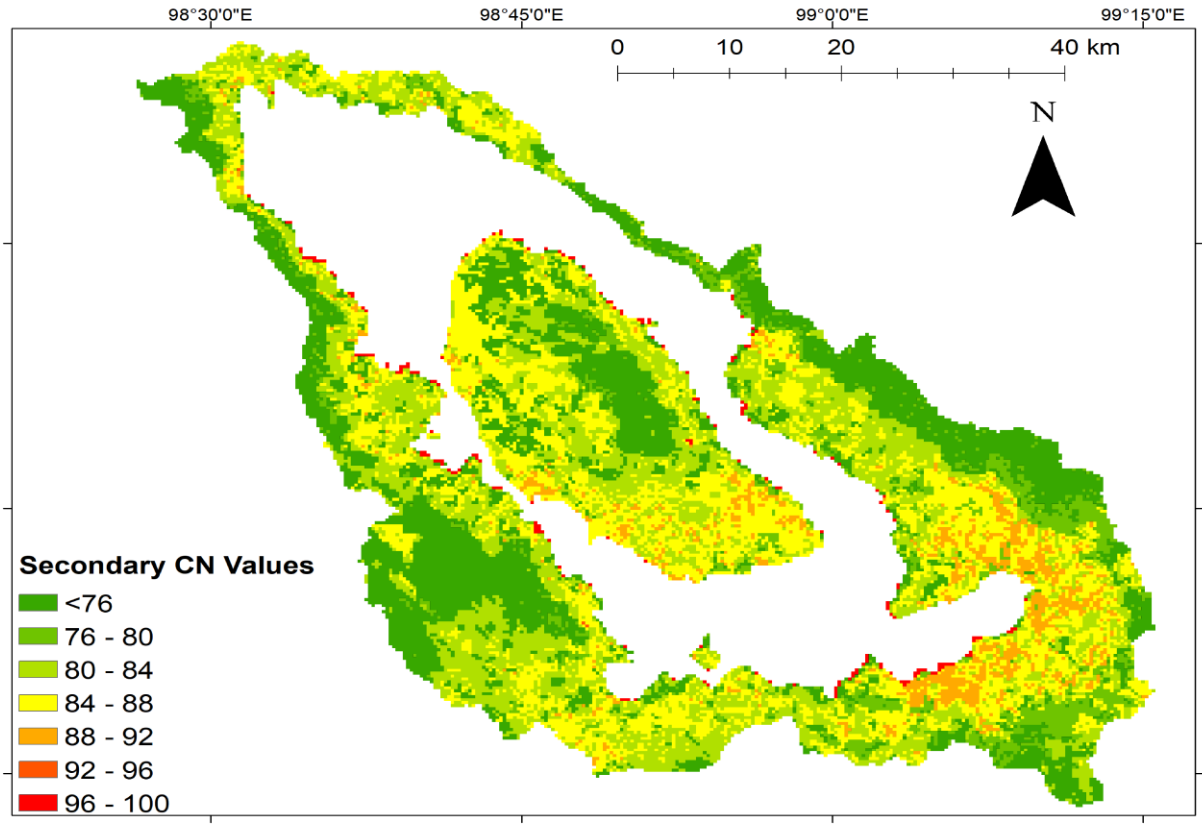

Figure 35 Secondary Curve Number Values of Toba Catchment in 2011

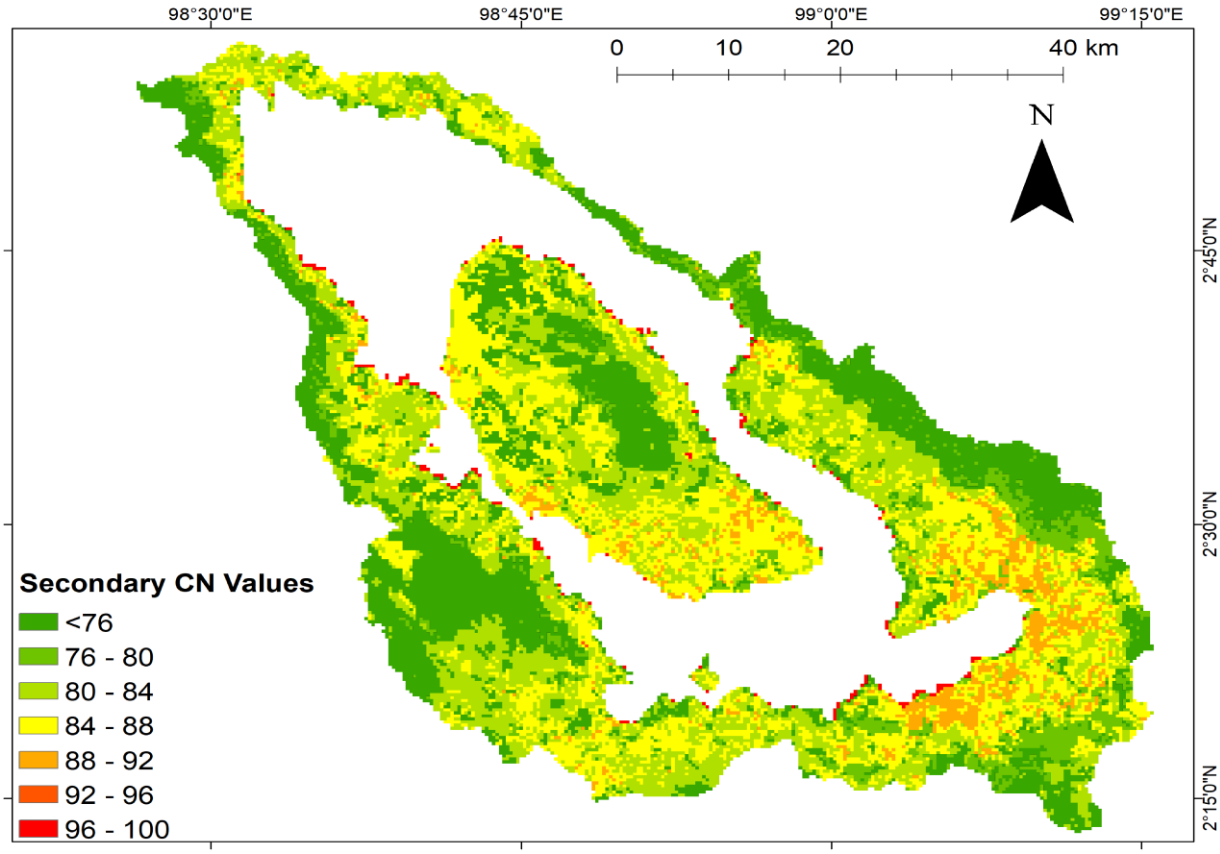

Figure 36 Secondary Curve Number Values of Toba Catchment in 2012

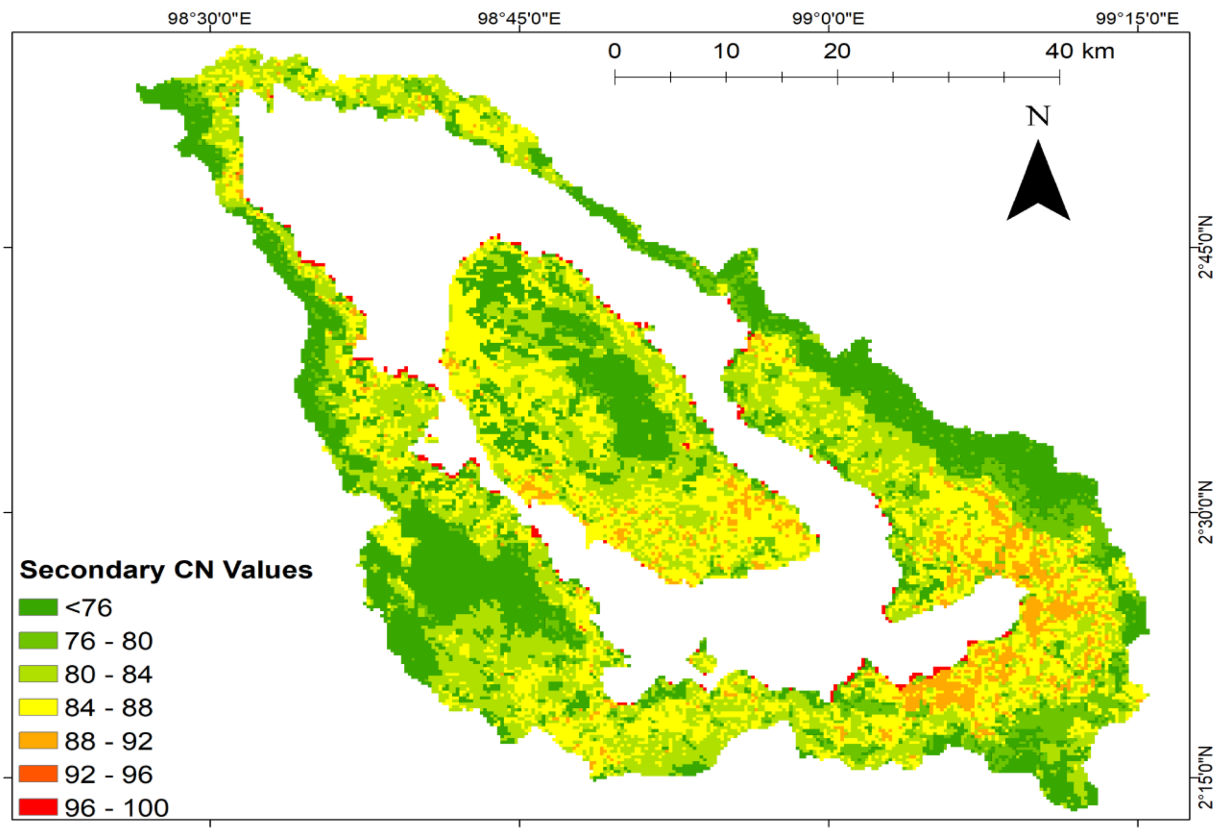

Figure 37 Secondary Curve Number Values of Toba Catchment in 2013

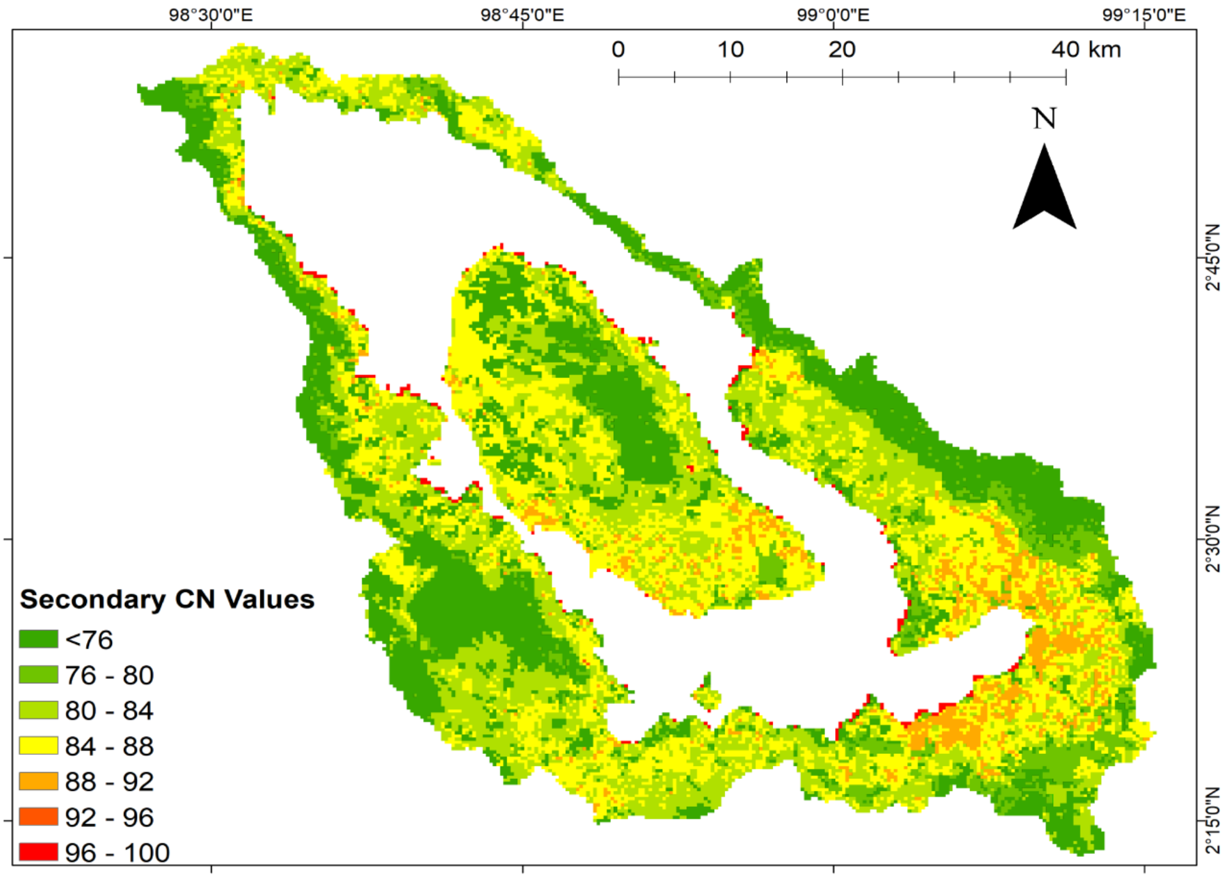

Figure 38 Secondary Curve Number Values of Toba Catchment in 2014

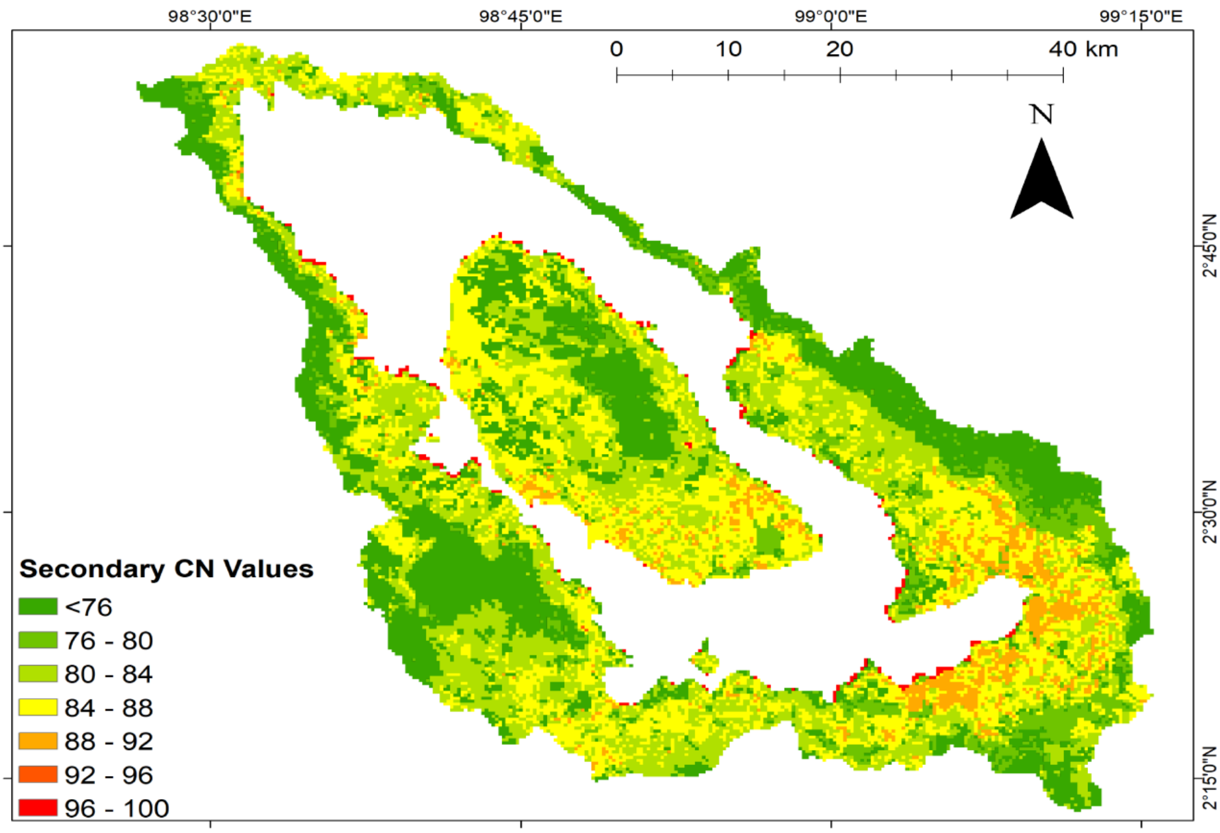

Figure 39 Secondary Curve Number Values of Toba Catchment in 2015

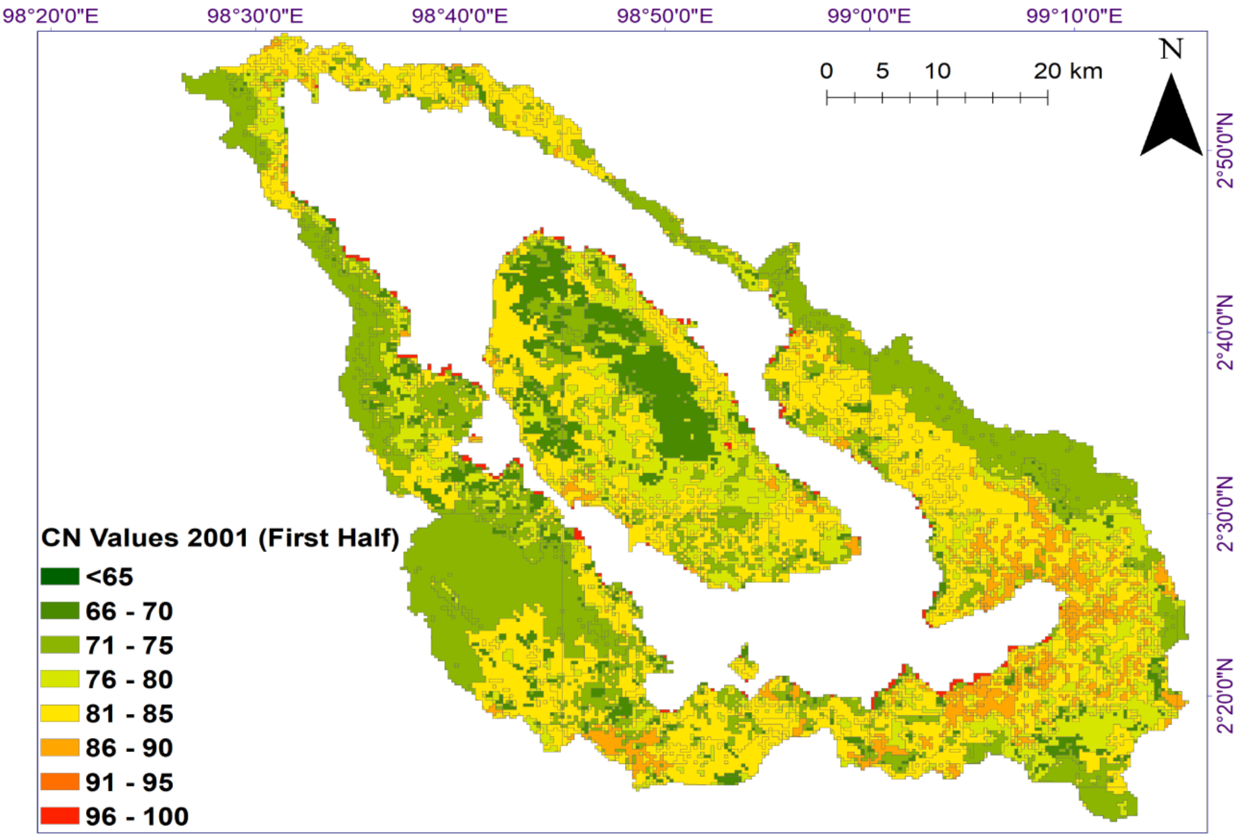

Figure 40 Curve Number (CN) Values of Toba Catchment in 2001 (First Half)

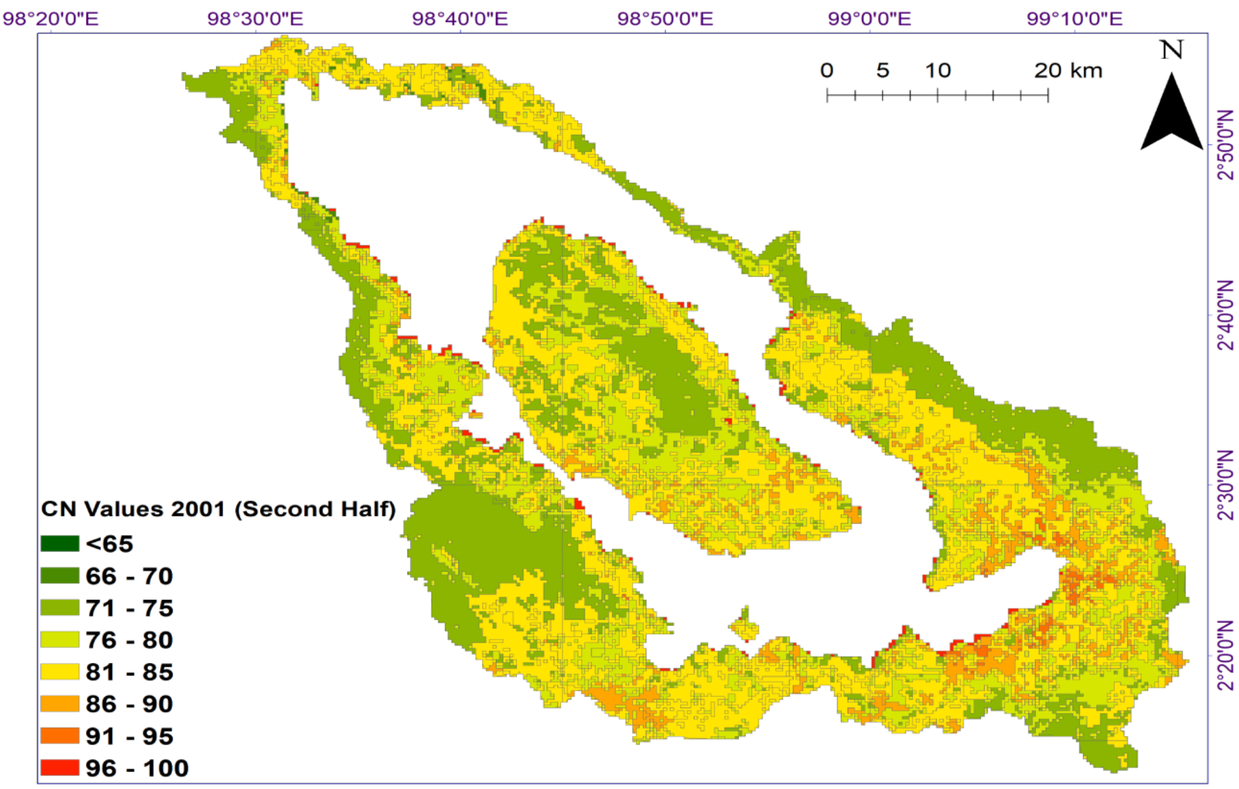

Figure 41 Curve Number (CN) Values of Toba Catchment in 2001 (Second Half)

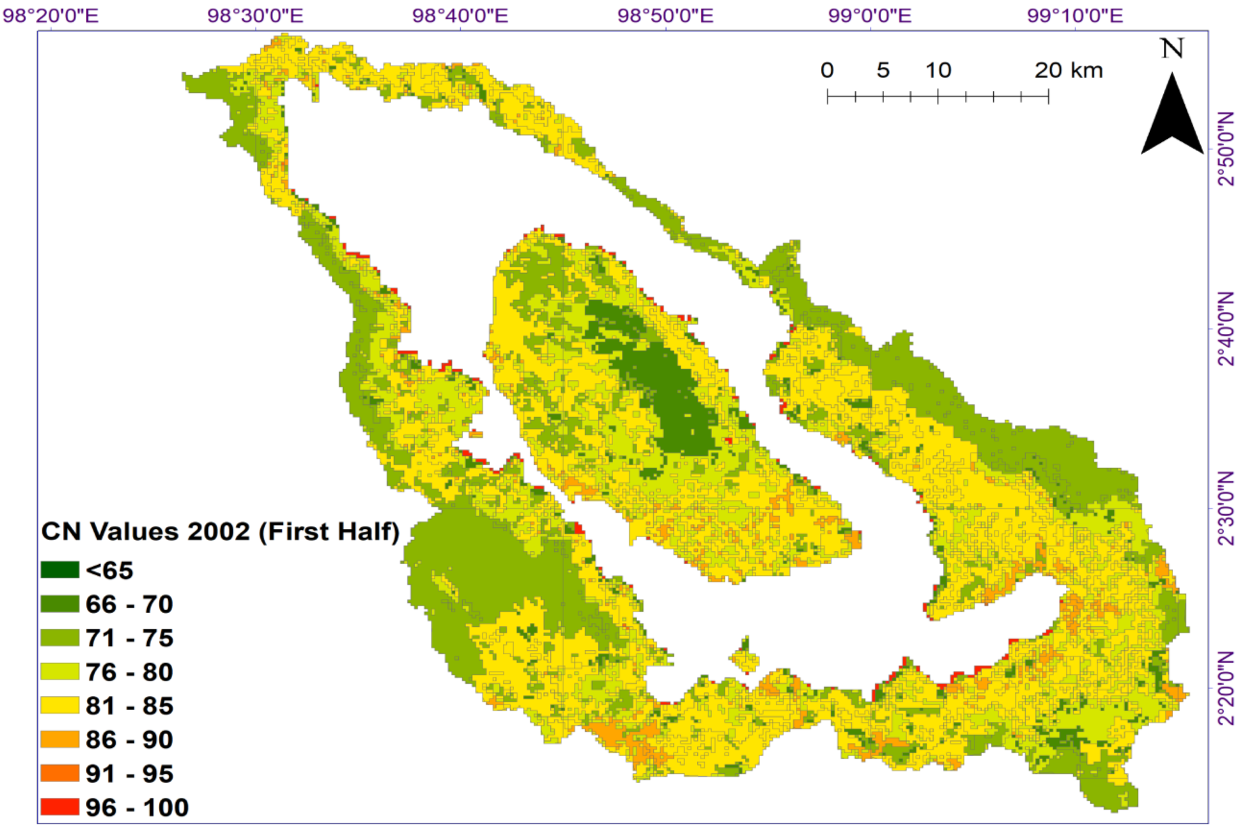

Figure 42 Curve Number (CN) Values of Toba Catchment in 2002 (First Half)

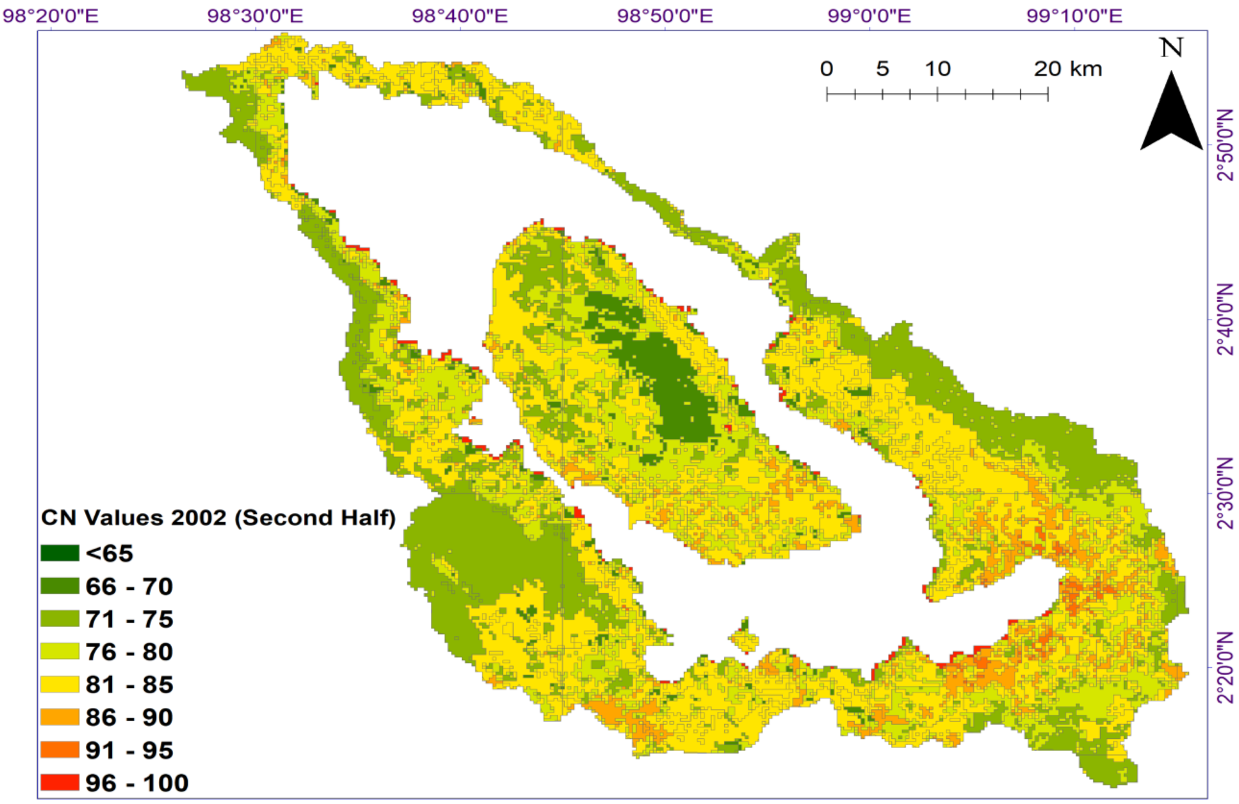

Figure 43 Curve Number (CN) Values of Toba Catchment in 2002 (Second Half)

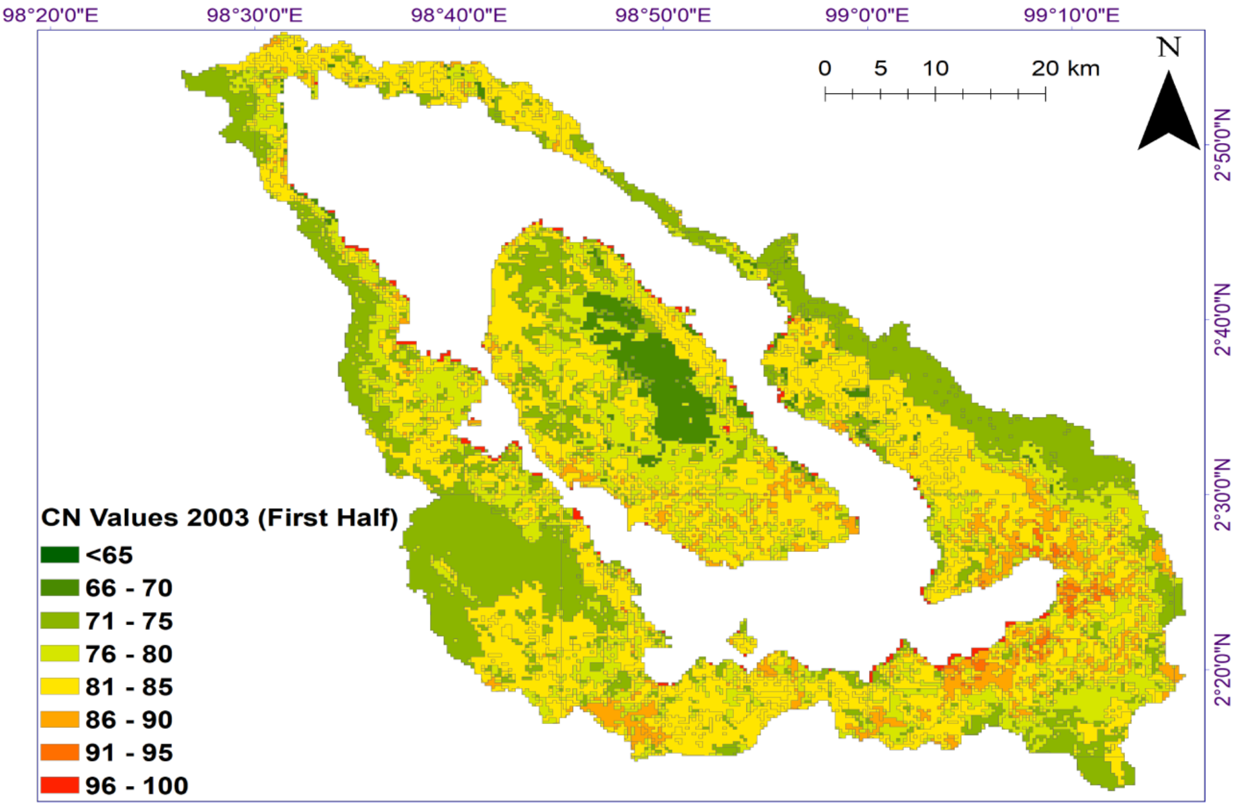

Figure 44 Curve Number (CN) Values of Toba Catchment in 2003 (First Half)

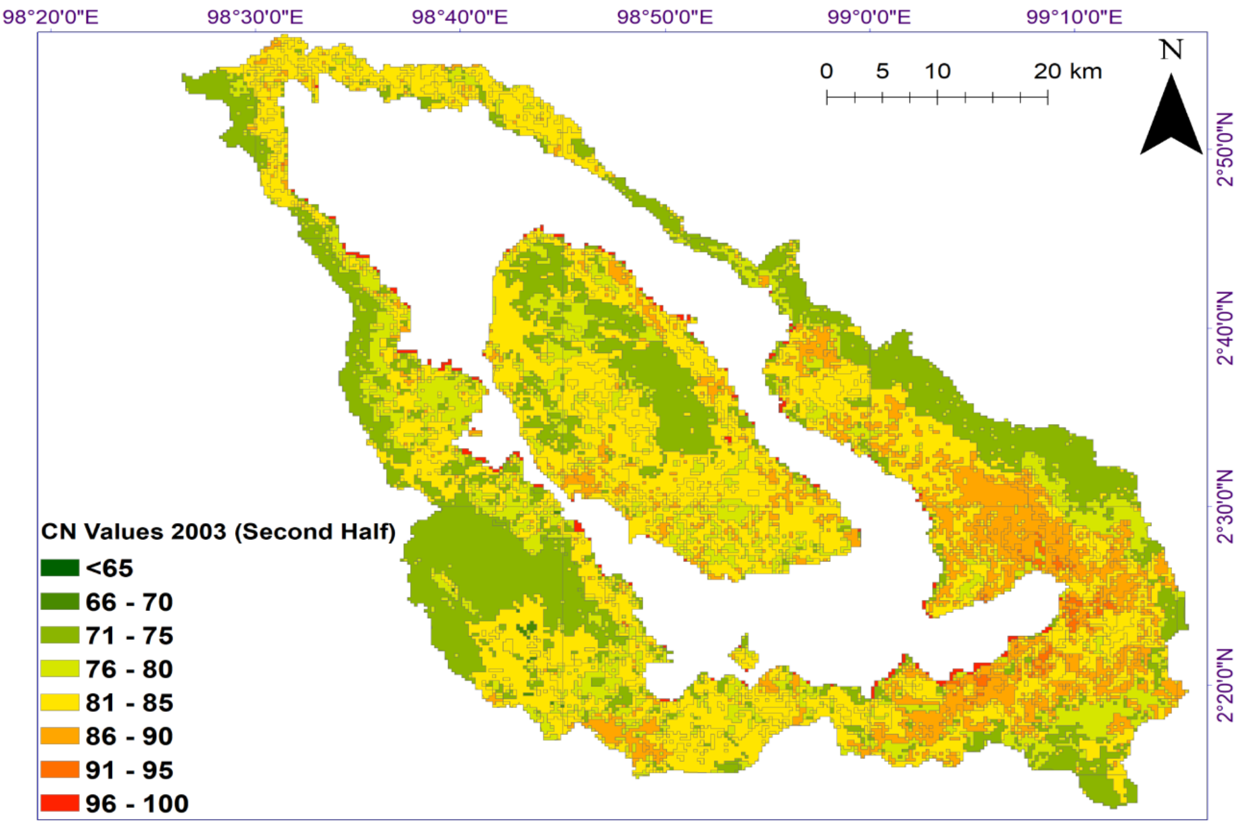

Figure 45 Curve Number (CN) Values of Toba Catchment in 2003 (Second Half)

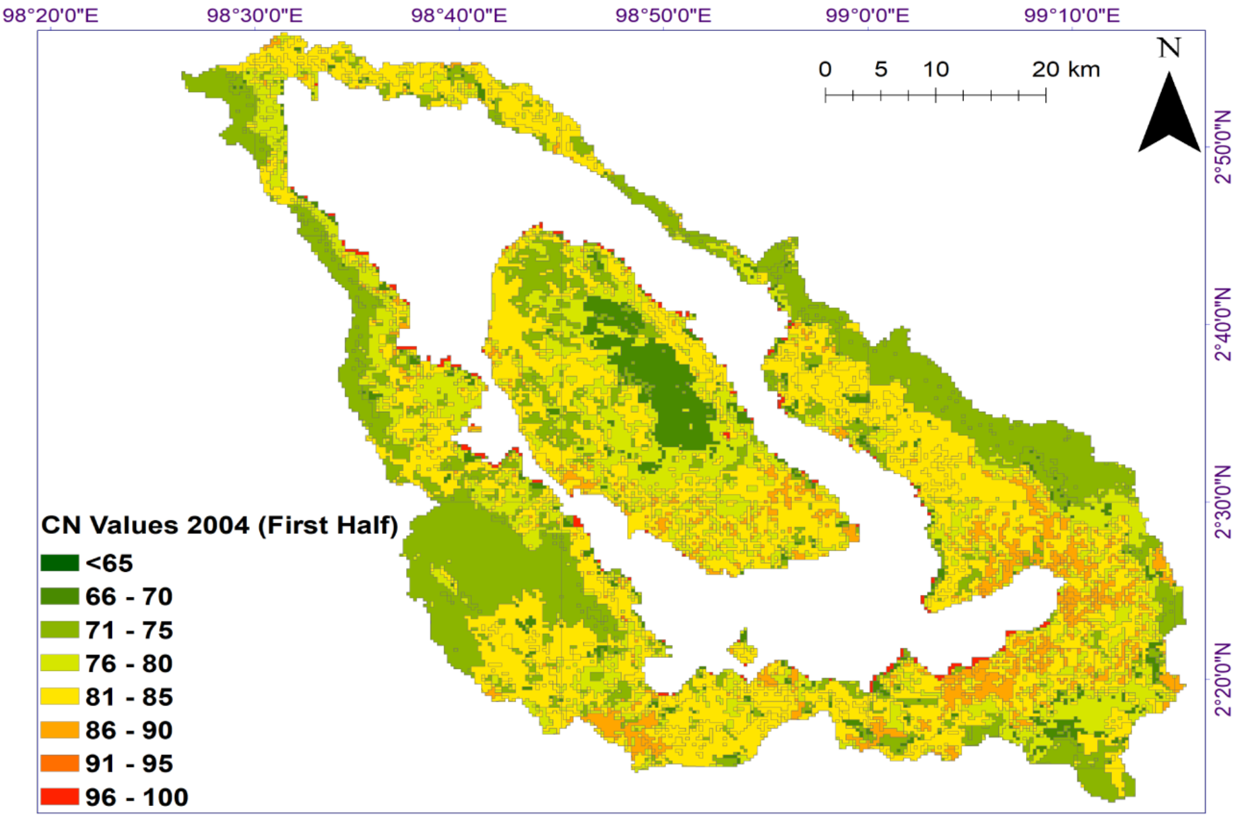

Figure 46 Curve Number (CN) Values of Toba Catchment in 2004 (First Half)

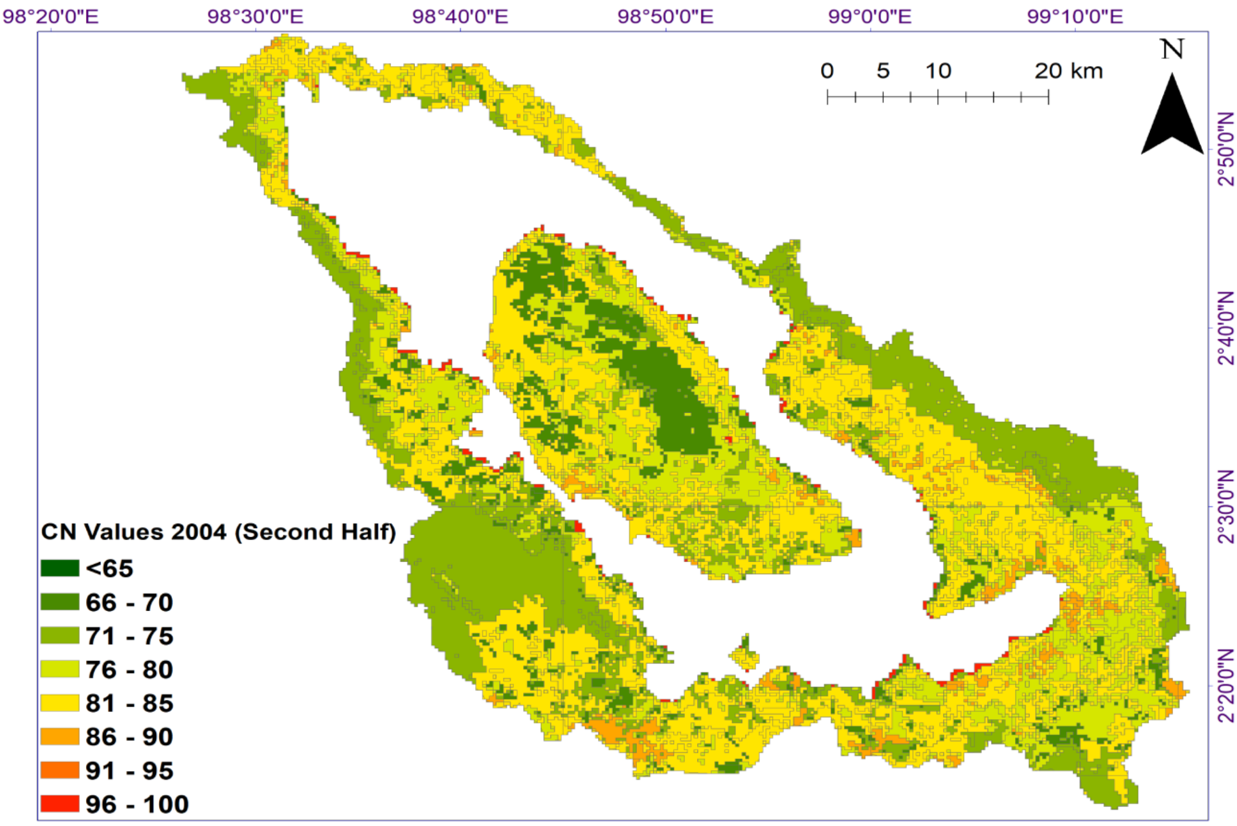

Figure 47 Curve Number (CN) Values of Toba Catchment in 2004 (Second Half)

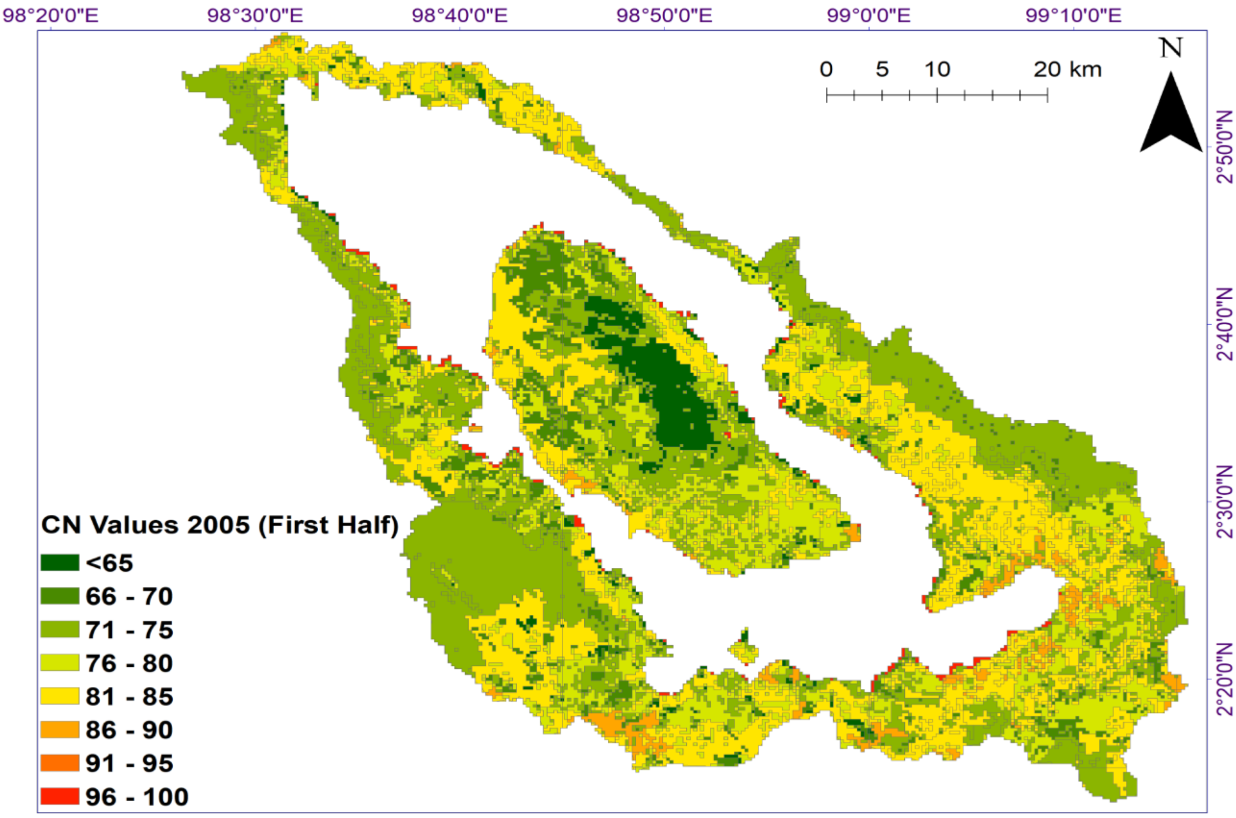

Figure 48 Curve Number (CN) Values of Toba Catchment in 2005 (First Half)

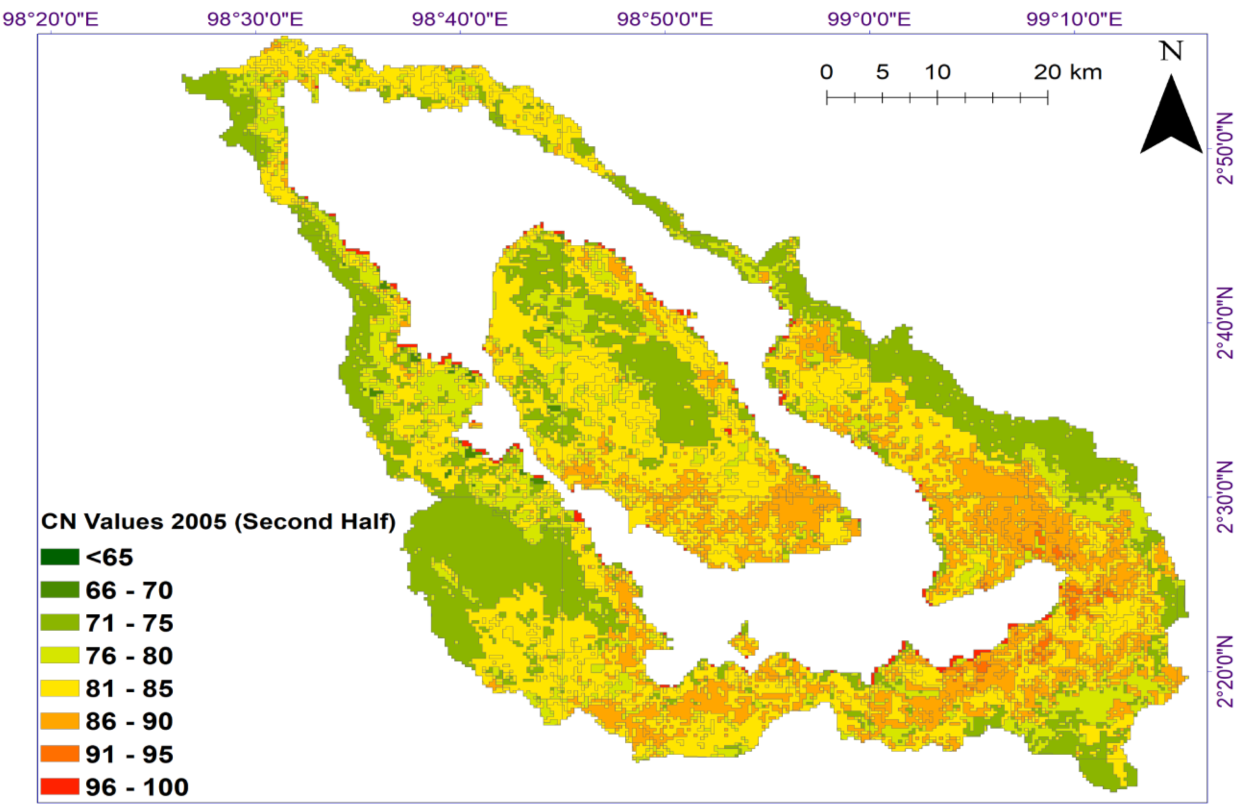

Figure 49 Curve Number (CN) Values of Toba Catchment in 2005 (Second Half)

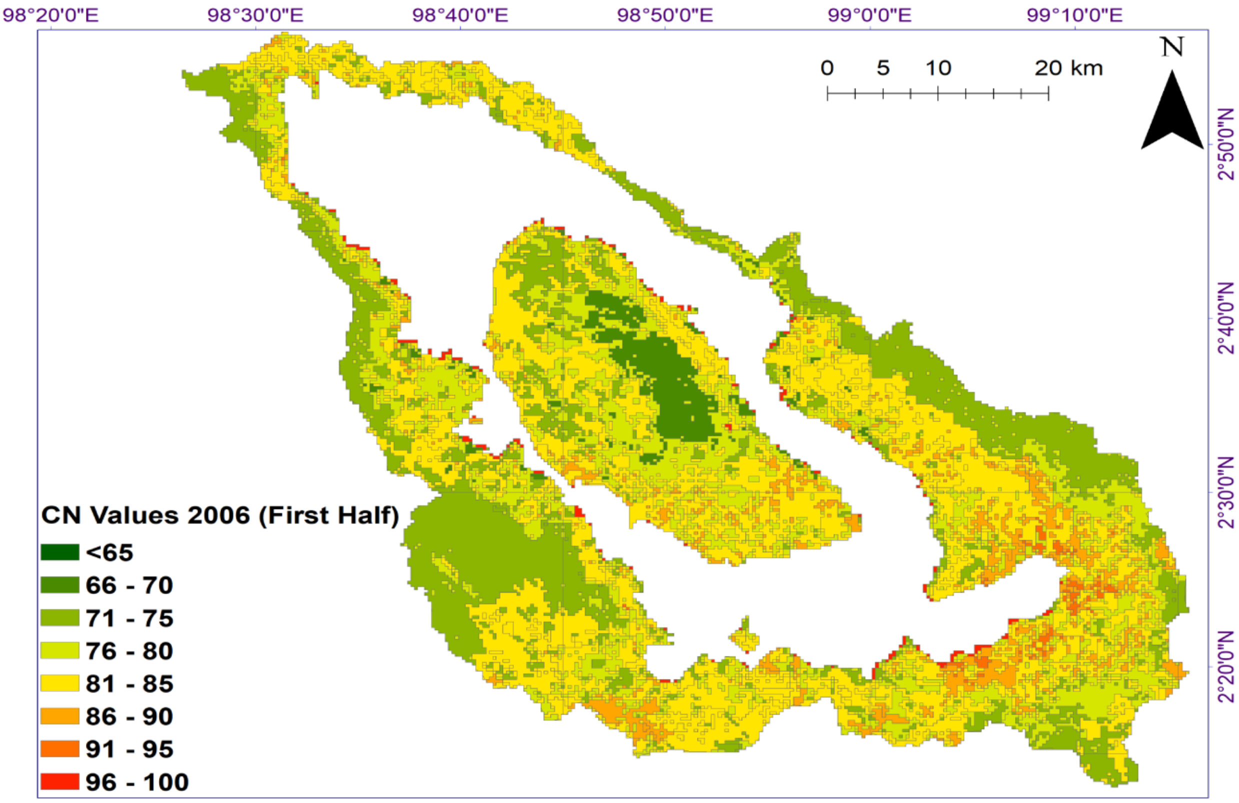

Figure 50 Curve Number (CN) Values of Toba Catchment in 2006 (First Half)

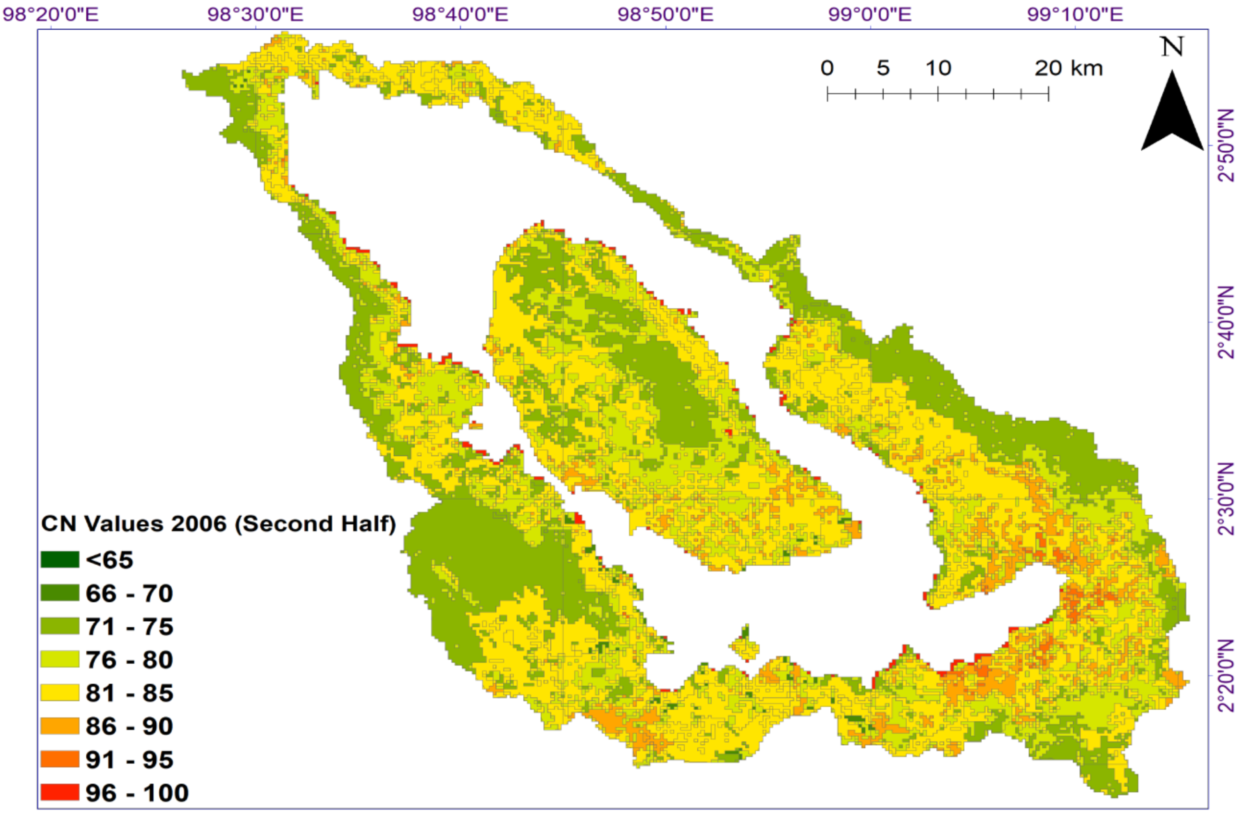

Figure 51 Curve Number (CN) Values of Toba Catchment in 2006 (Second Half)

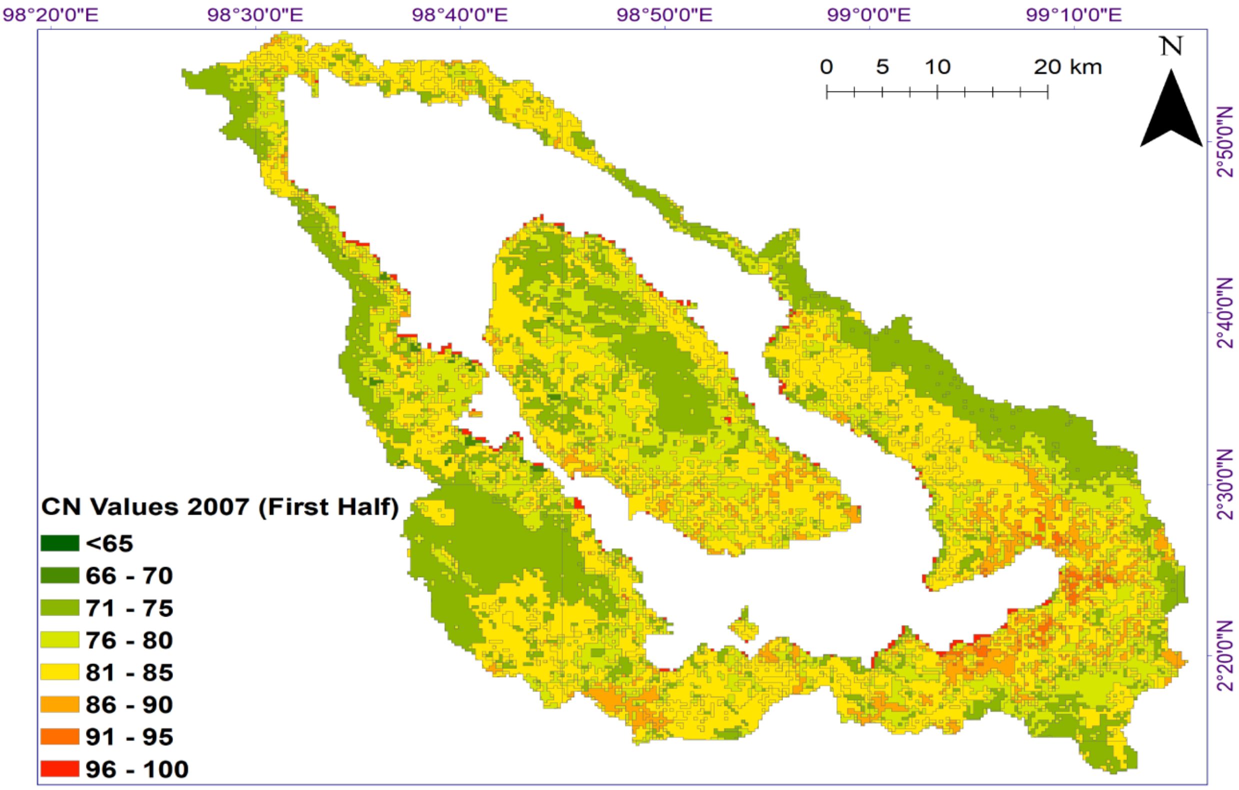

Figure 52 Curve Number (CN) Values of Toba Catchment in 2007 (First Half)

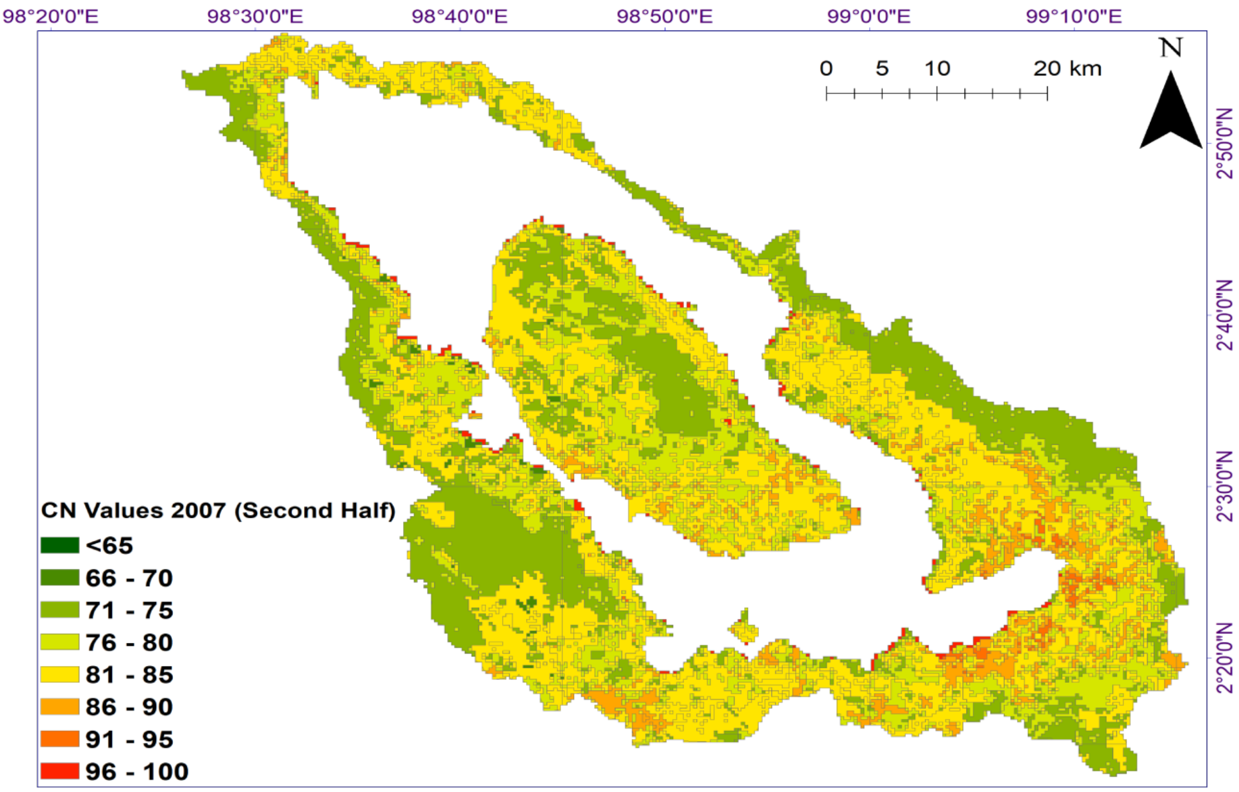

Figure 53 Curve Number (CN) Values of Toba Catchment in 2007 (Second Half)

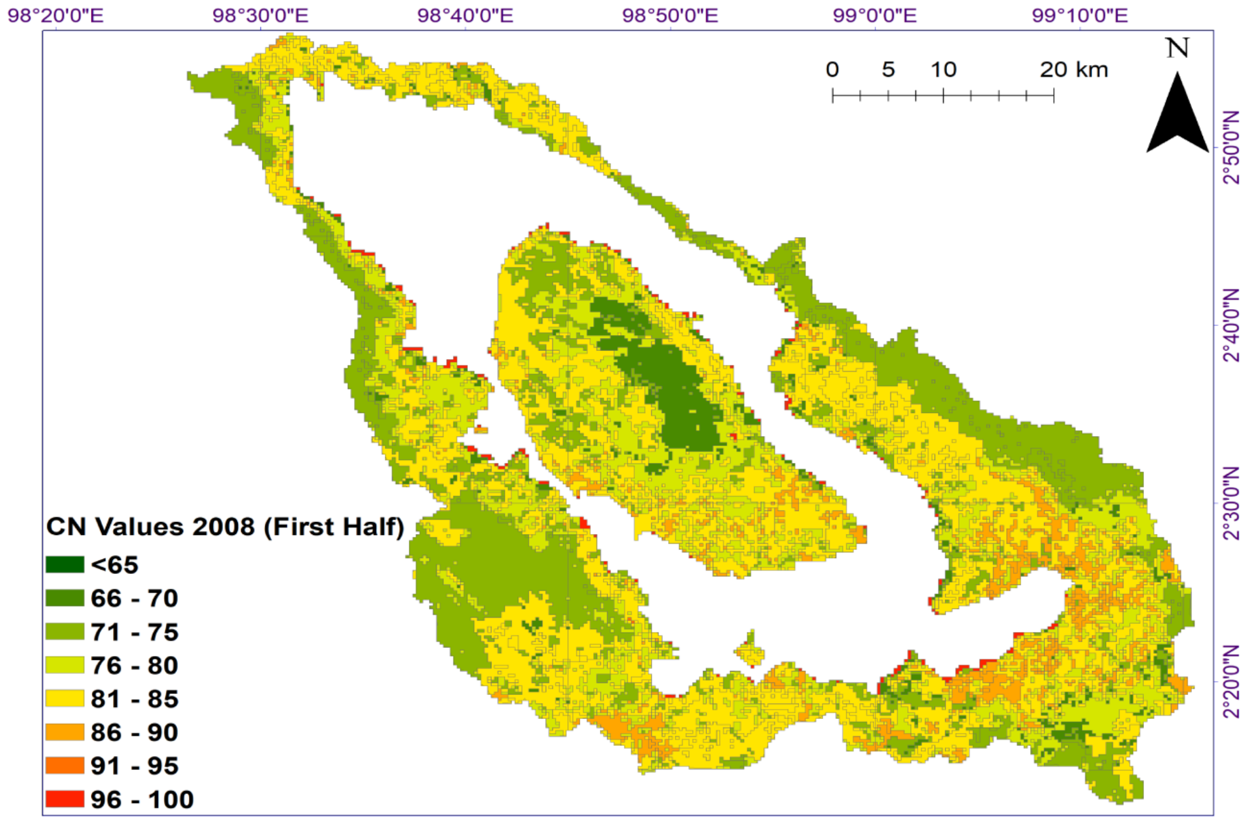

Figure 54 Curve Number (CN) Values of Toba Catchment in 2008 (First Half)

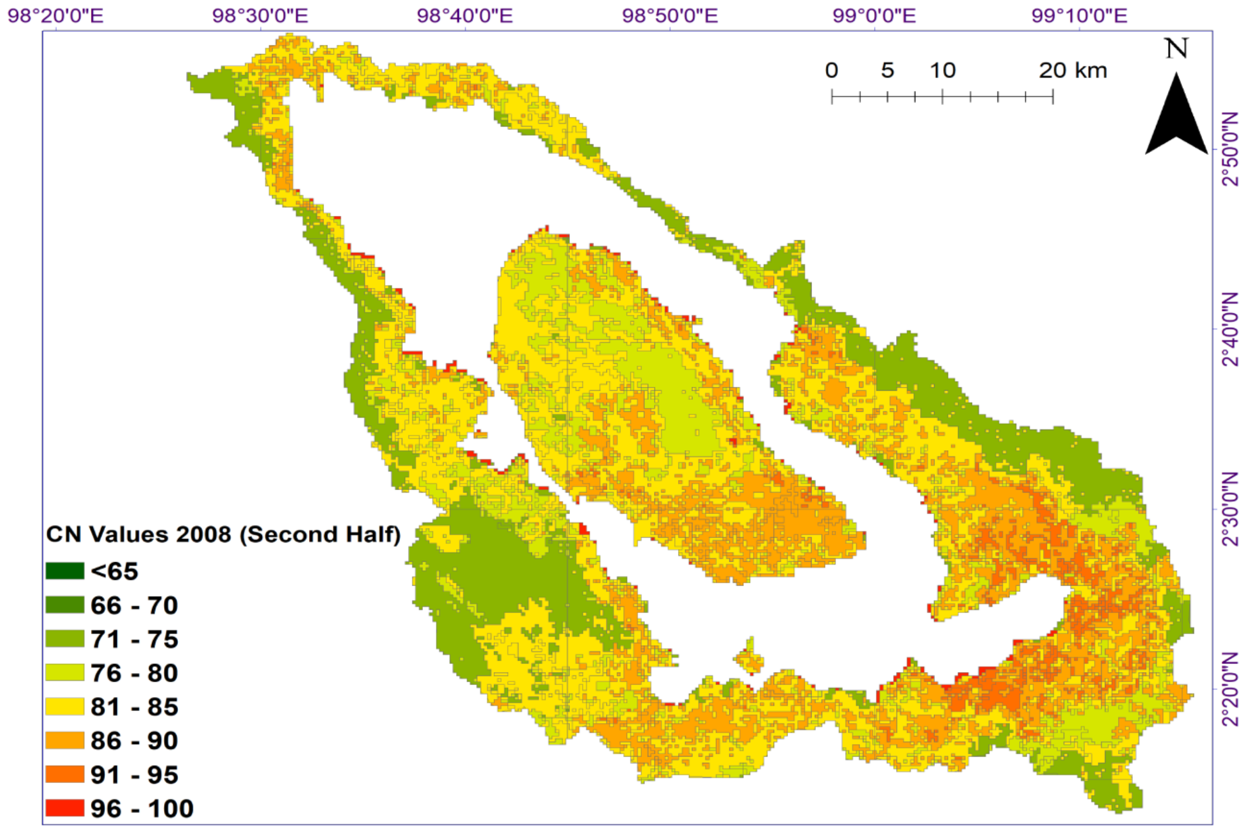

Figure 55 Curve Number (CN) Values of Toba Catchment in 2008 (Second Half)

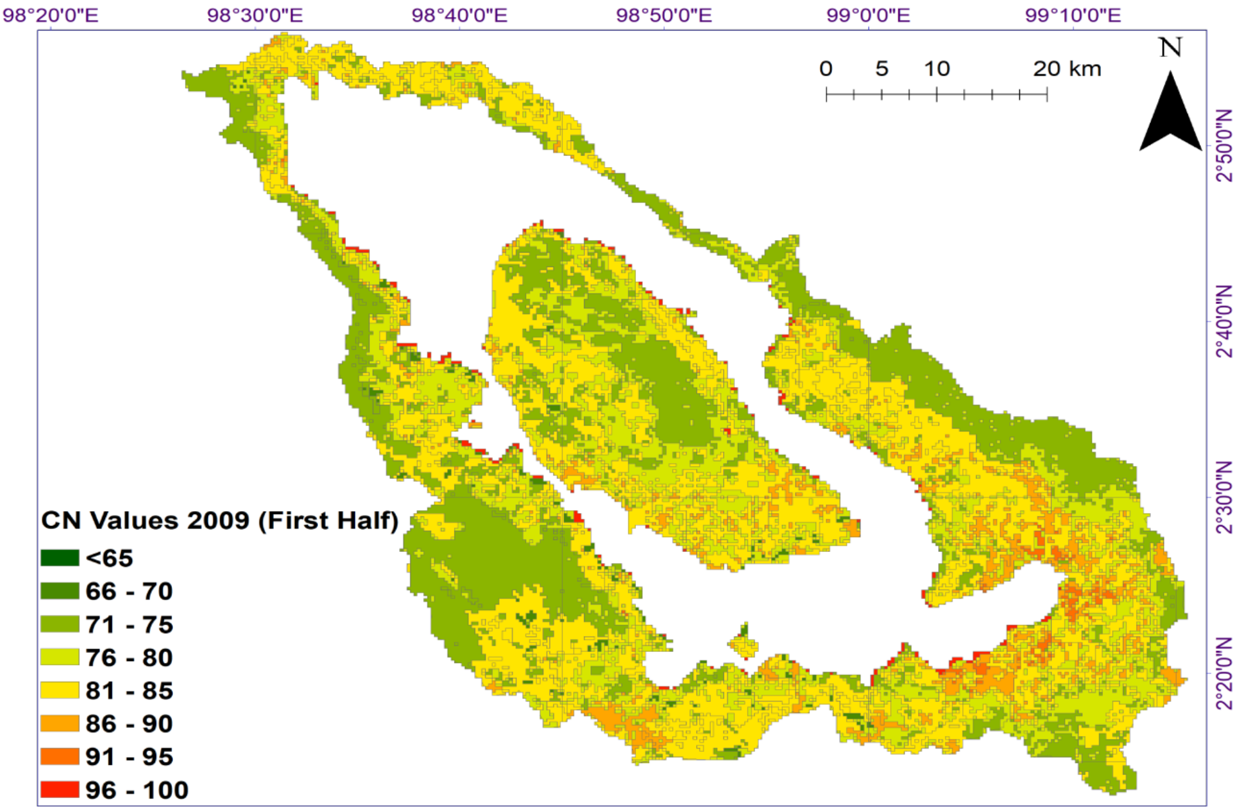

Figure 56 Curve Number (CN) Values of Toba Catchment in 2009 (First Half)

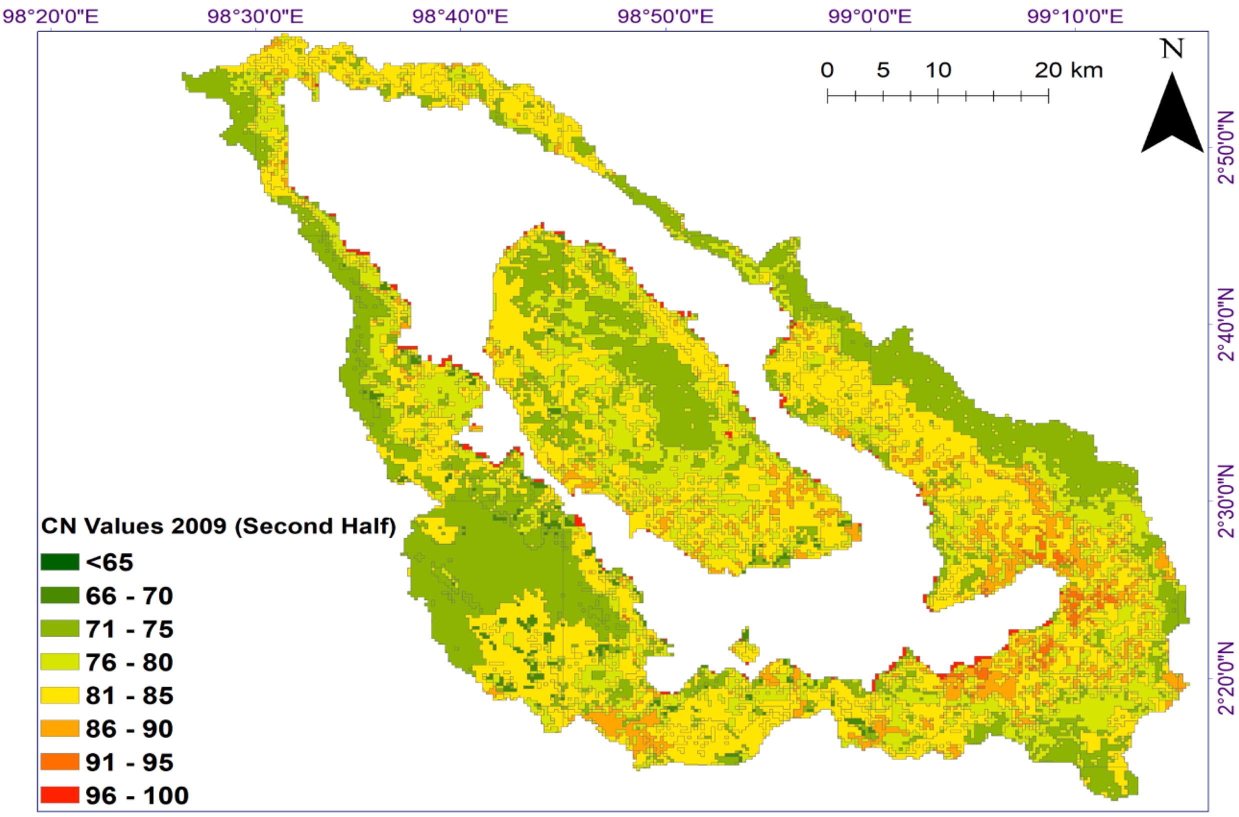

Figure 57 Curve Number (CN) Values of Toba Catchment in 2009 (Second Half)

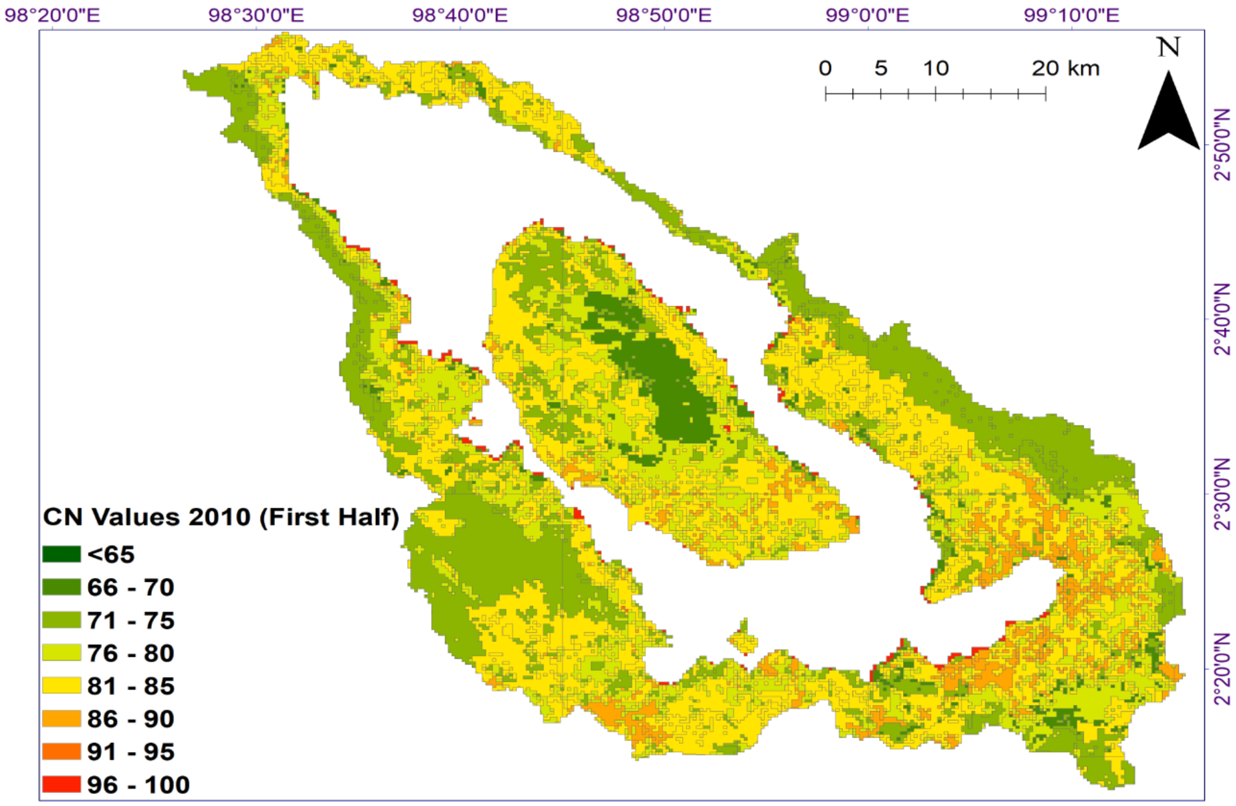

Figure 58 Curve Number (CN) Values of Toba Catchment in 2010 (First Half)

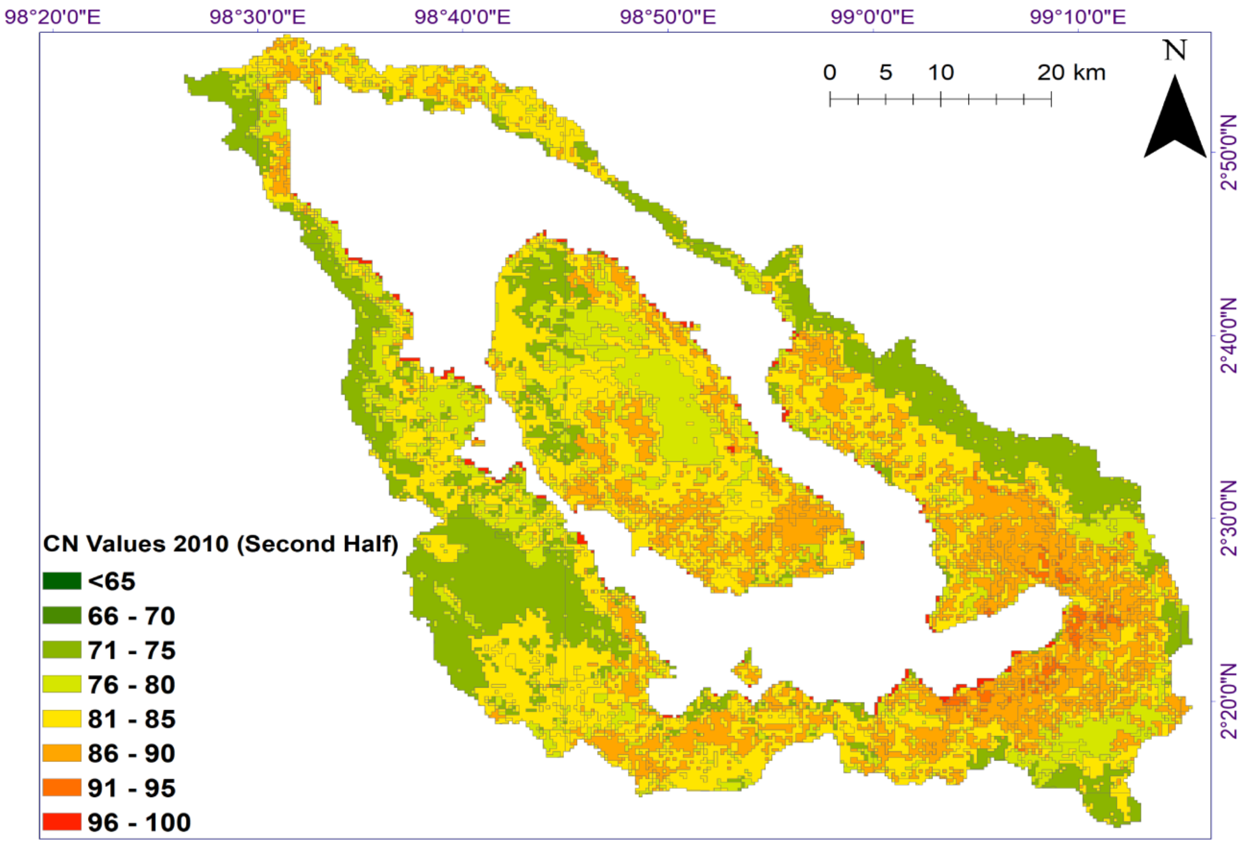

Figure 59 Curve Number (CN) Values of Toba Catchment in 2010 (Second Half)

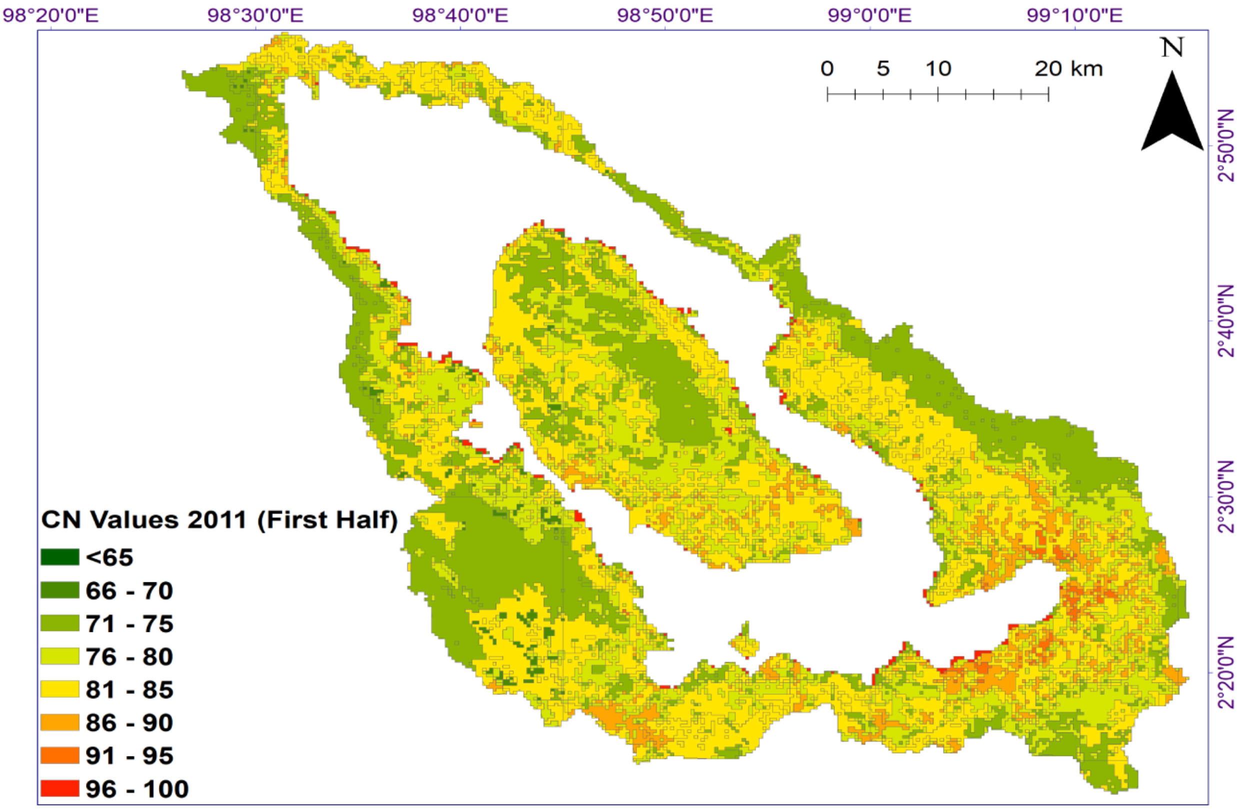

Figure 60 Curve Number (CN) Values of Toba Catchment in 2011 (First Half)

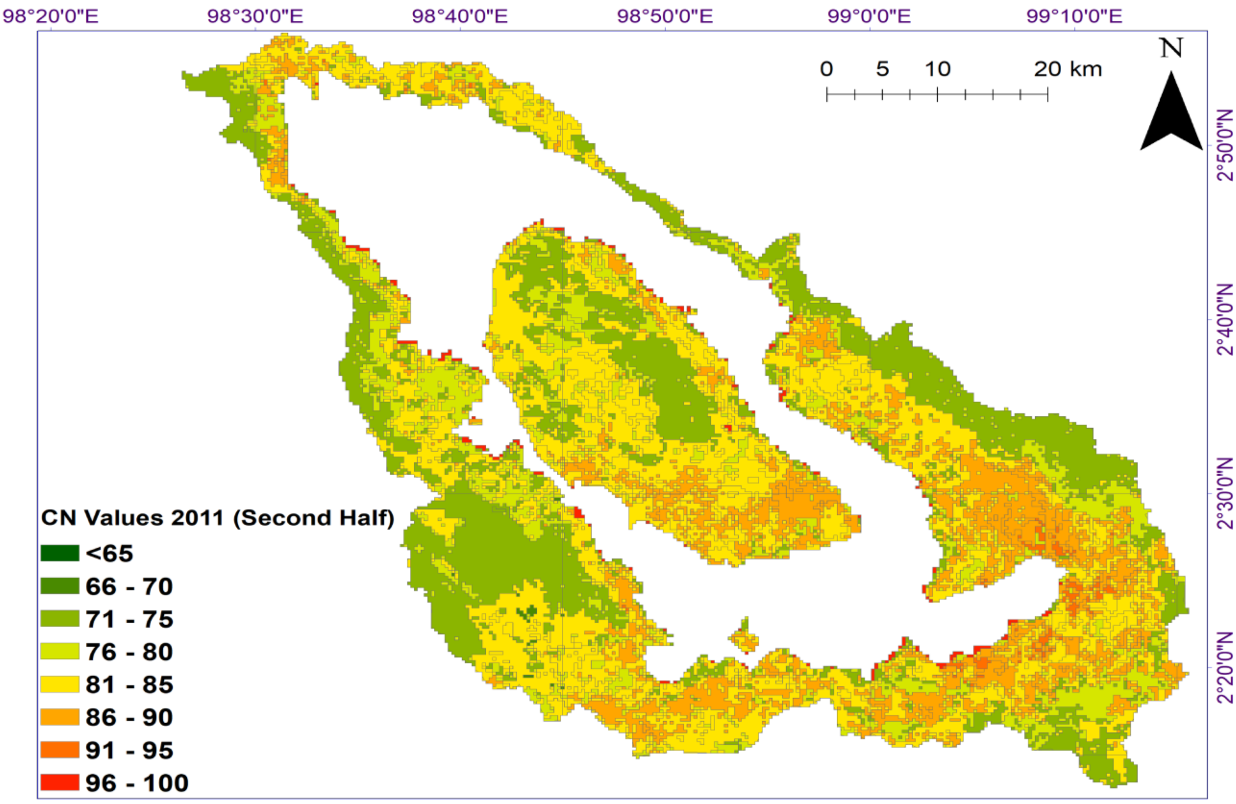

Figure 61 Curve Number (CN) Values of Toba Catchment in 2011 (Second Half)

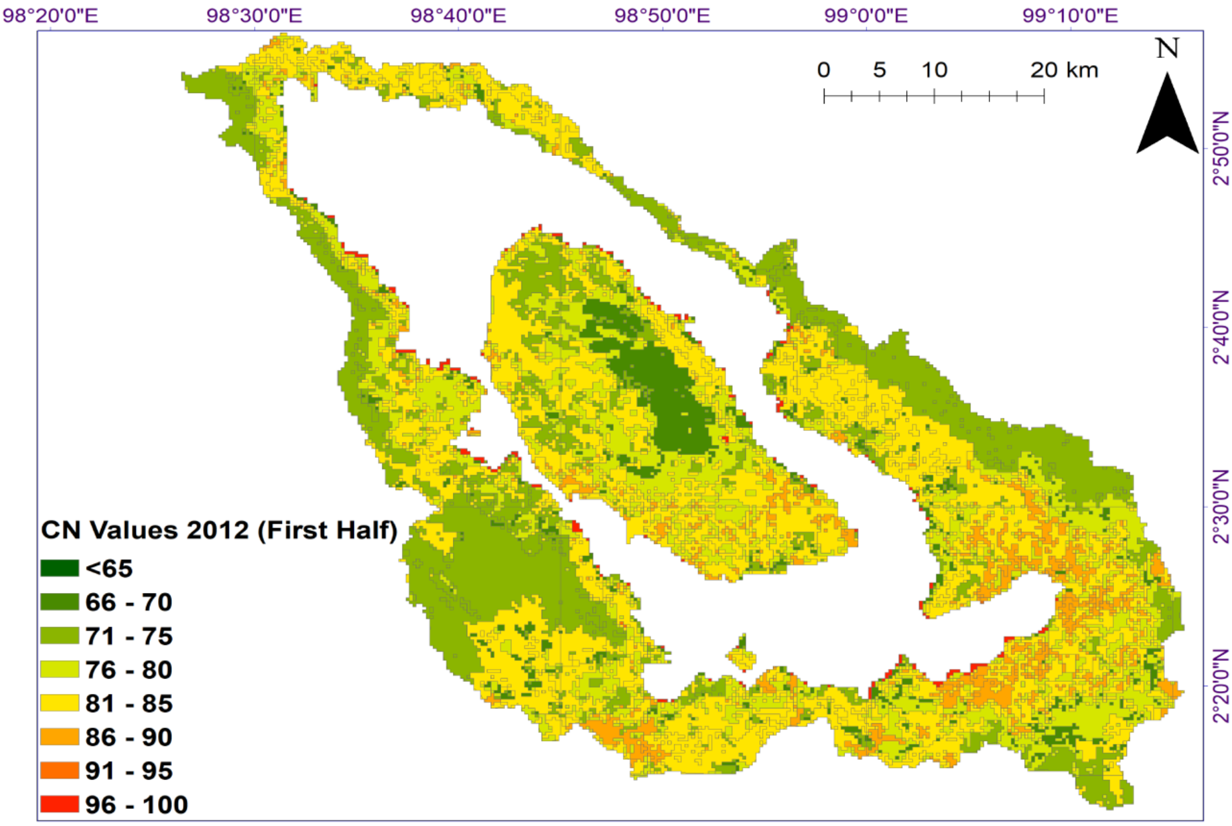

Figure 62 Curve Number (CN) Values of Toba Catchment in 2012 (First Half)

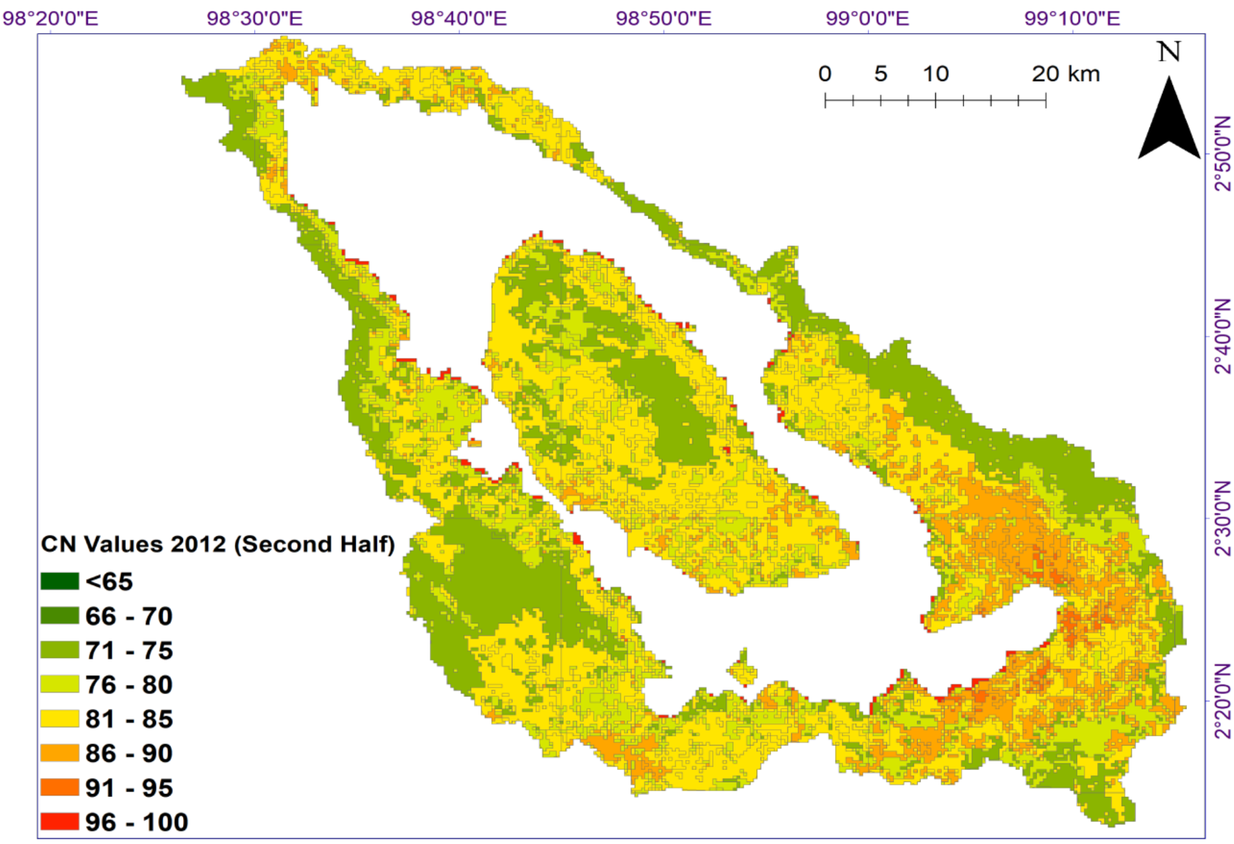

Figure 63 Curve Number (CN) Values of Toba Catchment in 2012 (Second Half)

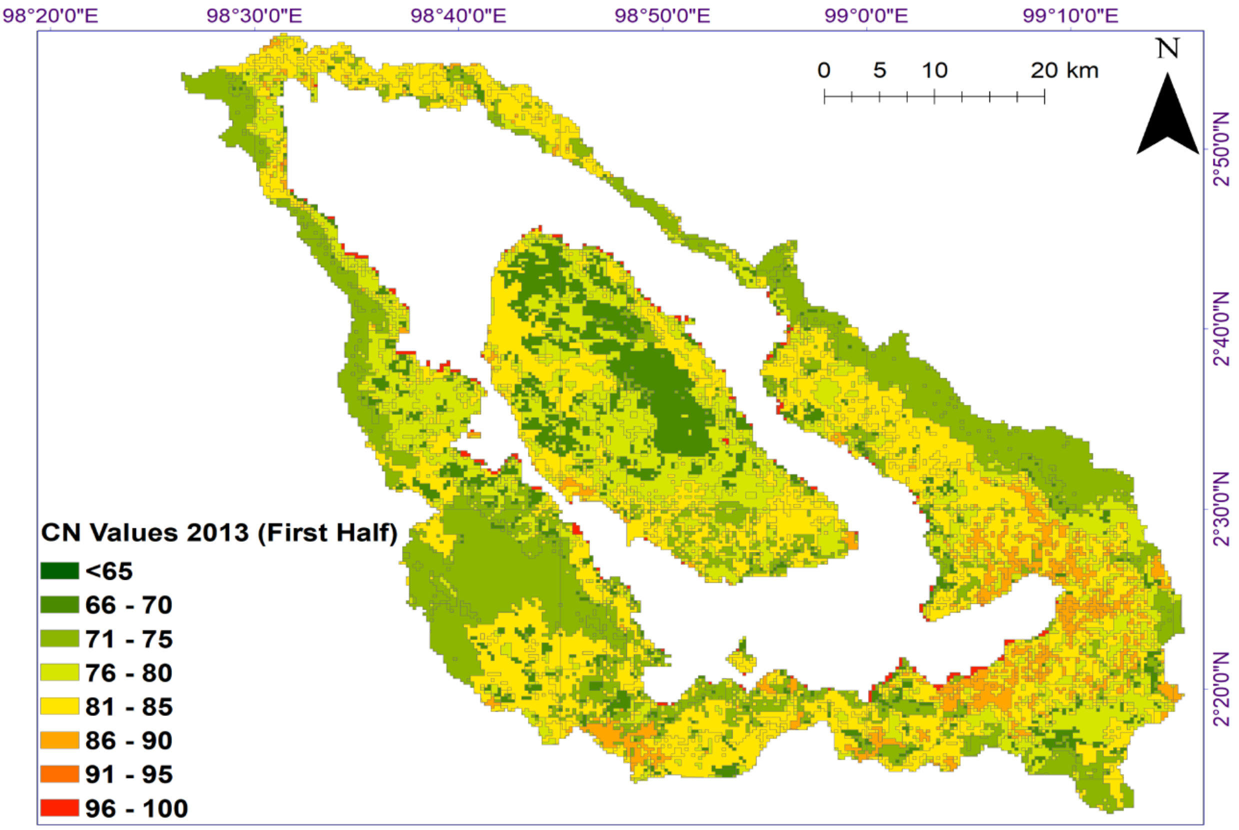

Figure 64 Curve Number (CN) Values of Toba Catchment in 2013 (First Half)

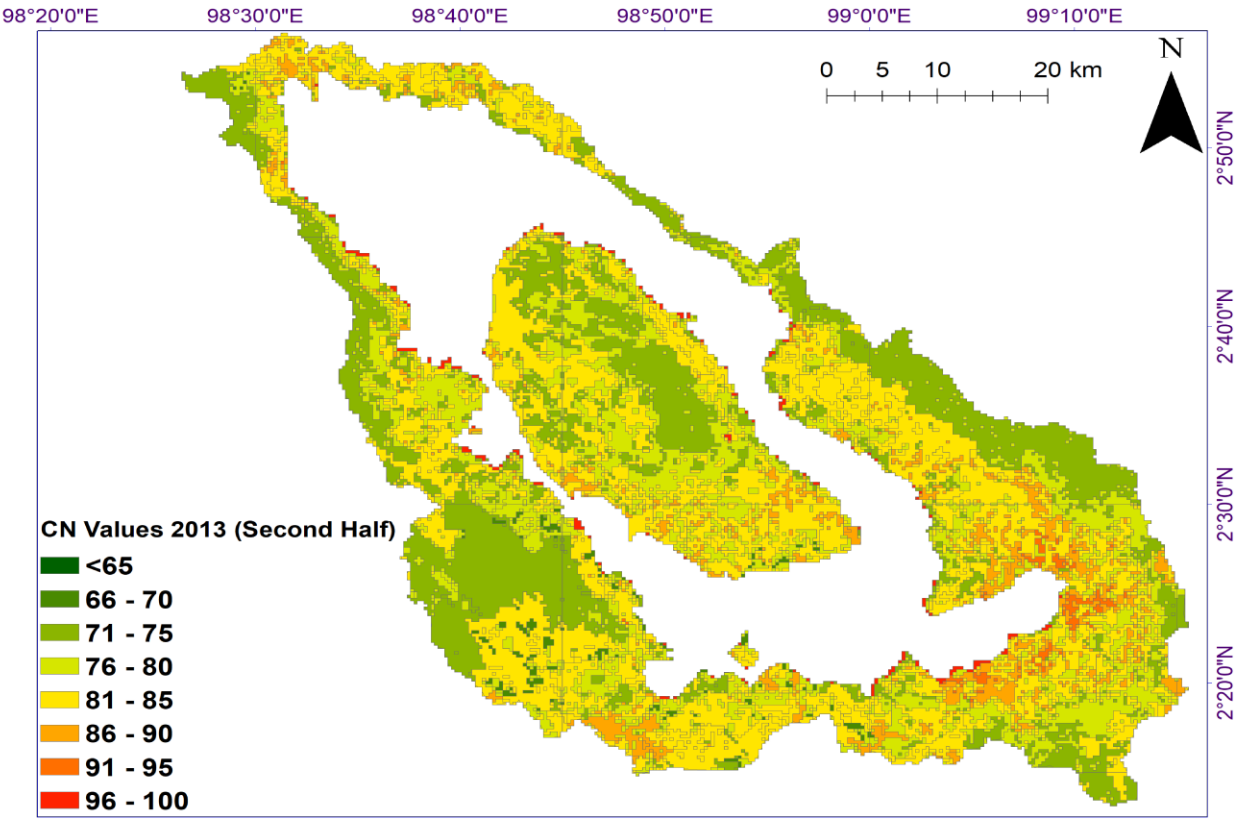

Figure 65 Curve Number (CN) Values of Toba Catchment in 2013 (Second Half)

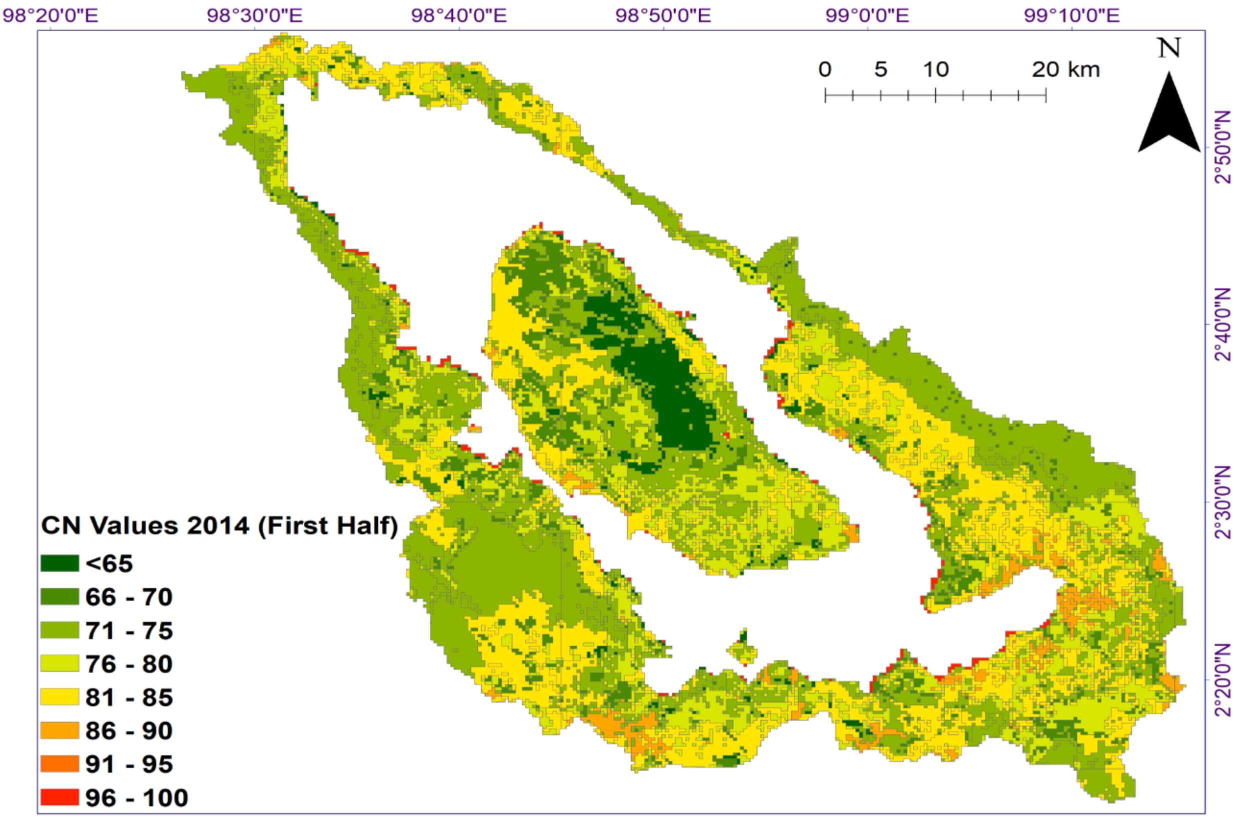

Figure 66 Curve Number (CN) Values of Toba Catchment in 2014 (First Half)

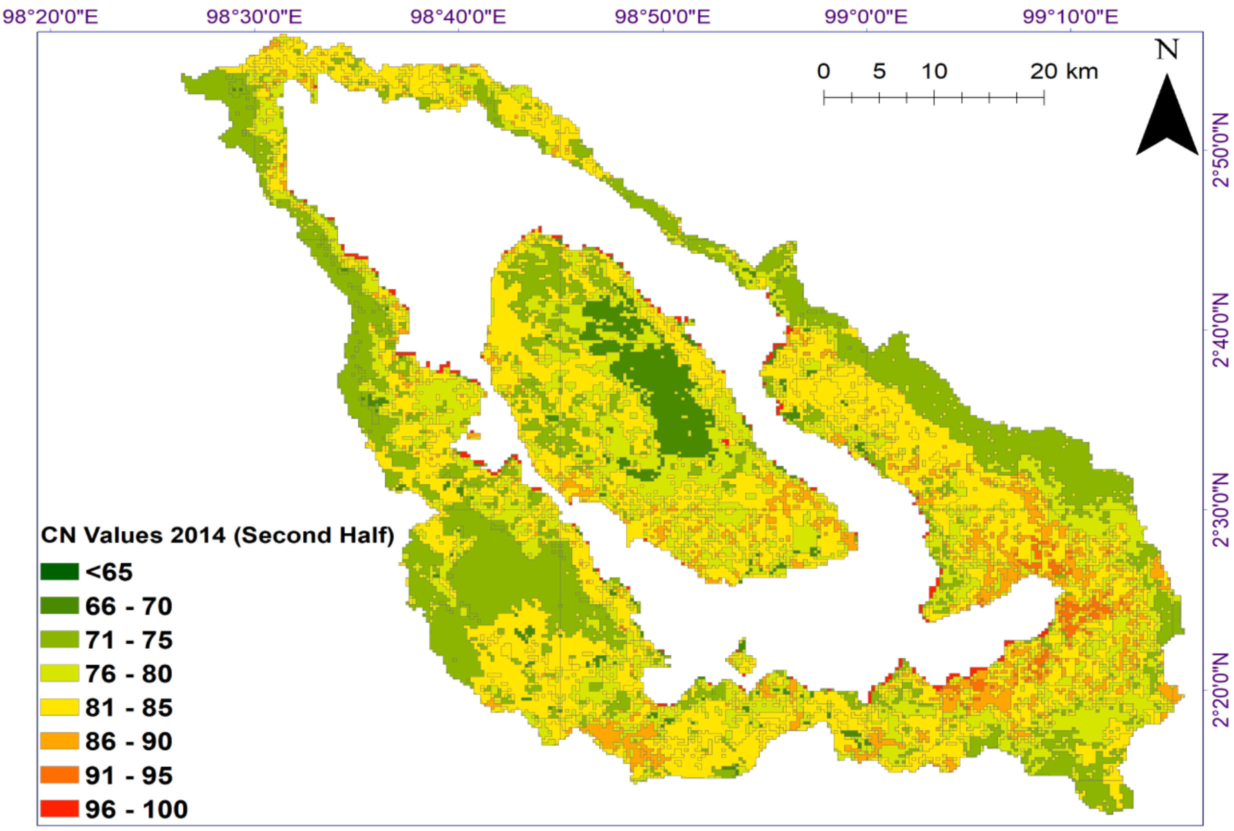

Figure 67 Curve Number (CN) Values of Toba Catchment in 2014 (Second Half)

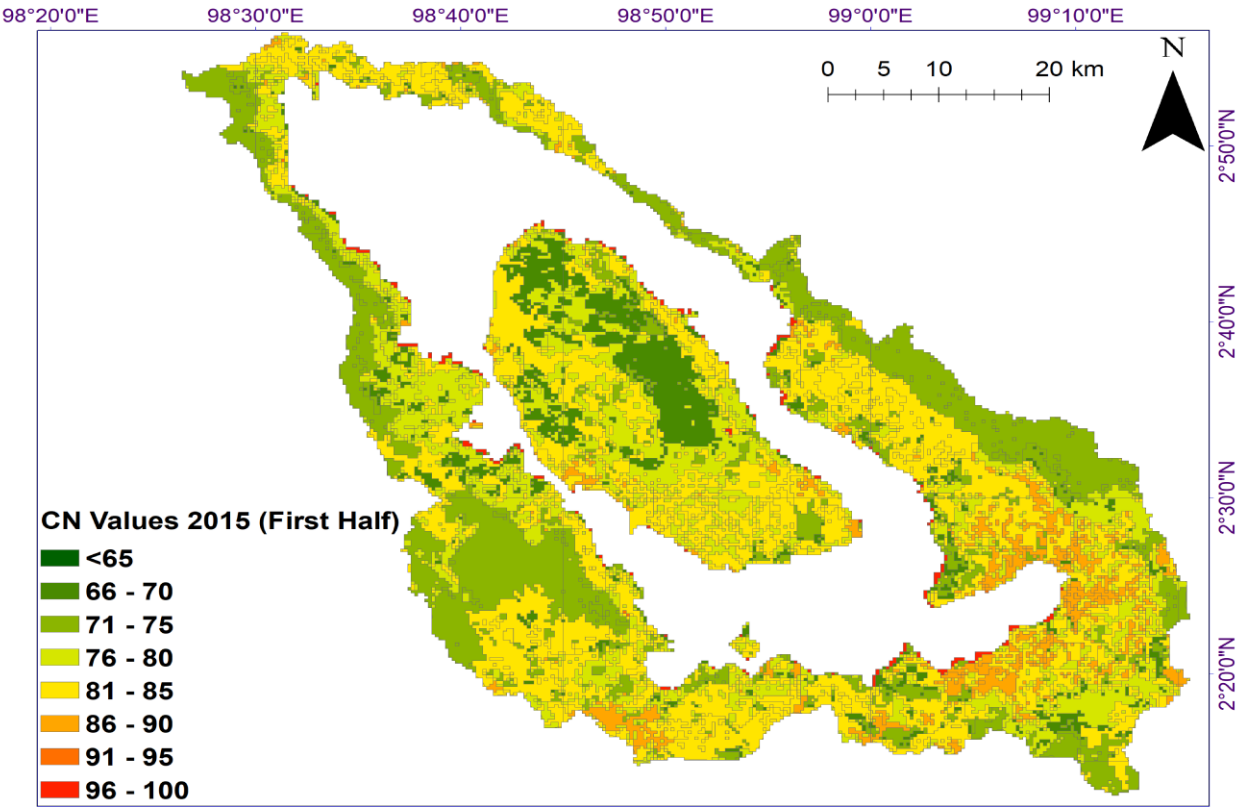

Figure 68 Curve Number (CN) Values of Toba Catchment in 2015 (First Half)

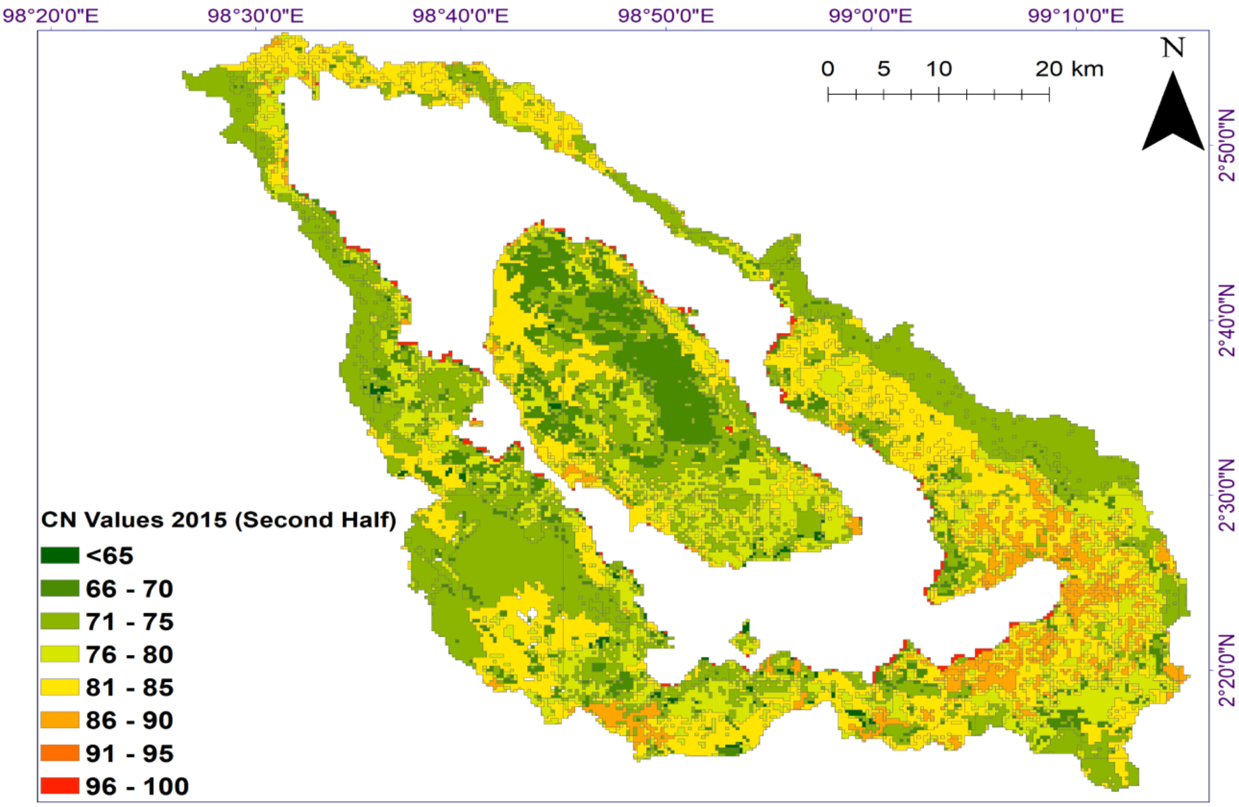

Figure 69 Curve Number (CN) Values of Toba Catchment in 2015 (Second Half)

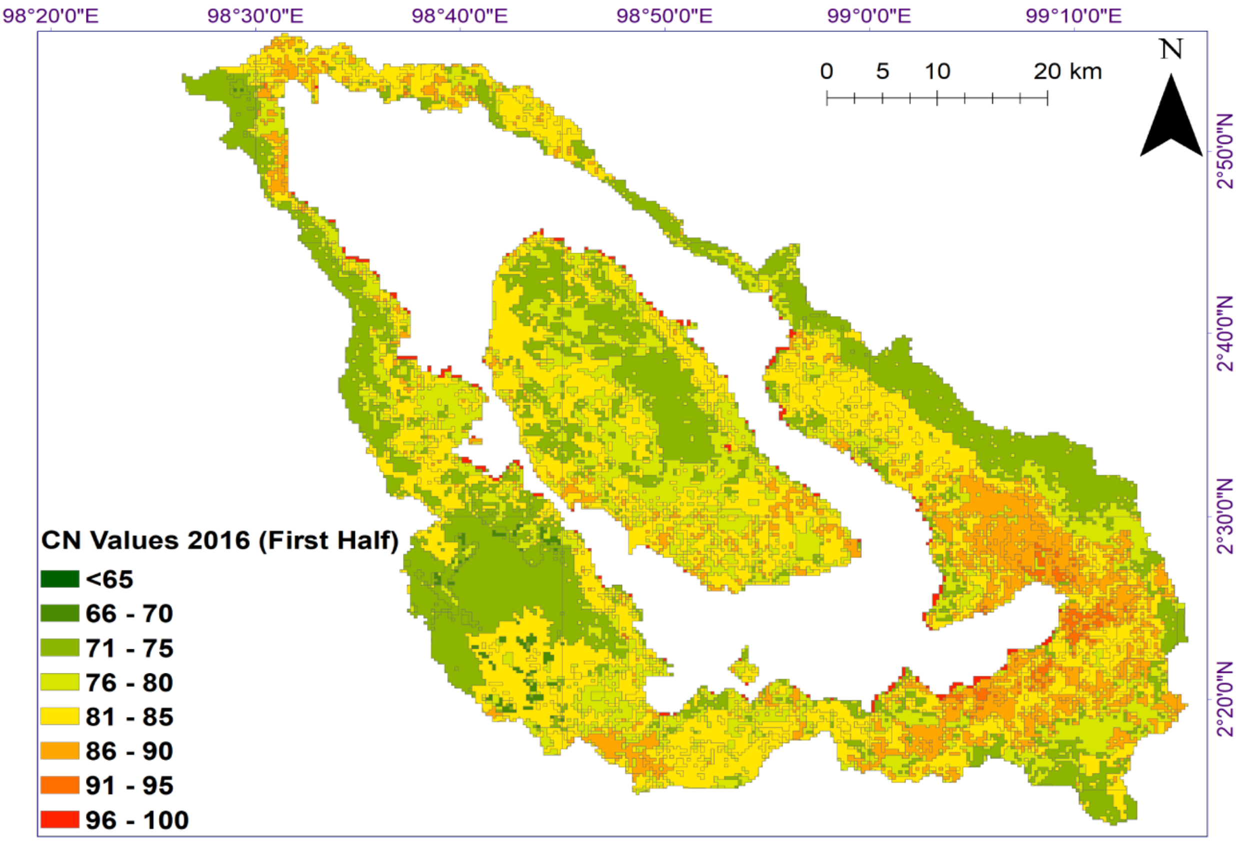

Figure 70 Curve Number (CN) Values of Toba Catchment in 2016 (First Half)

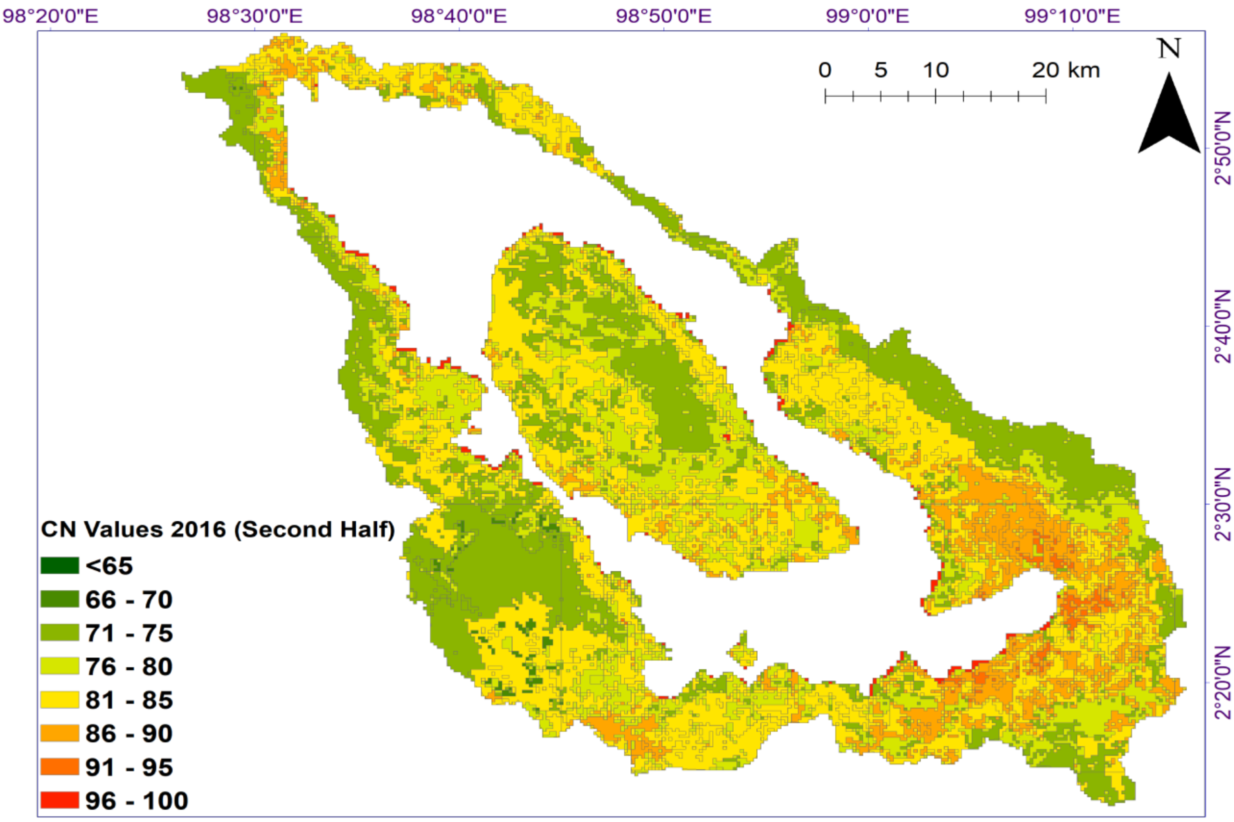

Figure 71 Curve Number (CN) Values of Toba Catchment in 2016 (Second Half)

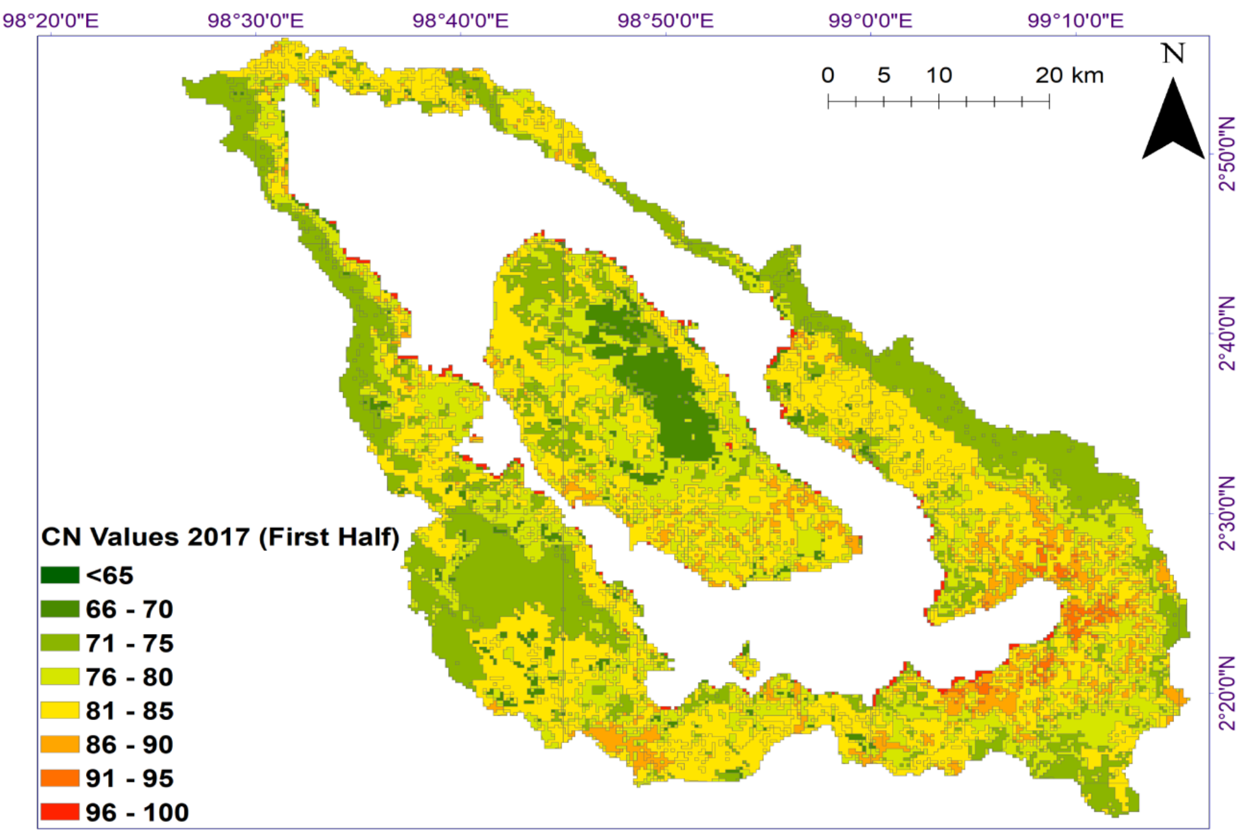

Figure 72 Curve Number (CN) Values of Toba Catchment in 2017 (First Half)

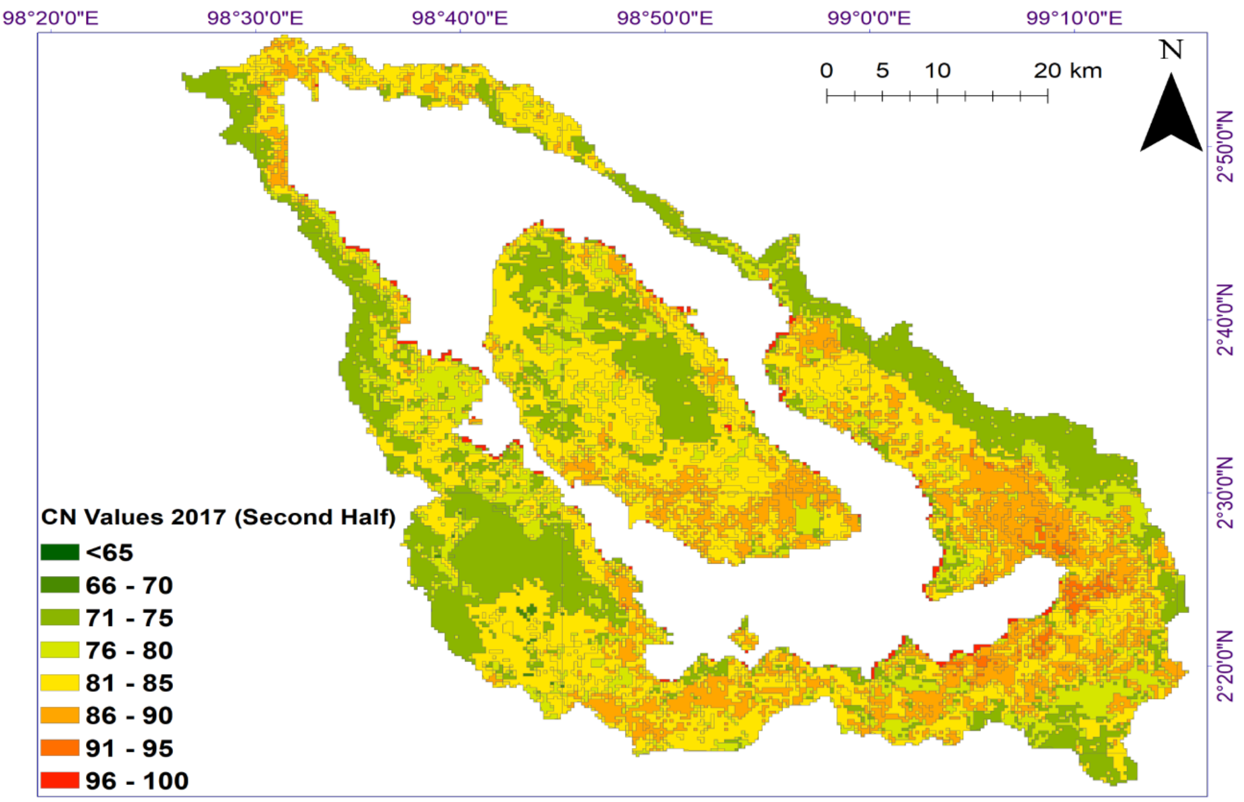

Figure 73 Curve Number (CN) Values of Toba Catchment in 2017 (Second Half)

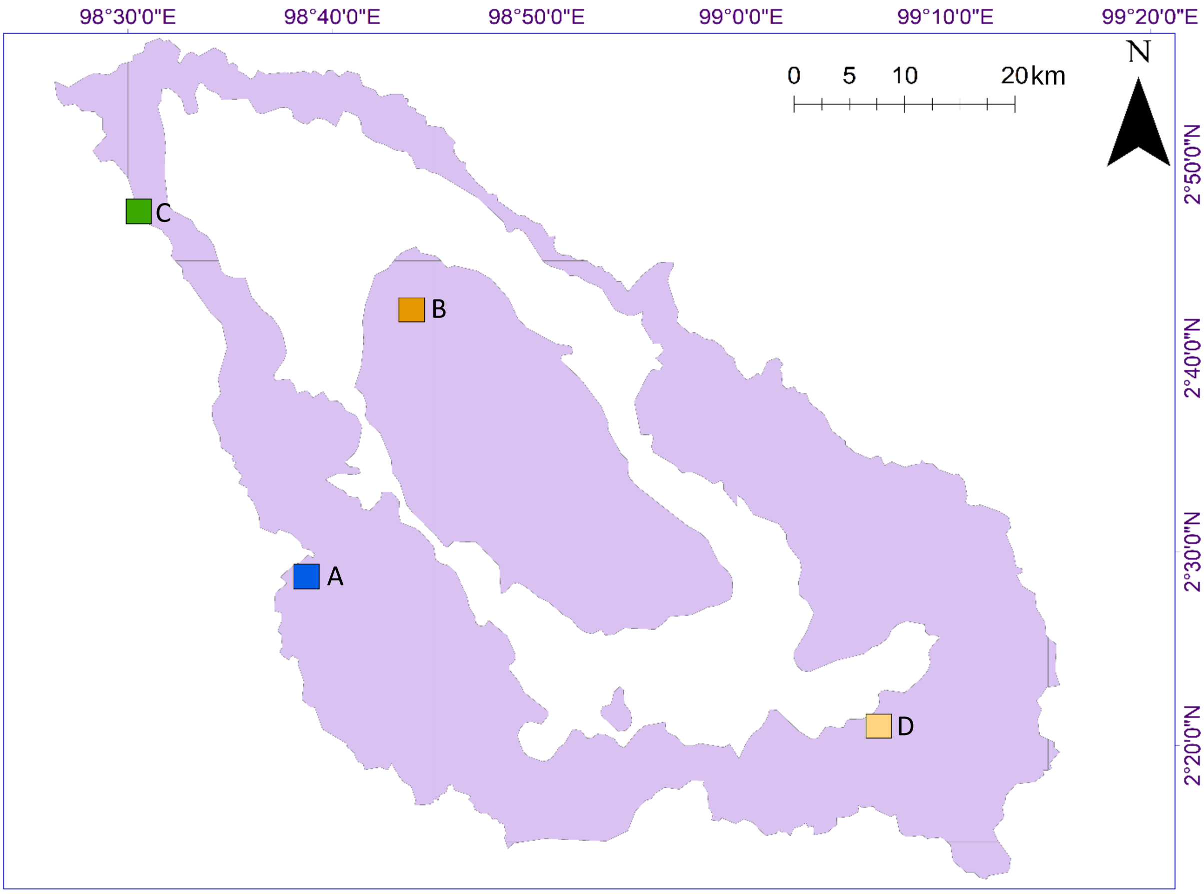

Figure 74 Map of Selected Points with Different Characteristics in Toba Catchment

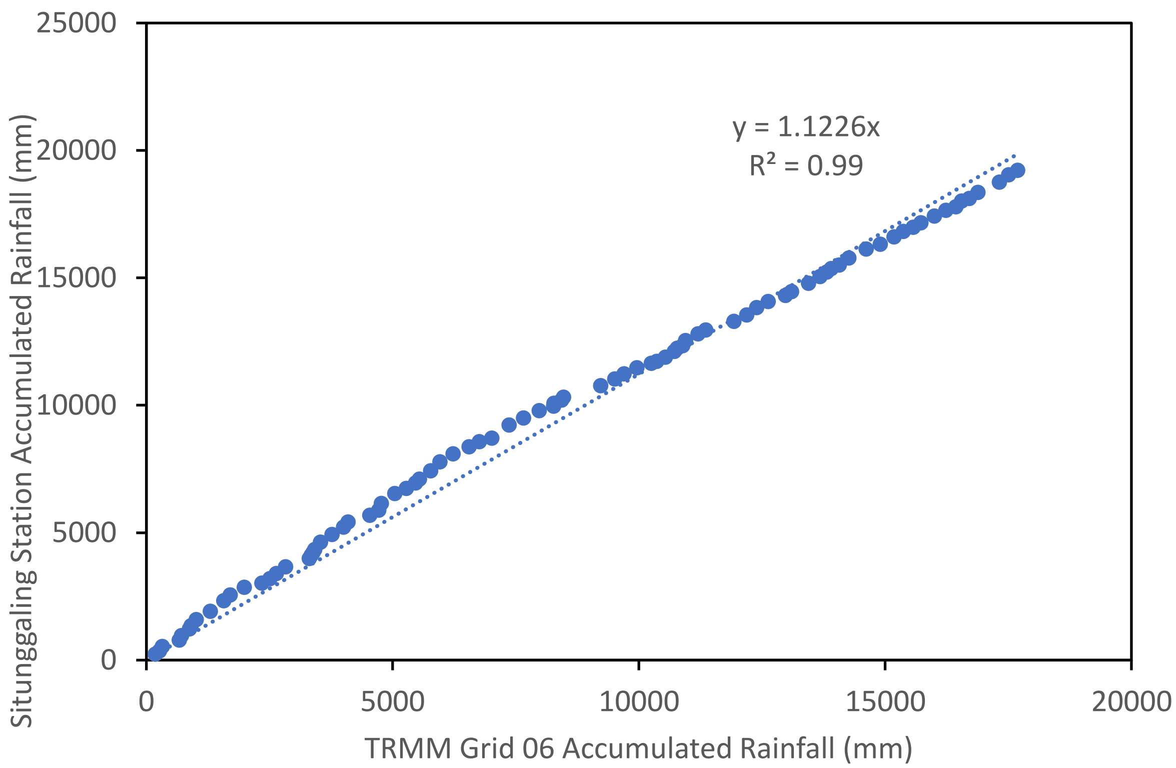

Figure 75 Precipitation Validation with Siregar (2010) (Situnggaling Station)

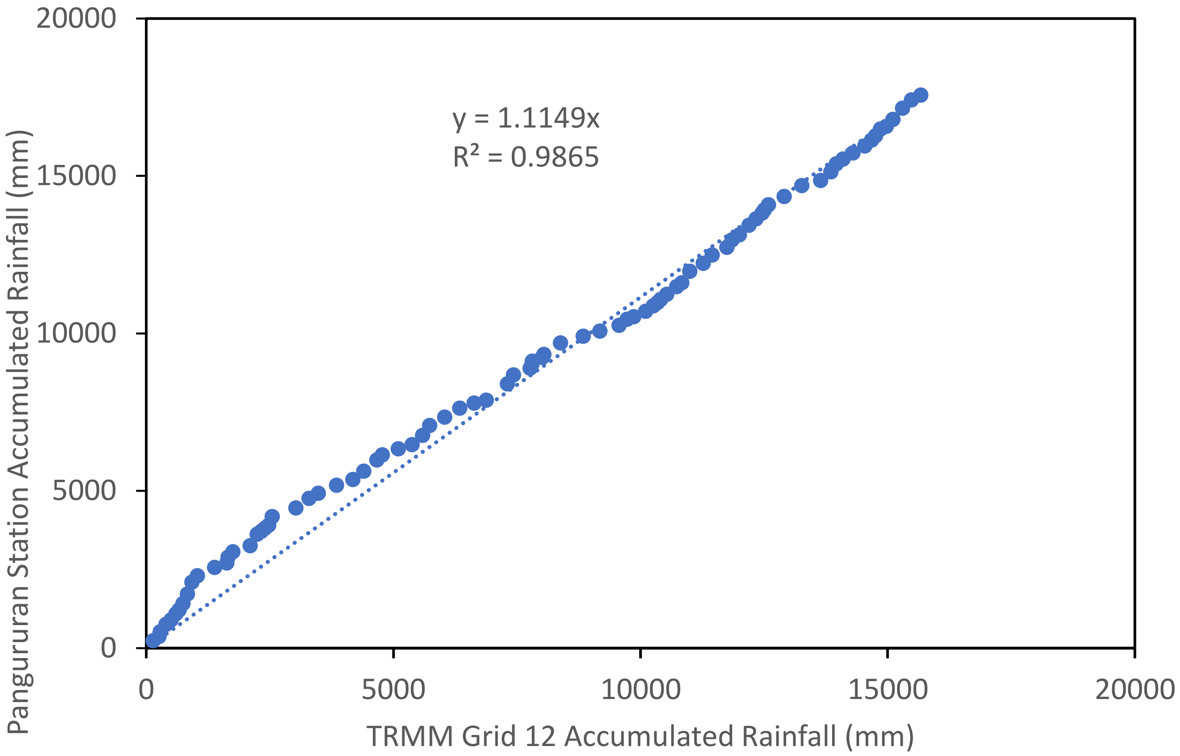

Figure 76 Precipitation Validation with Siregar (2010) (Pangururan Station)

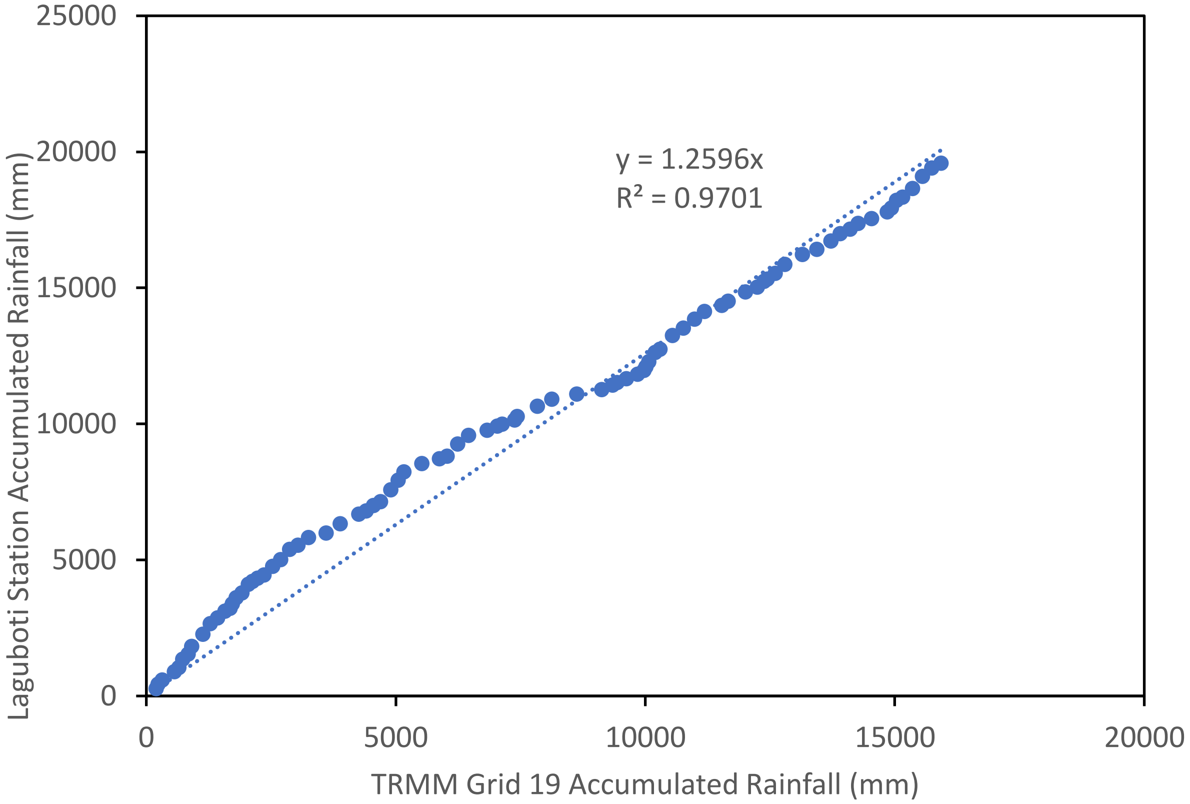

Figure 77 Precipitation Validation with Siregar (2010) (Laguboti Station)

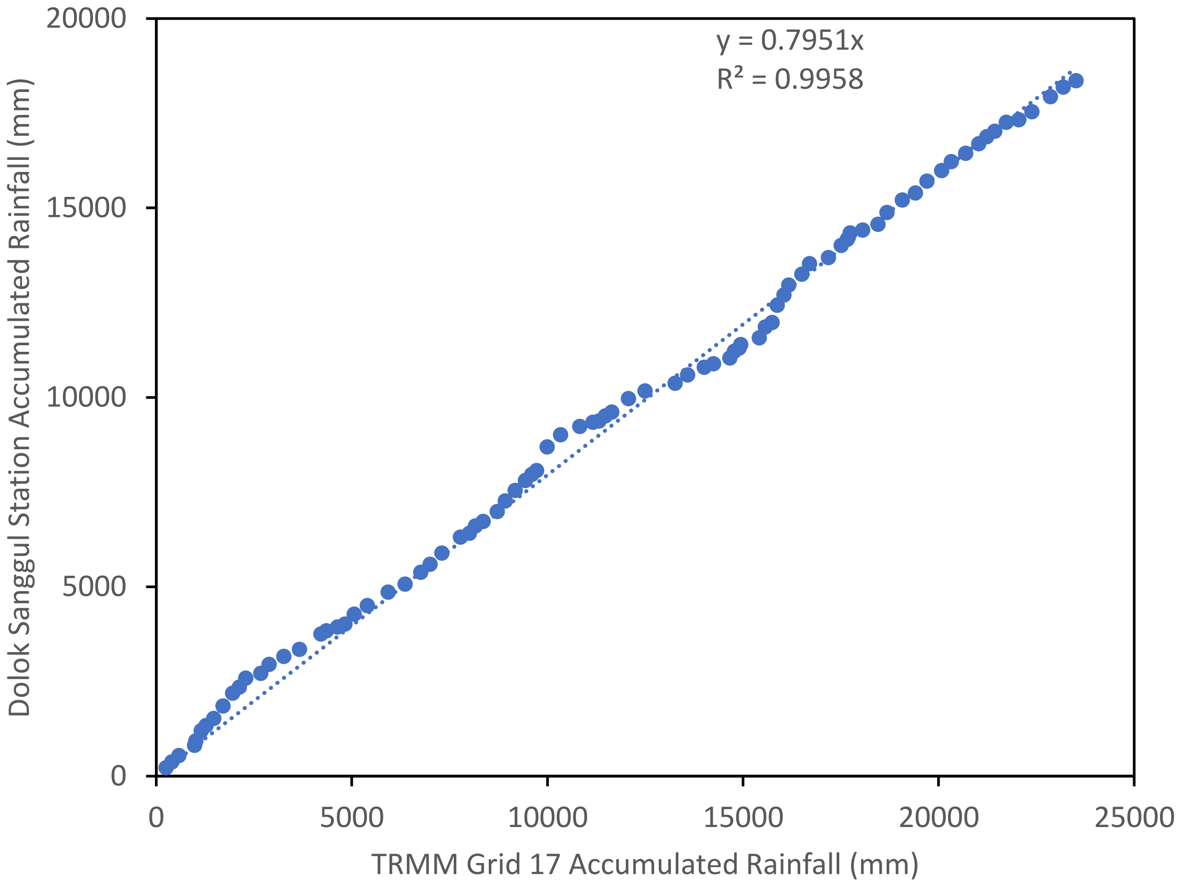

Figure 78 Precipitation Validation with Siregar (2010) (Dolok Sanggul Station)

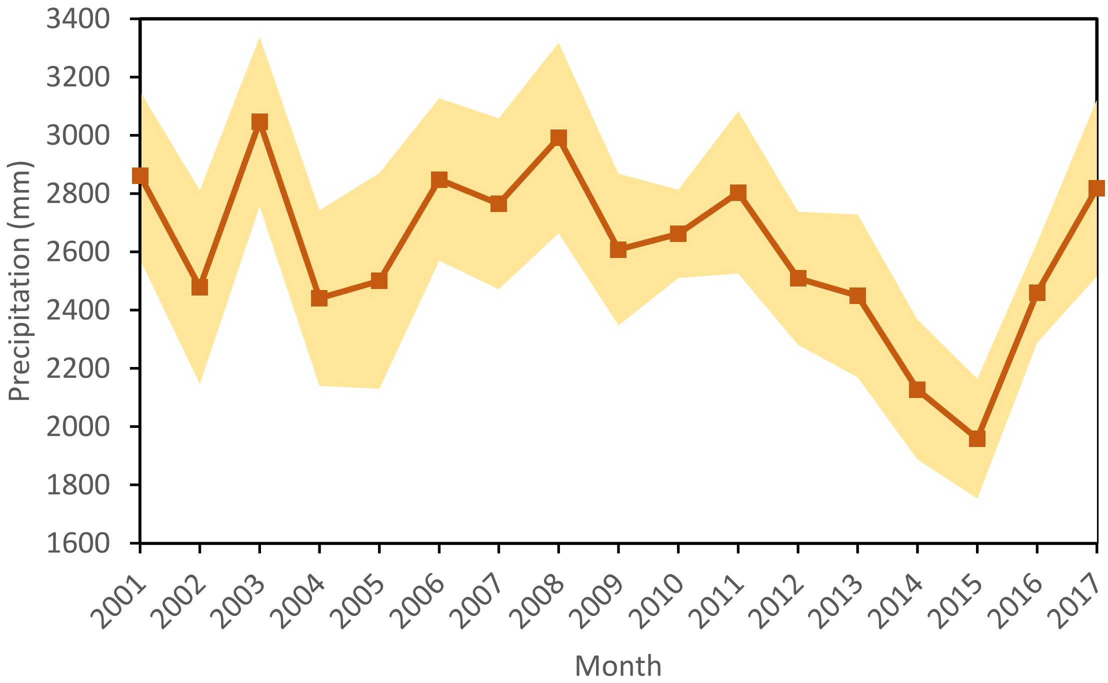

Figure 79 Annual Precipitation in Toba Catchment (2001-2017)

Red line represents precipitation trends whereas yellow area represents error range of precipitation trends.

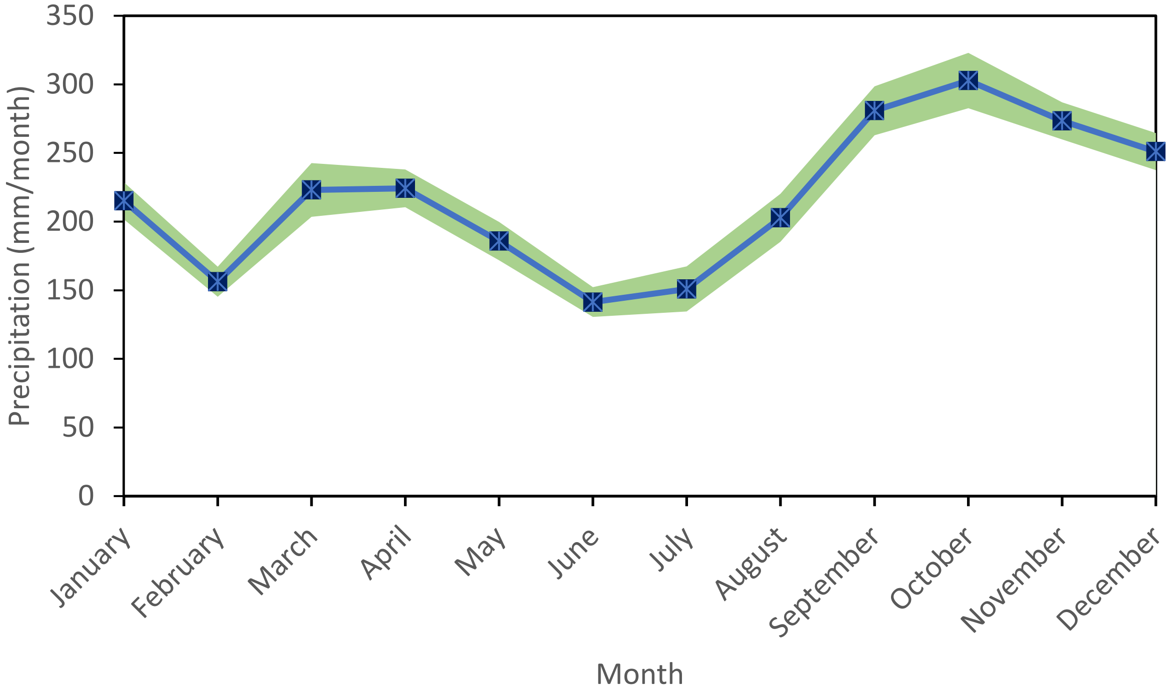

Figure 80 Average Monthly Precipitation in Toba Catchment

Blue line represents precipitation trends whereas green area represents error range of precipitation trends.

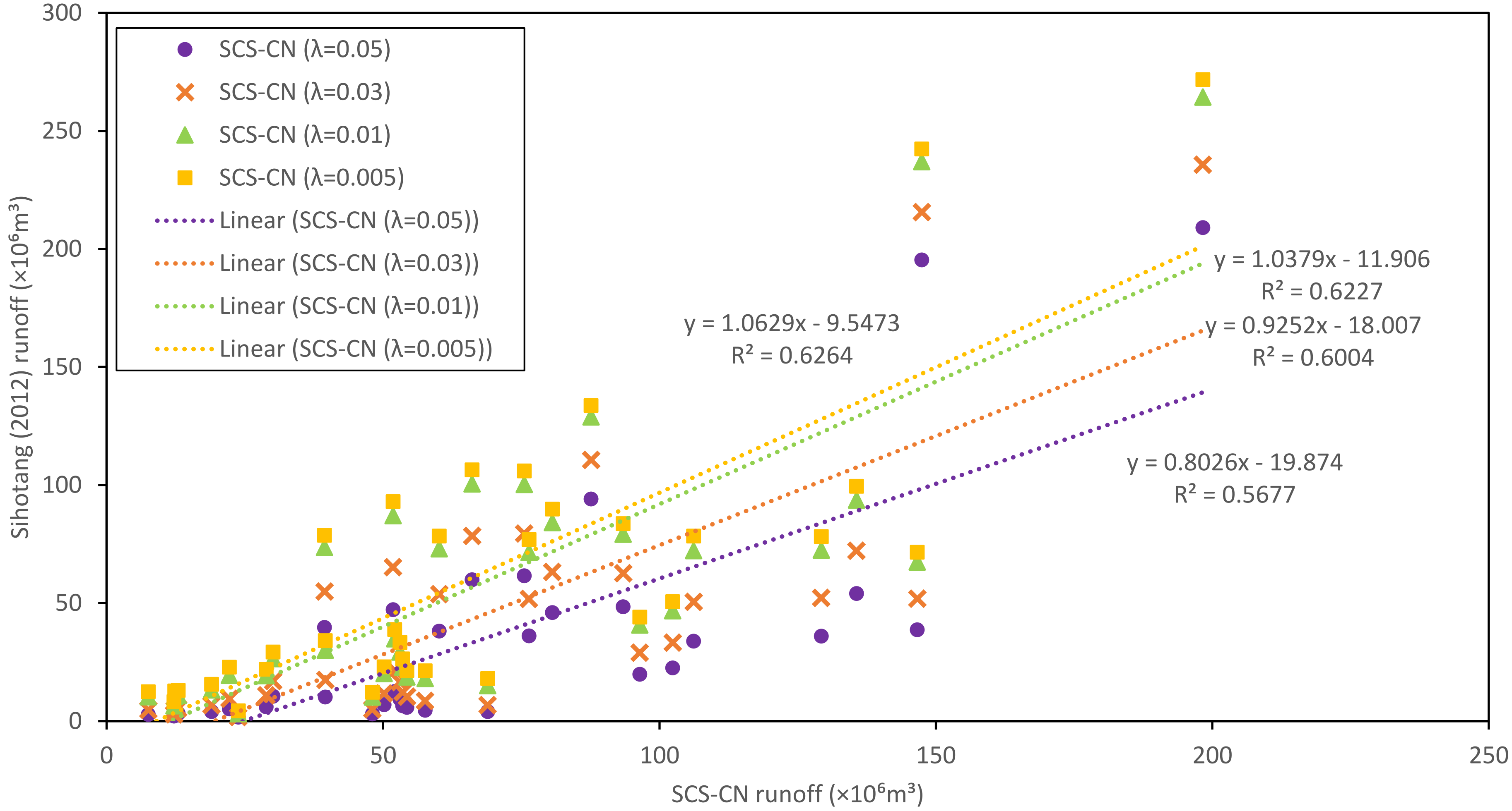

Figure 81 Direct Runoff Coefficient Calibration with Sihotang (2012)

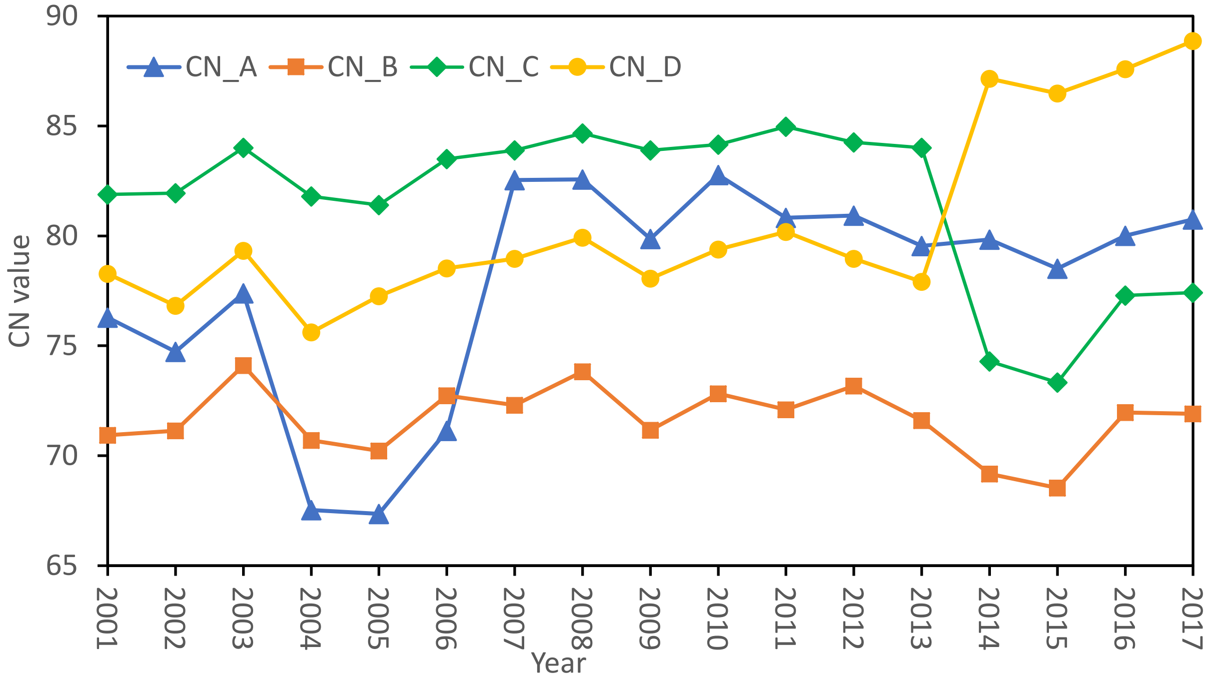

Figure 82 Curve Number (CN) Trends in Specific Areas in Toba Catchment (2001-2017)

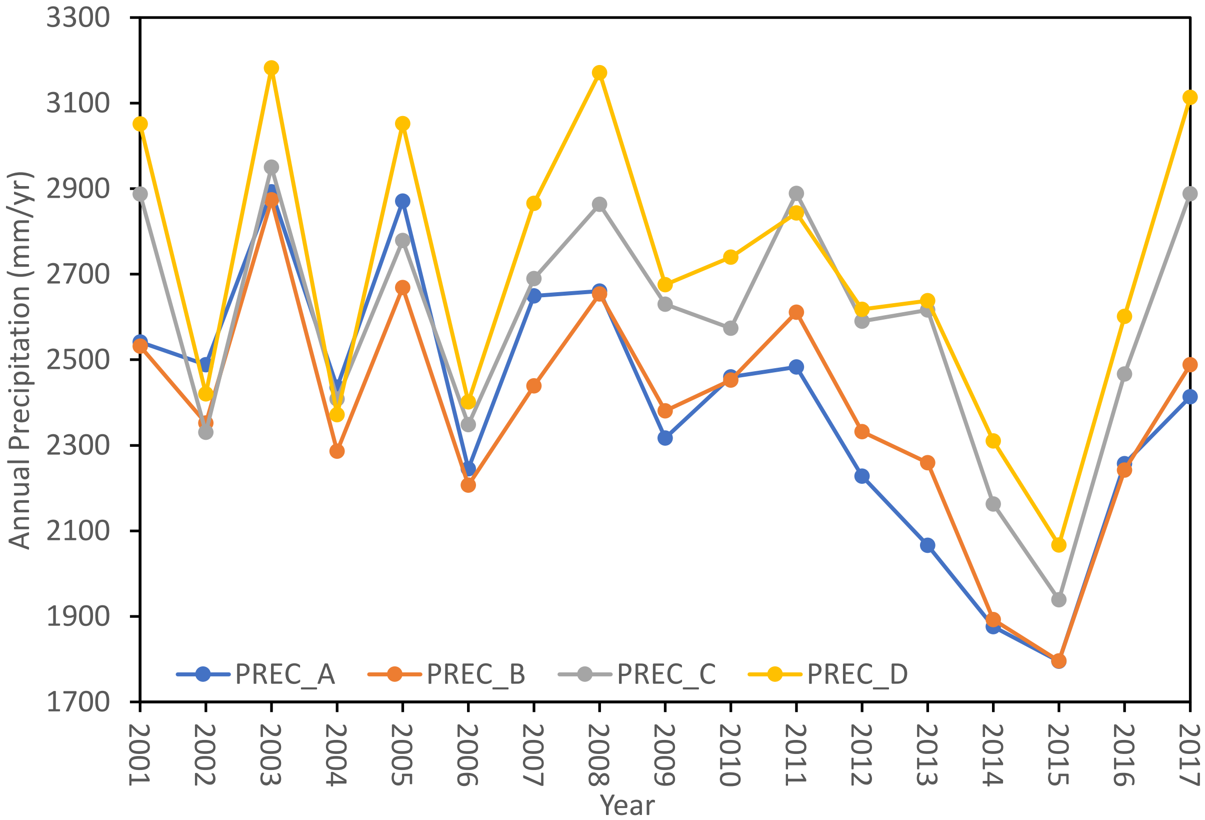

Figure 83 Precipitation trends in Specific Areas in Toba Catchment (2001-2017)

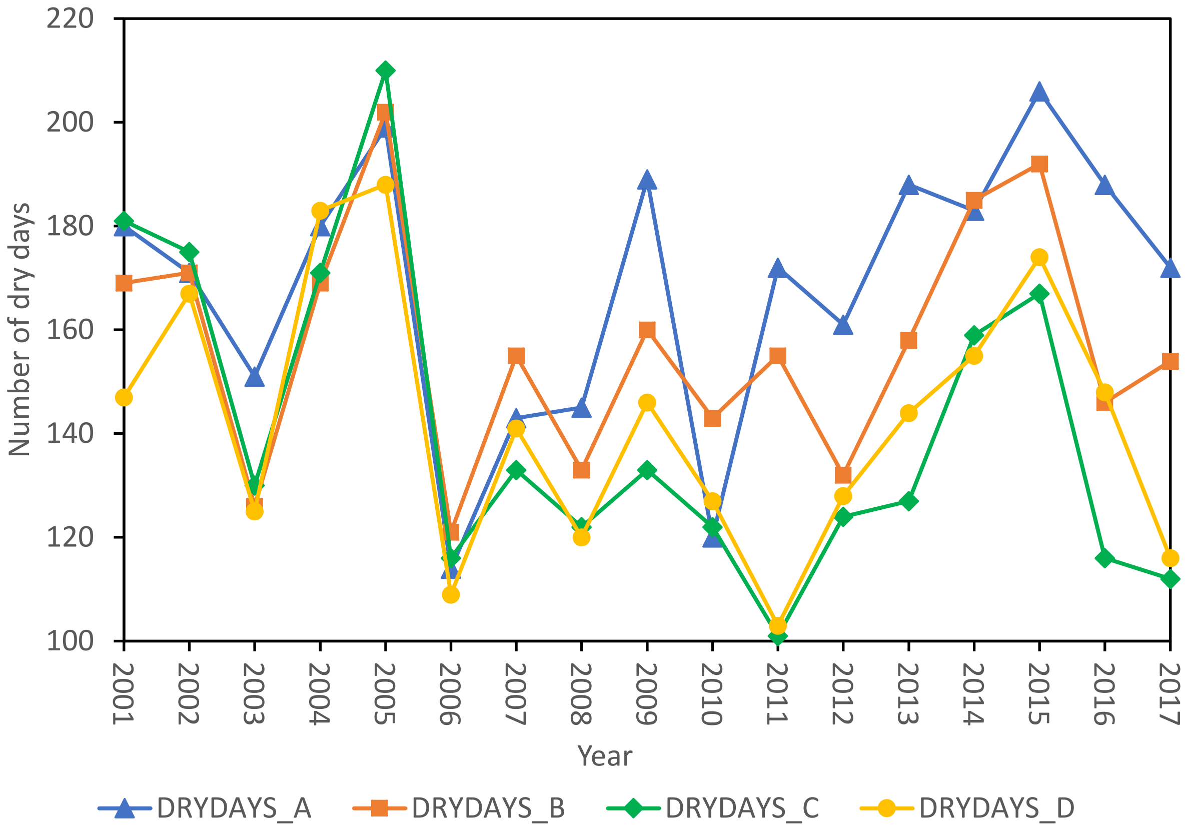

Figure 84 Number of Days with Dry Soil Condition (AMC I) in Specific Areas in Toba Catchment (2001-2017)

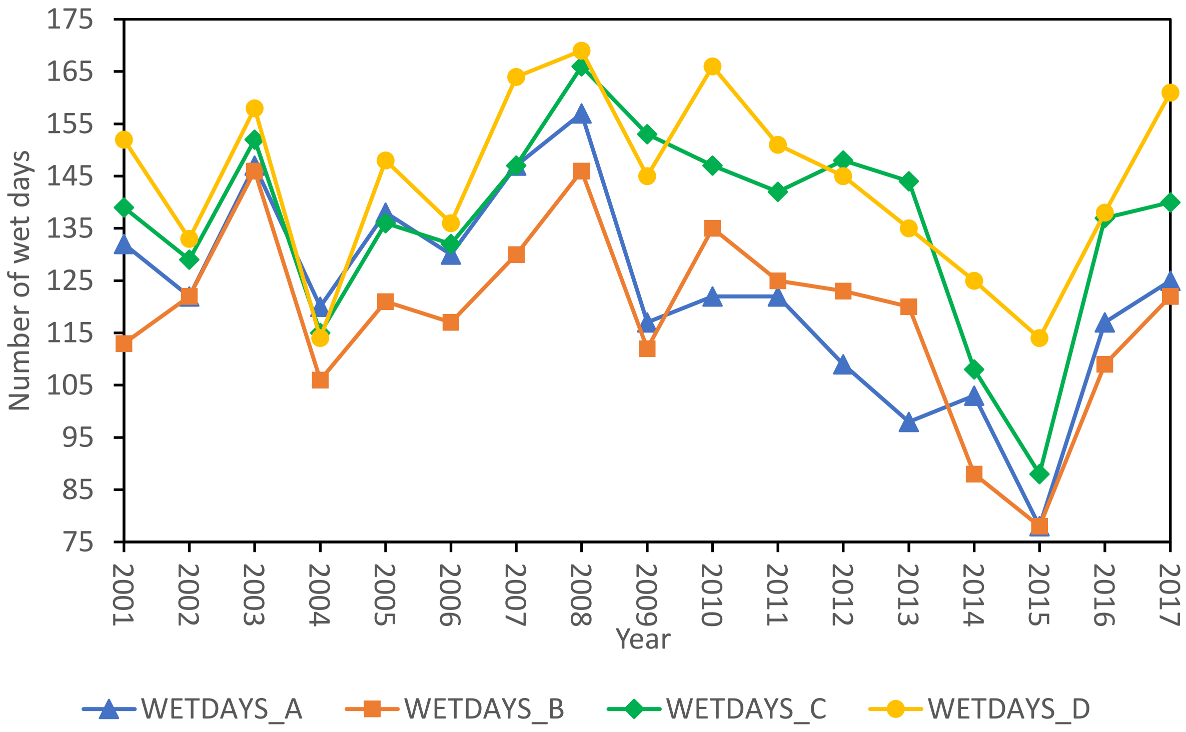

Figure 85 Number of Days with Wet Soil Condition (AMC III) in Specific Areas in Toba Catchment (2001-2017)

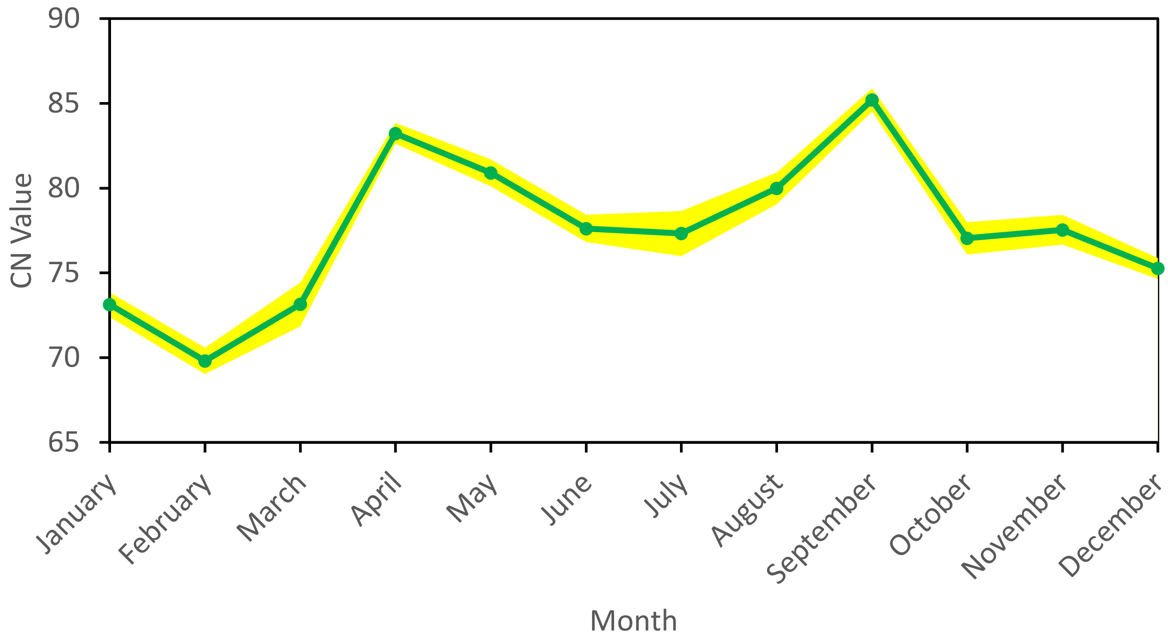

Figure 86 Average Monthly Curve Number (CN) in Toba Catchment (2001-2017)

Light green line indicates CN trends while yellow area represents error range of CN trends.

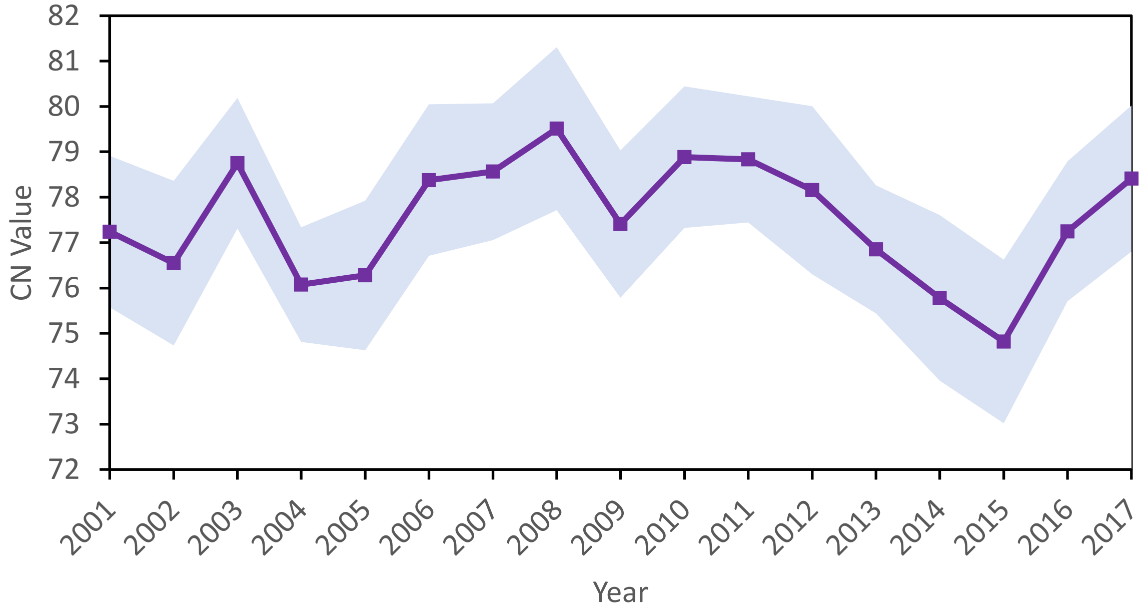

Figure 87 Annual Curve Number (CN) Trends in Toba Catchment (2001-2017)

Purple line indicates CN trends while light blue area represents error range of CN trends.

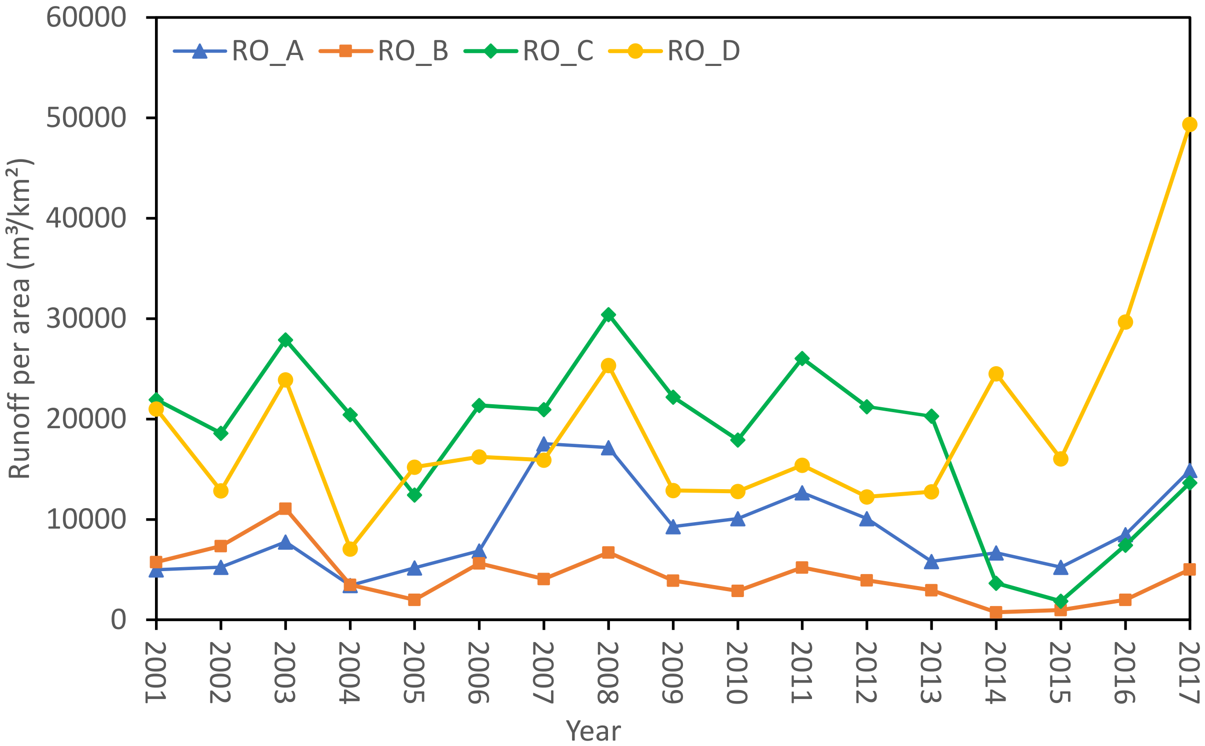

Figure 88 Direct Runoff Trends in Specific Areas in Toba Catchment (2001-2017)

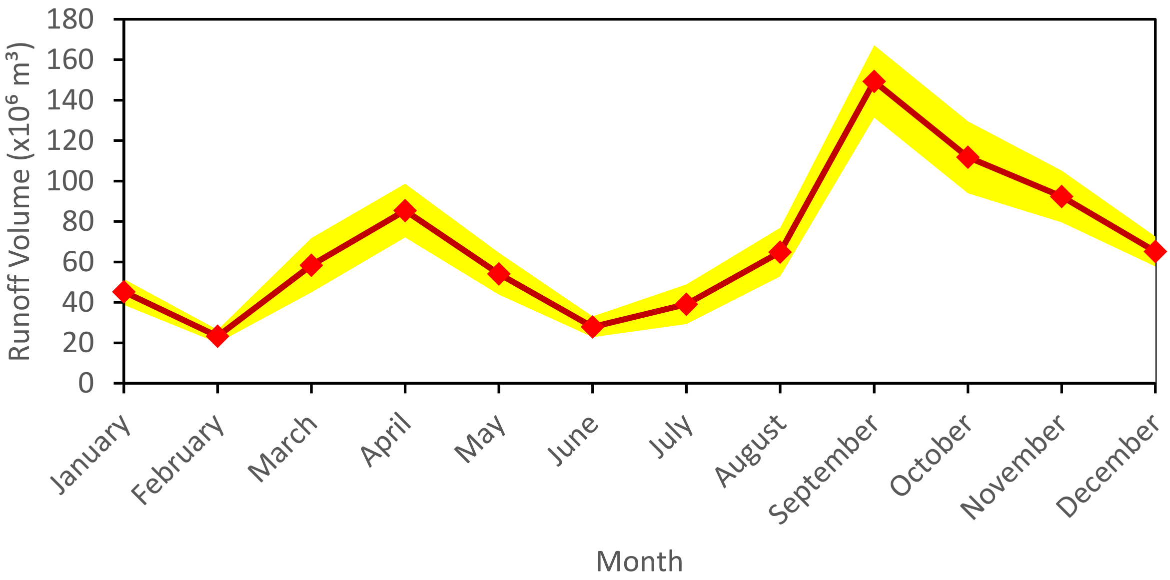

Figure 89 Monthly Direct Runoff Trends in Toba Catchment (2001-2017)

Red line indicates direct runoff trends while yellow area represents error range of direct runoff trends.

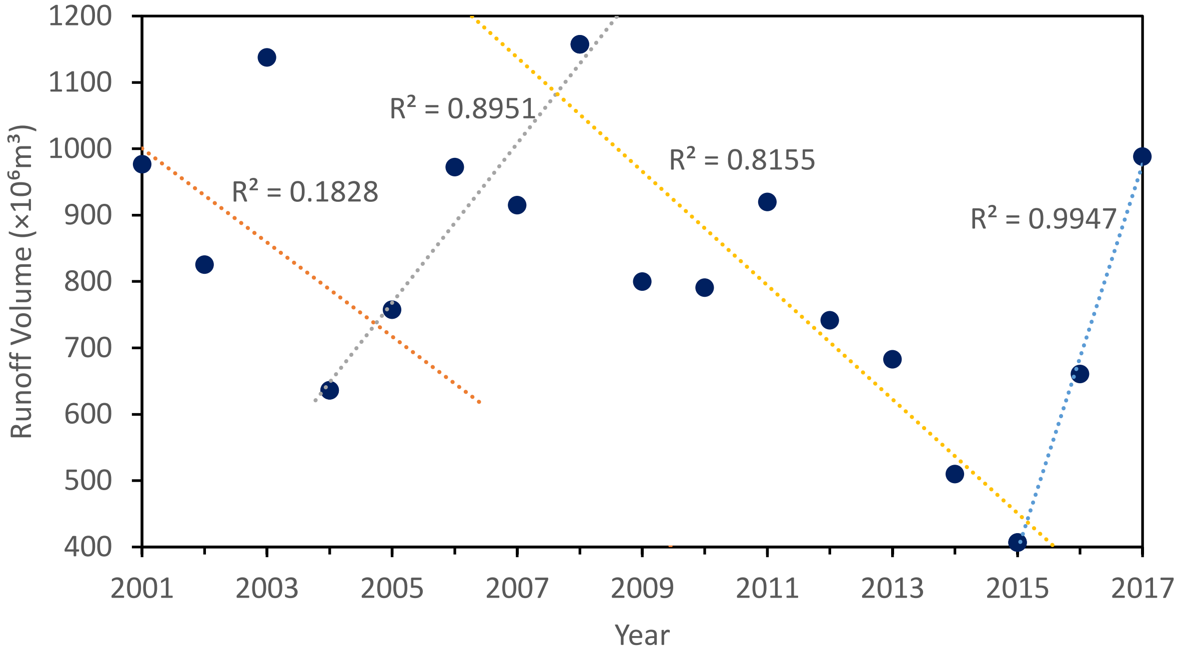

Figure 90 Annual Direct Runoff Trends in Toba Catchment (2001-2017)

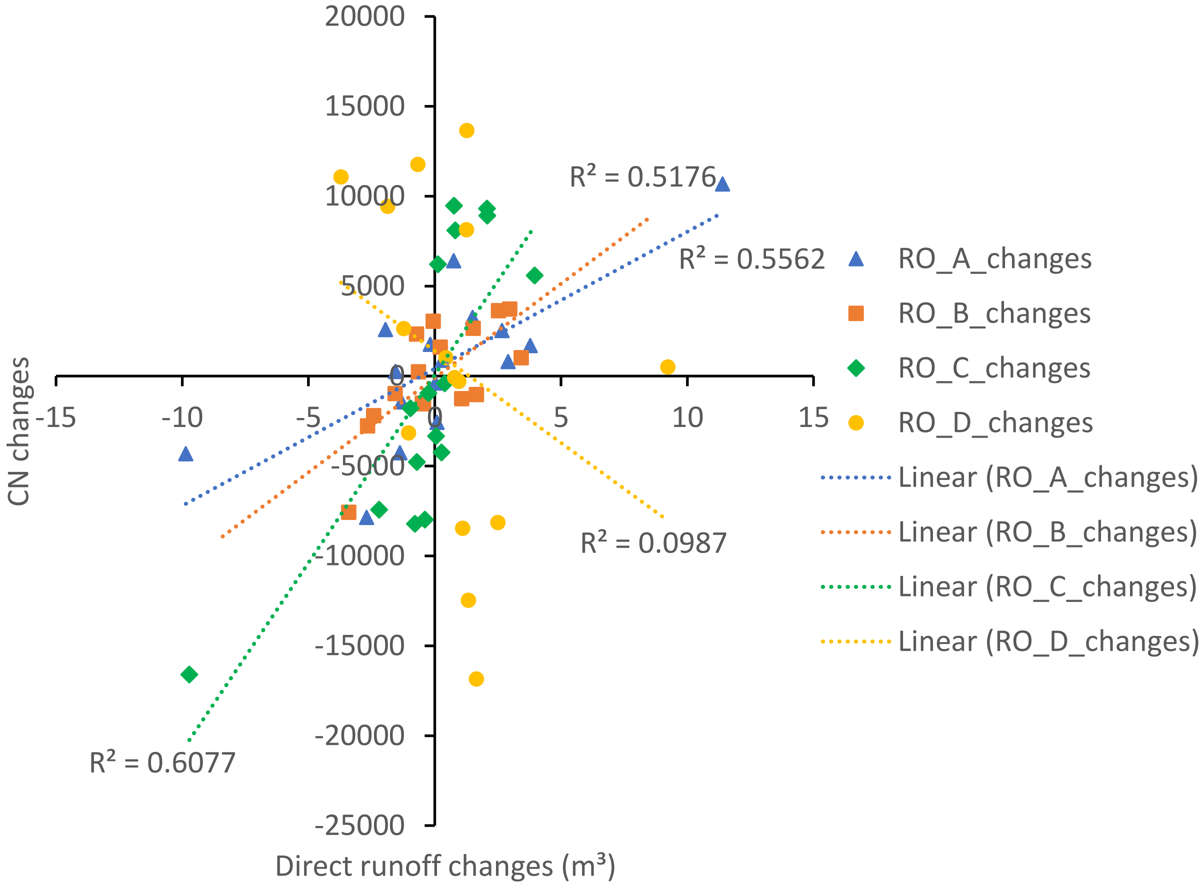

Figure 91 Curve Number (CN) Changes against Direct Runoff Changes in Specific Areas

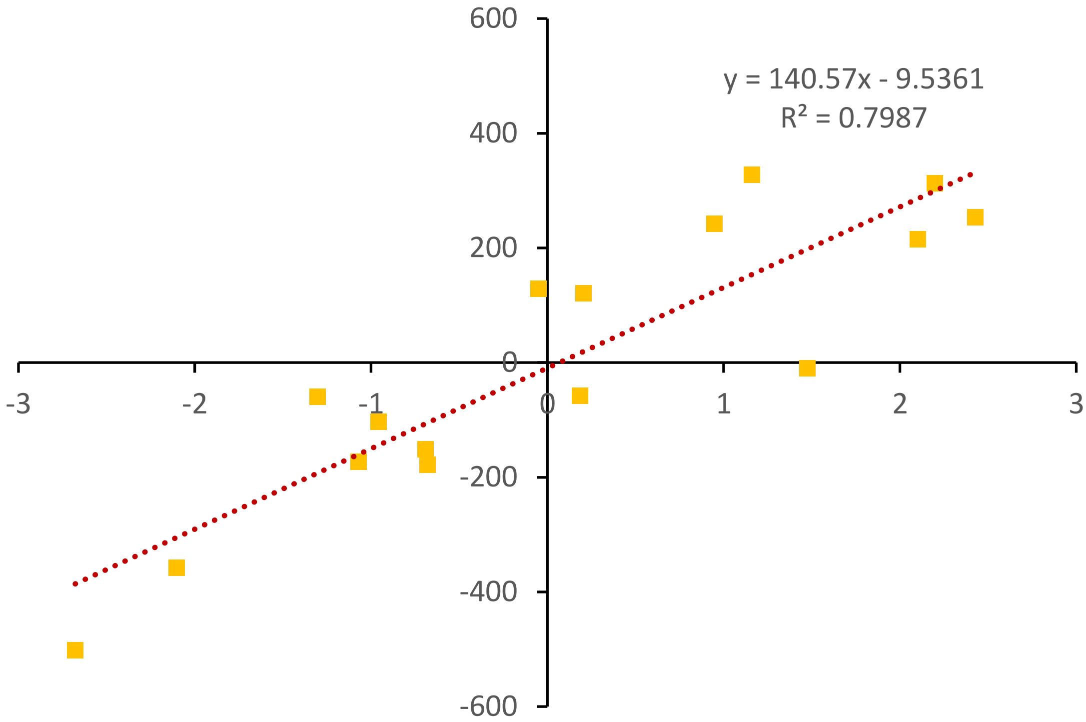

Figure 92 Curve Number (CN) Changes against Direct Runoff Changes in Overall Toba Catchment

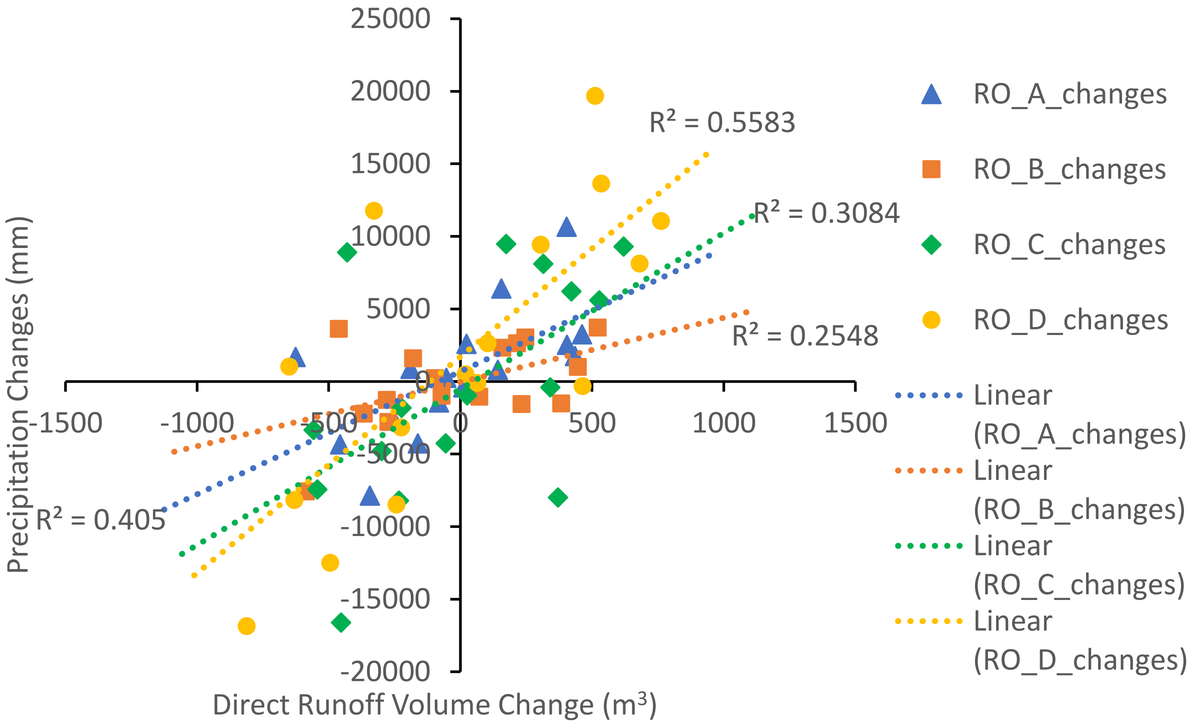

Figure 93 Precipitation Changes against Direct Runoff Changes in Specific Areas

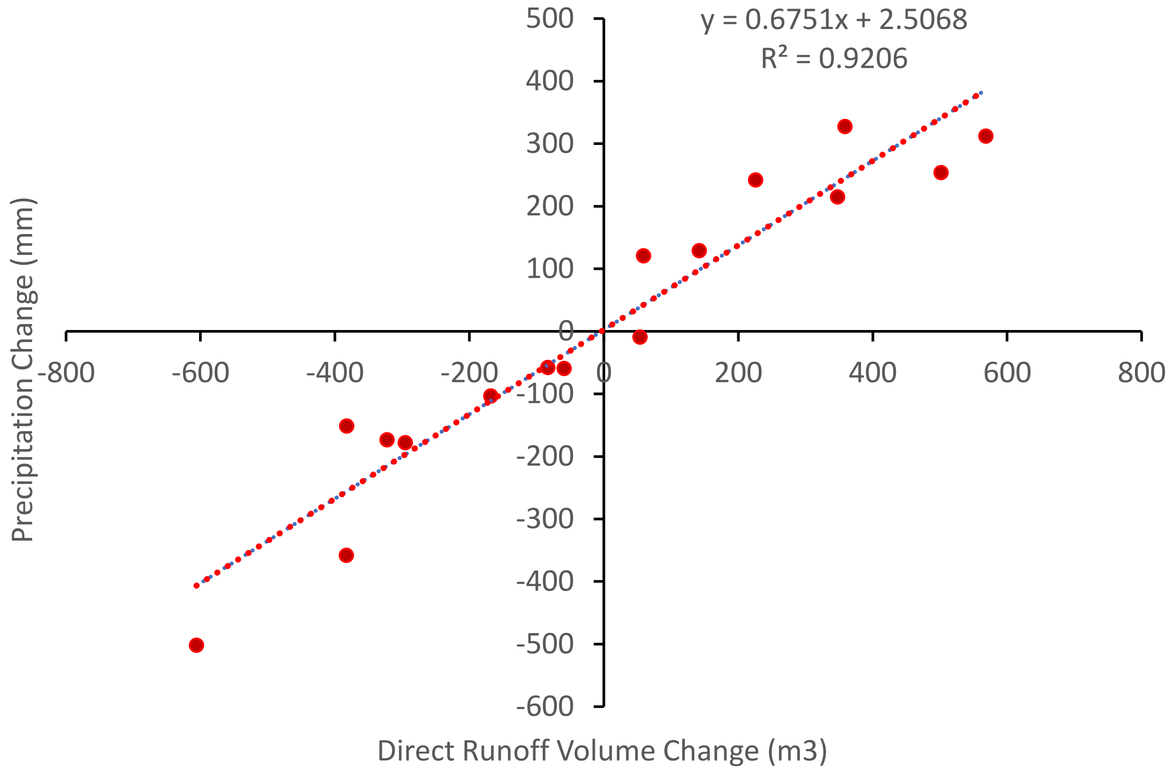

Figure 94 Precipitation Changes against Direct Runoff Changes in Overall Toba Catchment

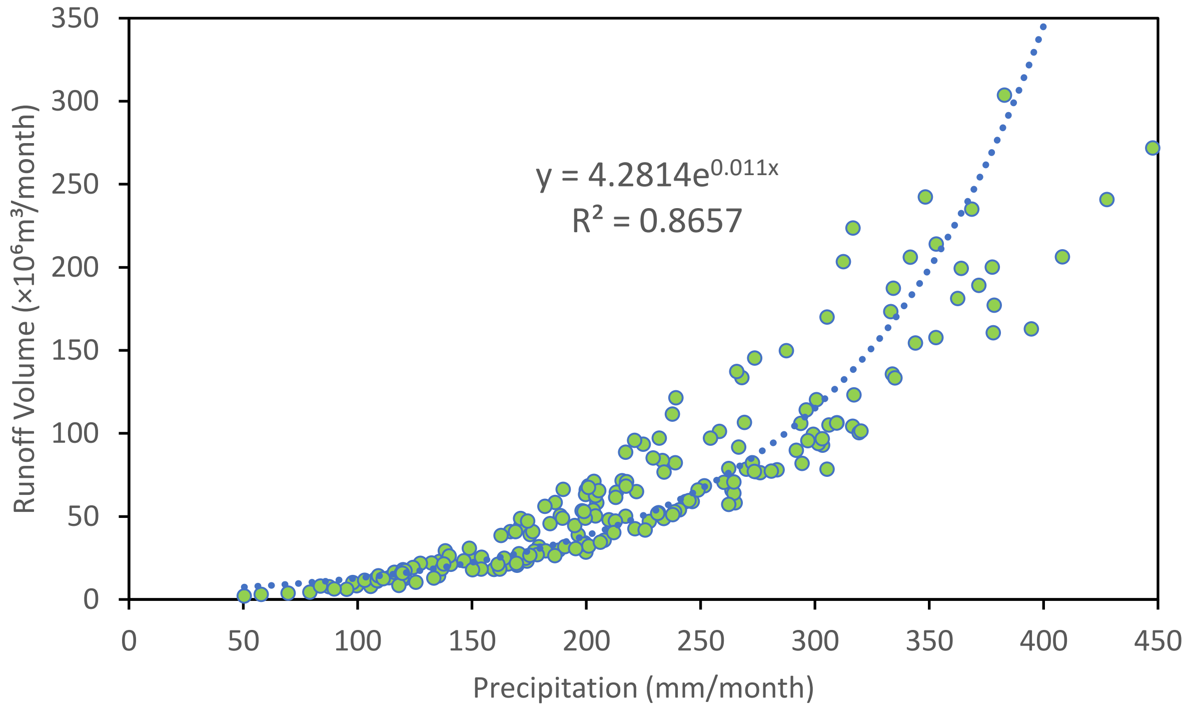

Figure 95 Relationship between Precipitation and Direct Runoff in Toba Catchment

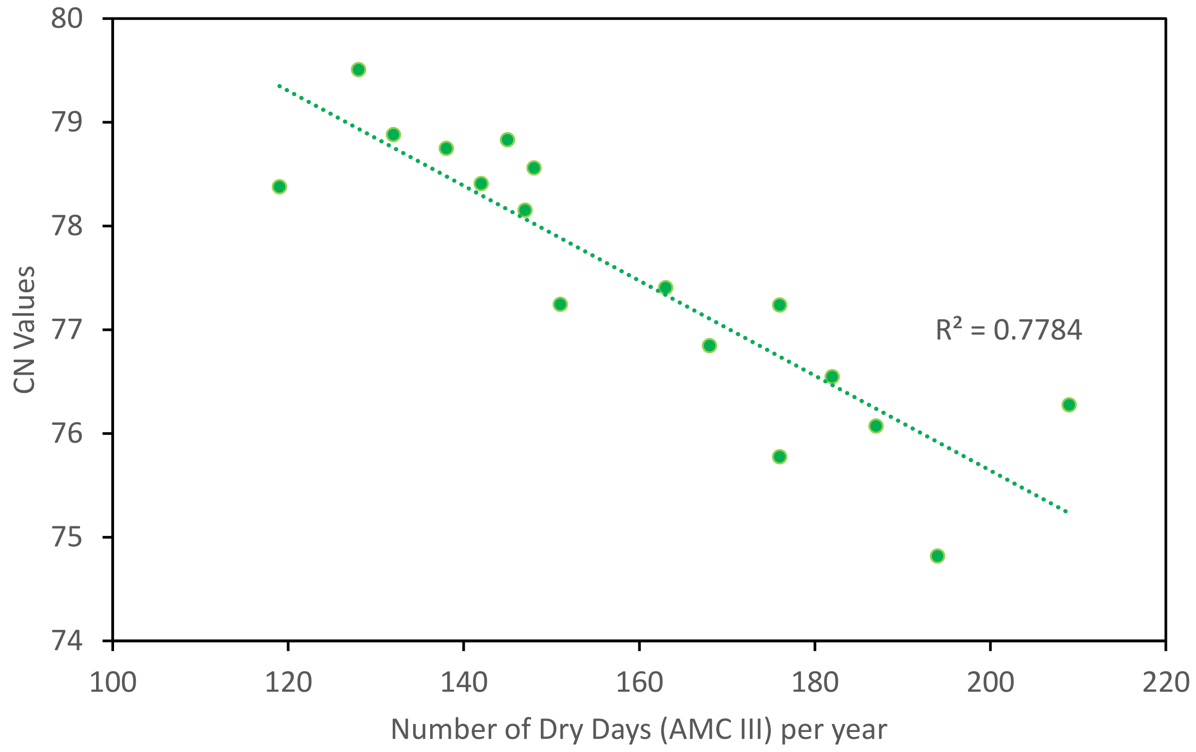

Figure 96 Number of Dry Days (AMC I) per year against CN Values

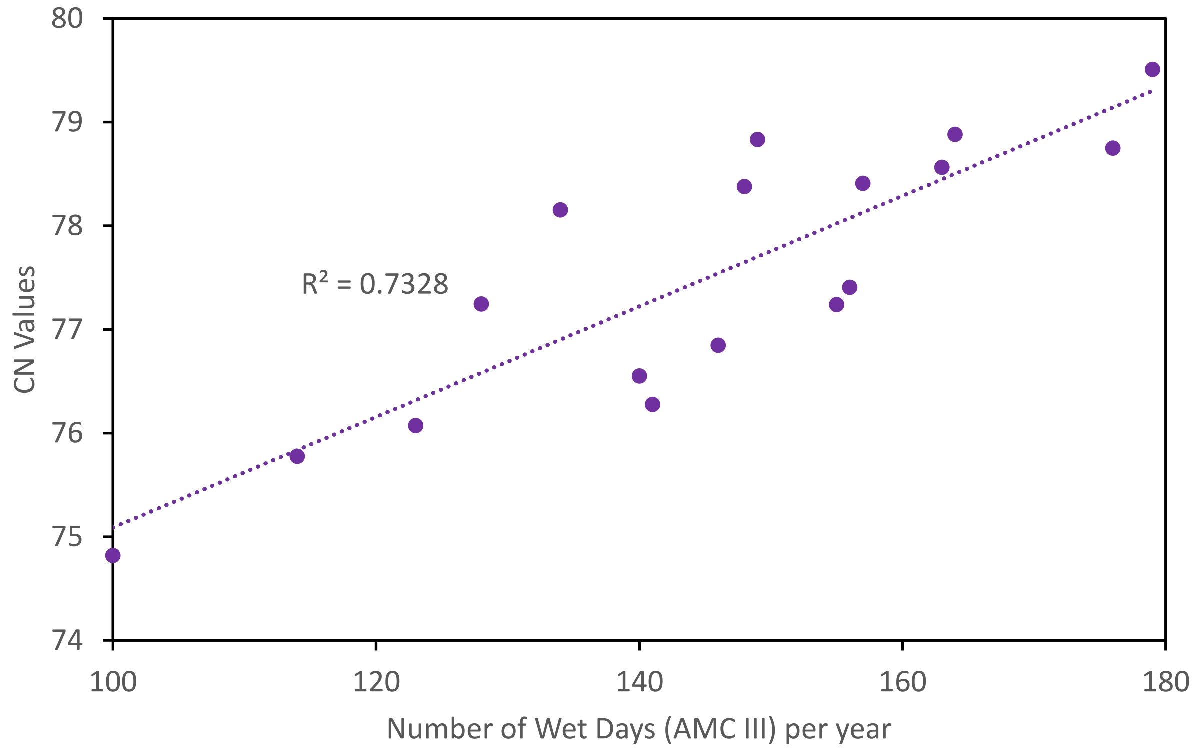

Figure 97 Number of Wet Days (AMC III) per year against CN Values

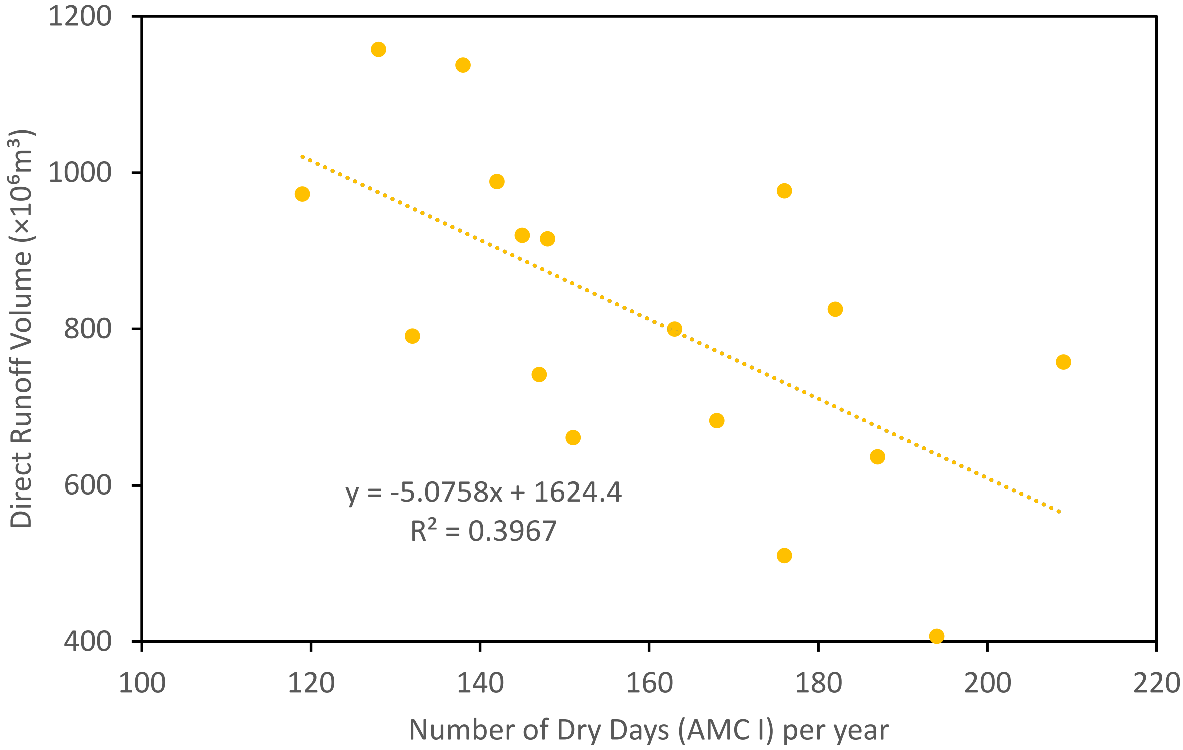

Figure 98 Number of Dry Days (AMC I) per year against Direct Runoff Volume

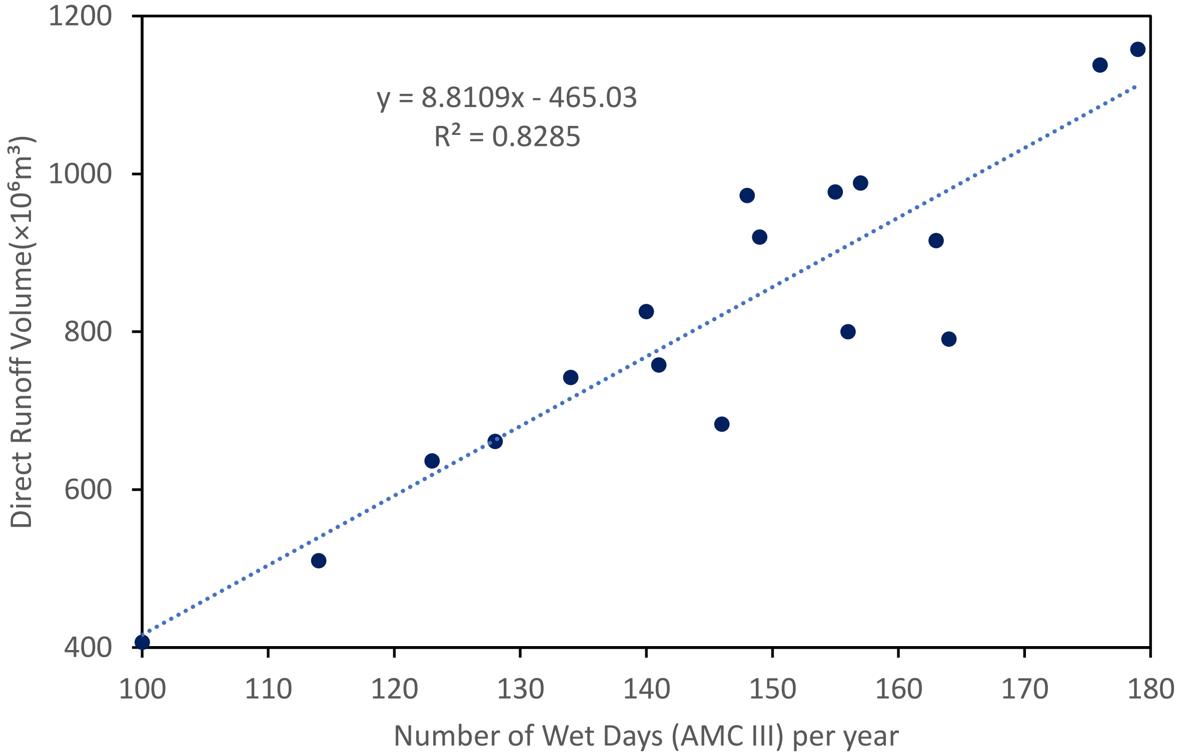

Figure 99 Number of Wet Days (AMC III) per year against Direct Runoff Volume