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Estimating Change in Runoff Caused by Land-Use Change over a Period of 13 Years in a Watershed in Keonjhar District (Odisha) using Gis Based SCS-CN Method

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Abstract

Change in land-use is an inevitable phenomenon that occurs within a landform over time, especially in human-intercepted areas. A watershed of 380.5 Km2 consisting major segment of mining and allied operations of Gandahamardhan Iron Ore mines was selected in the Keonjhar district of Odisha. The paper aims to estimate the difference in the runoff caused by the landuse change in the watershed over a period of 13 years (2008-2021). All the other factors such as Hydrological Soil Group (HSG), precipitation and topography were kept constant in order to understand the variation in runoff caused solely due to land-use change. The runoff estimation was done using Soil Conservation Service- Curve Number (SCS-CN) method and CN values for normal conditions (CNII) values were used for the calculation and incorporated in GIS platform. 16.62% increase in area under cropland, 48.5% increase in area under barren land, 21.86% decrease in area under woods and 0.76% increase in area under woods-grass combination was observed in 2021, keeping 2008 as the base year. A resulting increase in the runoff by 2.38%, 1.59%, 1.65% and 2.16% was observed in June, July, August and September of 2021 as compared to the corresponding values of runoff in 2008. Even though the range of runoff depth remained constant for both years (76.99 mm - 193.99 mm), but the mean runoff increased in 2021, as a result of the land-use change.

Keywords: GIS; SCS-CN; Runoff; Land-use change; Remote sensing

Introduction

Keonjhar district as of 2021 houses 17 mines: 10 Iron ore, 3 Chromite ore, 2 Manganese ore and 2 which extract both manganese ore and iron ore, as mentioned in the Status of Mineral Concessions, Odisha Mining Commission Limited website1. Half of Odisha's total mines are situated in this district, and has indirectly caused severe health impacts as well including malaria spread due to deforestation and potential lung damage and respiratory diseases. Numerous issues regarding the depleted quality of water came afloat in the recent years2. A recent case also showed women from Nayakot village under Bansapal block took their concerns of water shortage to the road and blocked Saukati-Dabuna road near their village3. These rising water related issues direct towards a common genesis- Land-use change. An area with mining operations is bound to undergo a drastic land-use change due to clearing down of forests, excavation, industrial and domestic infrastructure development, overburden changing the local geography and movement of extracted ore. A study by L.J.

Sonter et al. concluded that the land-use change in the mining regions is quite distinguishable from the non-mining regions. This study aims to investigate a part of the problem caused by the changing land-use in a mining area i.e. Rainfall runoff. Since natural boundaries give a more comprehensive understanding to the problems faced in an area, the entire study was done taking a watershed as a unit of measurement of change. A watershed is an area which directs all the surface runoff occurring after a precipitation event to a single point. One of the thirty-four operational mines in Odisha – Gandhamardan Iron Ore mine was used in the study, and a watershed was selected such that the mine area is included within the watershed.

The entire watershed has undergone many land-use changes which have been covered in the study, with one major change being the expansion of Gandhamardan Iron Ore mines as shown in Figure 1. The main aim was to understand the change in runoff caused by land-use alteration within a watershed. A study in the Narmada basin showed that the land-use change contributed to 5% increase in the runoff in 10 years provided the rainfall is kept constant. A strong relation between the vegetation cover and the runoff volume in a watershed was also observed, wherein decreasing vegetation cover and increasing urbanization led to increasing runoff volume. Therefore, a careful analysis of past patterns in land-use change in a watershed backed by precipitation forecasts can be used to increase the accuracy of runoff forecasting.

Future forecasting of the runoff within a watershed is critical in understanding the water yield potential and volume of water that would be lost from a watershed in the form of runoff. Also, the variation in the precipitation pattern due to climate change has resulted in a loss of a lot of potentially harvestable water as surface run off. With an estimated 15% decline in the rainfall in the country in 2030, the necessity to accurately estimate the surface runoff has increased significantly so as to plan and design hydraulic structures to sustain water dependent livelihoods and preserve the local ecology of the area. Many hydrology models such as Soil Conservation Service-Curve Number (SCS-CN) model and Soil Water Assessment Tool (SWAT) are able to forecast the runoff, but the land-use which is assumed to be constant for the purpose of forecasting future values. As against this common assumption, land-use is a dynamic system influenced by multiple variables such as precipitation pattern, crop selection, afforestation and reforestation activities, industrial expansion, urbanization policies. Areas with dynamic land-use change such as forest fringe areas and urban areas can have significant changes in land-use in a very short span of time mostly due to anthropogenic interventions like diverting lands for expansion of cities and agricultural lands, setting up of industries, mines etc. Such rapid changes in areas with multiple land-uses quickly alter the hydraulics of a watershed and impacts the surface runoff volumes when the change is cumulatively addressed over a longer span of time. The SCS-CN method which is a method for the estimation of rainfall runoff modelling (USDA, 1972) has been used in this study to compute runoff in the years 2008 and 2021 [1]. SCS-CN has method has been claimed to be an effective and successful model in estimating the surface runoff and proved to be accurate in ungauged catchments of Vindyanchal region. High correlation has also been achieved between the real and simulated runoff values using SCS-CN method as suggested by Nayak and Jaiswal. Since the objective of the study is to understand the change in runoff caused solely due to change of land-use, all other variables that affect the runoff such as precipitation and spatial distribution of soil were assumed to remain constant. Use of Geographic Information System (GIS) and remote sensing (RS) techniques in the hydrologic models have proved to be cost and time effective with high accuracy and have been used for this study (Figure 1).

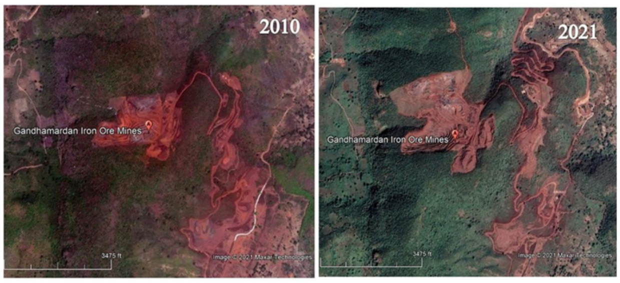


Figure1: Gandhamardan Iron Ore mines in 2010 and 2021.

The study area includes parts of Gandhamardan Iron Ore mines in the South East corner. The satellite imagery suggests that the mine underwent expansion during the period of the study. Further, the Forest lands accounted for the maximum area in 2008 whereas in 2021 agricultural land accounted for the maximum area [2]. Based on the meteorological observations by the Indian Meteorological Department the district receives most of its precipitation in the monsoon months of June, July, August and September. Maximum rainfall occurs in the month of July followed by August, September and June respectively. The mean rainfall for the four months between 1981 and 2017 was observed to be 1118.88 mm (Figure 2).

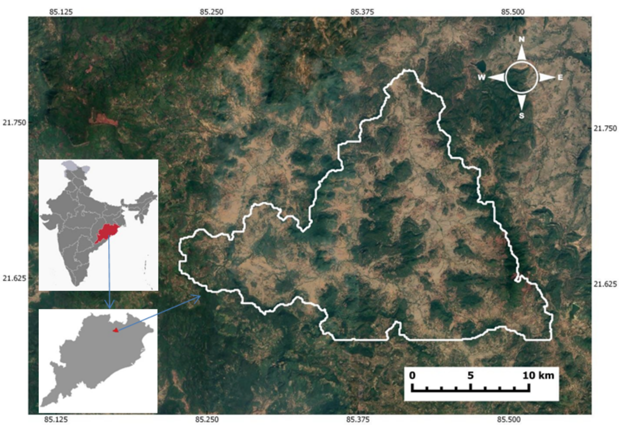


Figure2: Location map of our study area.

Materials and Methods

Site selection for the study area was done using Google Earth imagery of mining affected areas. Stream network, slope, elevation and watershed boundary have been generated using SRTM Digital Elevation Model (DEM) of 90m resolution in GIS focussing on the land parcels which underwent significant changes in the last decade due to mining activities [3]. Represent the elevation map and the stream network of the study area respectively. The year 2008 has been taken as the baseline year to compute the degree of changes in runoff and land-use undergone in the year 2021. The flowchart representing the methodology of the current study has been shown in (Figure 3).

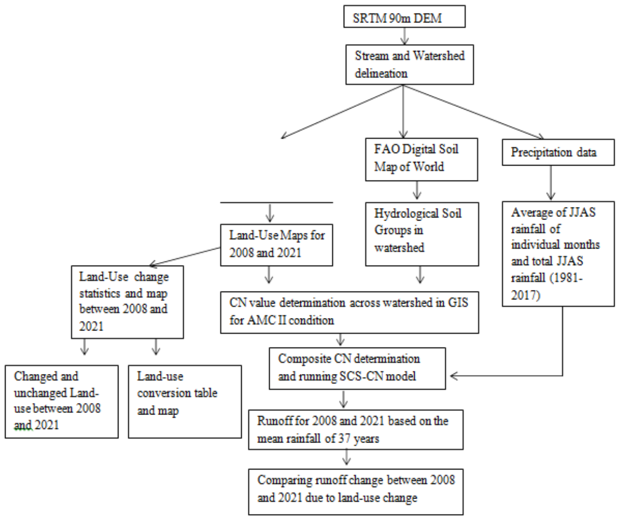


Figure3: Methodology flowchart for the study.

The watershed covers approximately 4.62% of the district's area. Baitarani is the major river system in the area and the river system in the watershed follows a dendritic drainage pattern (Figure 4).

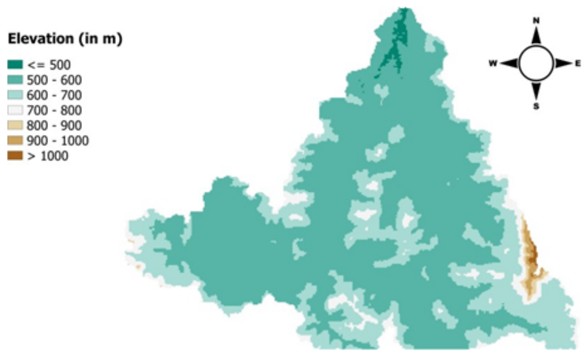


Figure4: Elevation map of the watershed.

Four major LULC classes had been identified based on the acquired images i.e., Woods, Woods and grass combination, cropland and barren land. Figure 6 shows the generated LULC maps of the study area for 2008 and 2021 respectively (Figure 5).

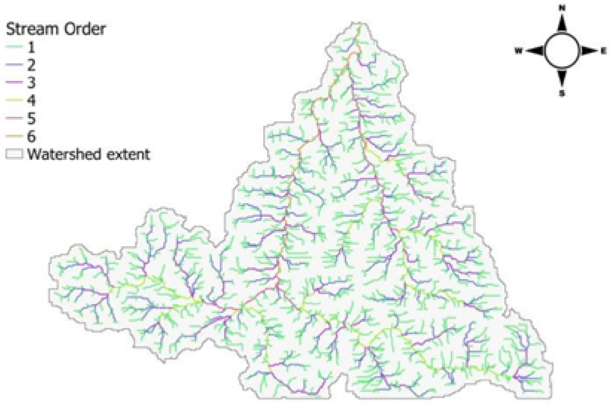


Figure5: Stream network map of the watershed.

Land-Use / Land Cover (LULC)

Land Cover solely deals with the physical characteristics of a patch of earth while Land-use refers to the way in which the patch of earth has been modified to suit to the functionality of economic activities. The LULC map has been generated by processing the multispectral data of LANDSAT 7 ETM+ in GIS platform [4]. Satellite images have been acquired for the same season for both years in order to minimise distortions to land-use caused by seasonal variations. Table 1 shows the details of satellite data extracted for the purpose of this study (Table 1).

LULC Year	Sensor	Date of Acquisition	Spatial Resolution
2008	ETM +	39501	30m
2021	ETM +	44279	30m

Table 1: Details of acquired satellite images used for making LULC.

The LULC was cross checked with the actual space image in order to increase the accuracy of classification done. Comparative analysis of the LULC map for 2021 was run in Semi-automatic Classification Plugin taking 2008 as the base year. Out of the sixteen pairs of possible land transformation identified, four classes had unchanged land classes and the remaining twelve classes had transforming land classes i.e, cropland to barren land, cropland to woods, cropland to woods and grass combination, barren land to cropland, barren land to woods, barren land to woods and grass combination, woods to cropland, woods to barren land, woods to wood and grass combination, wood and grass combination to cropland, wood and grass combination to barren land and wood and grass combination to woods.

Cross class codes were assigned to each pair of land class transition as shown in Table 4. This was done to identify the kind of land class transformation undergone by every pixel between 2008 and 2021 [5]. The result enables us to rank the land-use change in our study area from highest to lowest. Represents the land-use change diagram based on the Cross Class Code assigned distinguishes the areas that underwent changes in their land-use from the ones that did not (Figure 6).

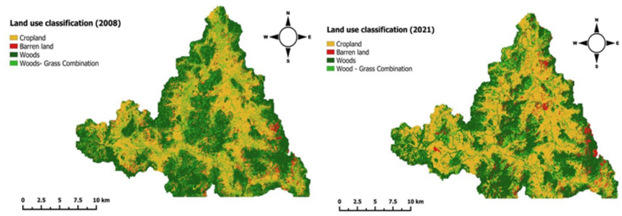


Figure6: Land-use classification 2008 and 2021.

National Resources Conservation Centre (NRSC) categorized soil into 4 Hydrological Soil Groups (HSGs): A, B, C and D, on the basis of their water transmission capacity, drainage condition, texture, and infiltration rate. The runoff decreases with an increasing infiltration (Figure 7).

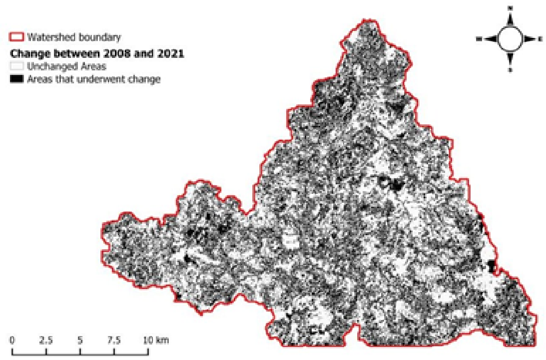


Figure7: Areas of land-use change between 2008 and 2021.

Hydrological Soil Group (HSG)

The infiltration rate decrease as we move from HSG A to HSG D (NRCS, 2009). Based on the FAO Digital Soil Map of World, the study area primarily constituted two soil types, i.e., Dystric nitosols (27% of the study area) and lithosols (73% of the study area). Dystric nitosols and lithosols fall under the HSG category of B and D respectively. Since a majority of the watershed constitutes dystric nitosols (HSG D) soil it is fair to assume that the watershed would have a higher runoff because HSG D has the highest runoff potential amongst all other soil groups. The HSG, texture, runoff potential, water transmission and final infiltration range of the soils within the study area have been listed. The distribution of HSG in our study area has been shown (Table 2).

Soil in our study area	HSG soil	Soil Texture	Runoff potential	Water transmission	Final infiltration
Dystric Nitosols	Group B	Moderately deep to deep, moderately well drained to well drained with moderately fine to moderat	Moderate	High	3.8-7.5

		ely coarse textures			
Lithosols	Group D	Clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious materials	High	Low	<1.3

Table2: Soil characteristics of soils in the study area (USDA-SCS, 1974).

Mean monthly rainfall over a period of 37 years (1981-2017) was used as the input value for the SCS-CN model for both the years (Figure 8).

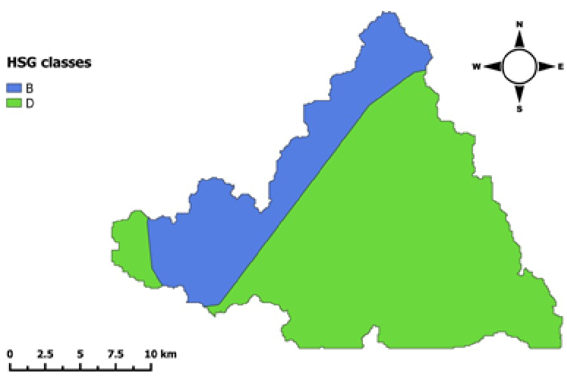


Figure 8: Hydrological Soil Group map of the watershed.

Precipitation

Precipitation data for the study area was derived from NASA POWER (Prediction of Worldwide Energy Resources) website. Random points were sampled for precipitation observations in the watershed. Precipitation distribution was found to be same across all the sampled points and hence uniform distribution of rainfall was assumed for the entire watershed. In order to understand the change in the runoff caused solely by land-use change, all other parameters that affect runoff in the SCS-CN model i.e., soil type, watershed boundary, and precipitation are kept constant. As crop cover is sensitive to the season in which model is run, hence(nr) the Curve Number and runoff estimation was done specific to monsoon months i.e., June, July, August and September [2].

SCS-CN Method

Runoff Curve Number (CN) value is based on the combination of land-use and soil taken from the SCS handbook of Hydrology (NEH-4), section-4 (USDA, 1972). The SCS-CN method allows us to determine the runoff characteristics of a landscape based on land-use characteristics, soil characteristics and antecedent moisture condition.

The amount of rainfall that occurred preceding the modelled rainfall event impacts the runoff due to the presence of antecedent moisture in the soil. AMC –III condition that uses CN III value suggests that higher amounts of preceding rainfall would mean higher moisture concentration in the soil causing less infiltration and higher runoff. AMC- I condition that uses CNI value suggests that lesser amounts of preceding rainfall would mean less moisture concentration in the soil causing higher infiltration and lesser runoff. CN numbers for dry, normal and wet antecedent moisture conditions are denoted by CNI, CNII and CNIII respectively and can be computed using the Equations.

CNI= □□□□

2.281−0.0128 □□□□

CNIII= □□□□

0.427+0.00573 □□□□

Ideally, an average moisture condition is used while modelling a rainfall event. Thus, AMC –II that uses CNII has been used to calculate the runoff. The CN values extracted from the study area has been shown in Table 3. Weighted curve number (CNw) of the watershed was then calculated based on the area falling under different CN values [3].

CN value distribution map generated in GIS platform by assigning CN value to every pixel in the study area based on the LULC map and HSG map. CNII values were used for generation of the CN distribution map. Figure 9 shows the CN distribution in the watershed in years 2008 and 2021. The watershed has CN values ranging from high CN value areas such as barren lands with HSG D to low CN value areas such as woods with HSG B. Based on the 2008 values, CN value of 77 i.e. woods with HSG D, covers the maximum area, and CN value of 86 i.e. Barren land with HSG B, covers the least area. Whereas in 2021, CN value of 87 i.e. Cropland with HSG D covered the maximum area and the least area covered by a CN value remains same for both years (Table 3).

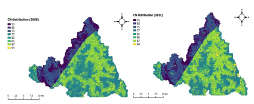
	HSG		**Area based on CN classification (Km2)**	**Area based on Land- use type (Km2)**
Cropland	D	87	97.3	134.1
Cropland	B	75	36.8	
Barren land	D	94	11	13.8
Woods	B	55	41.5	154.1

Woods-Grass combination	D	82	57.2	78.5
Woods-Grass combination	B	65	21.3	

Land-use	**HSG Group**	**CN**	**Area based on CN classification (Km2)**	**Area based on Land- use type (Km2)**
Cropland	D	87	111.7	156.4
Cropland	B	75	44.7	
Barren land	D	94	17.4	20.5
Barren land	B	86	3.1	
Woods	D	77	92.8	124.4
Woods	B	55	31.6	
Woods-Grass combination	D	82	56.2	79.1
Woods-Grass combination	B	65	22.9	

Table : CN values.

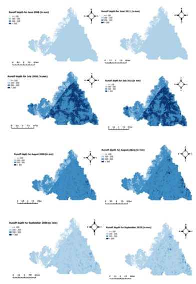
Potential maximum retention (in mm) after the runoff begins denoted by S varies with land cover and soil based on the weighted curve number. S is related to the CNw by Equation (USDA, 1972)



Initial abstraction (in mm) denoted by □□ refers to the losses before the runoff begins such as vegetation interception, evaporation, infiltration, and water retained by impervious structures built on ground and surface depressions. □□ is related to the S as shown in Equation.

□□ = 0.2 S

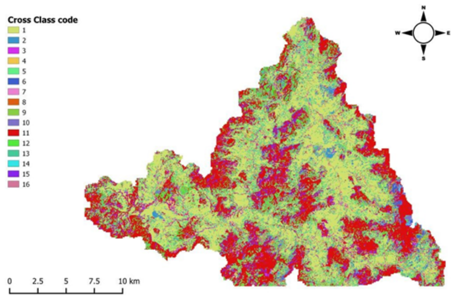
Runoff (in mm) denoted by Q was calculated using the following Equation.



The runoff for 2008 and 2021 was calculated for average net monsoon precipitation for 37 years and any variance caused in the runoff was attributed to the land-use change that occurred within the watershed during that period. Runoff distribution maps over the watershed have been generated for the monsoon months of 2008 and 2021 based on the CN value and S value distribution map generated. The month- wise runoff distribution maps for June, July, August and September of 2008 and 2021 have been broadly classified into 4 groups

- Areas of runoff less than or equal to100 mm,
- Areas of runoff between 100 and 200mm,
- Areas with runoff between 200 and 300 mm
- Areas with runoff more than 300 mm.

The month-wise runoff distribution for years 2008 and 2021. The percentage change in the runoff in 2021 with reference to 2008 was calculated using Equation.



where □2021 and □2008 represents the runoff in the watershed in the year 2021 and 2008 respectively (Figure 9).

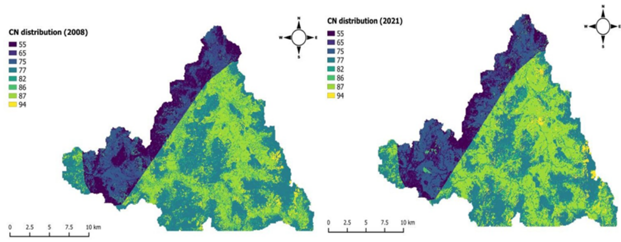


Figure 9: CN value distribution.

The formula is applicable for a situation where P >□□. If the Initial abstraction is less than the precipitation (P >□□), then no runoff would occur, and hence precipitation event with precipitation higher than the initial abstraction was considered (Figure 10).

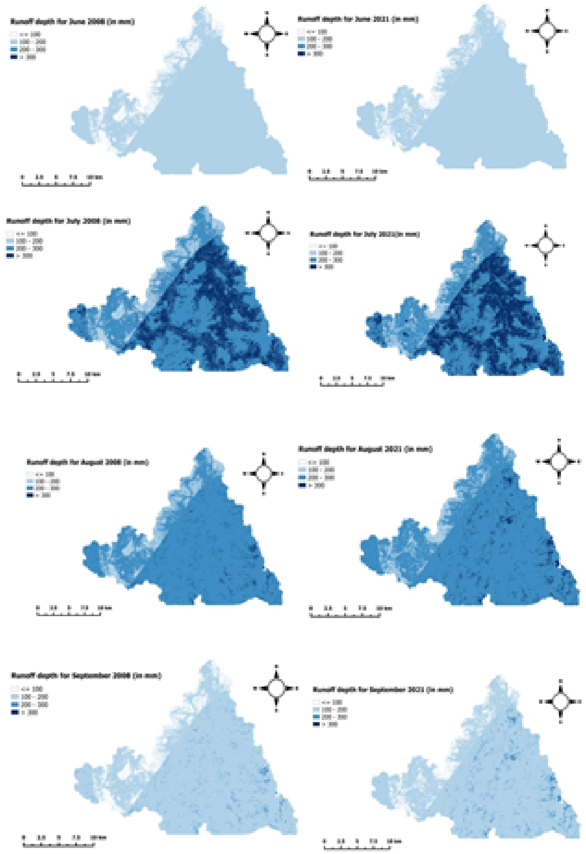


Figure 10: Monsoon months runoff distribution.

Results and Discussion

Land-use Land Cover Change (LULCC)

The watershed is spread across an area of 380.5 Km^2 .The highest amount of land class transformation of 9.33% was seen from Woods i.e. dense forests to Wood grass combination i.e. less dense forest with almost 50% area covered by grass. Thus it can be concluded that the major change happening in the watershed is conversion of dense forests to less dense forest, followed by 7.9% of wood-grass combination converted to cropland. Increasing food demand due to increasing population can be a driving factor in expansion of agricultural croplands. 5.68% of area was converted from less dense wood-grass combination to woods, majorly due to afforestation programs undertaken by the Forest Department. 2.26% of woods were converted to barren land which could primarily be due to expansion of mines and related mining and associated activities. 2.06% of barren land has been converted into cultivated land [1]. Least amount of change was seen in conversion of barren lands to woods i.e. 0.18% followed by barren land to wood-grass combination i.e. 0.8%. This can be inferred as either it takes a longer time frame for degraded lands to reach significant levels of vegetation cover, or the second inference can be made that not inadequate afforestation activities have been undertaken over the barren lands, and even if undertaken must not have been able to sustain vegetation. Moreover most signatures of barren land were from areas related to mining activities. Therefore, it can be said that the mining activities are still active in such areas thereby leaving very less scope for increase in vegetation cover. Overall in 2021, based on 2008 land cover situation there was a 16.62% increase in area under cropland, 48.5% increase in area under barren land, 21.86% decrease in area under woods and 0.76% increase in area under woods-grass combination (Table 4).

Cross Class Code	2008 land class	2021 land class	Area (sq km)	Percentage of total area	Change type	Rank based on change (1= Highest, 12 = Lowest)
1	Cropland	Cropland	104.2	27.38	Unchanged	-
2	Cropland	Barren land	5.9	1.54	Changed	9
3	Cropland	Woods	6.4	1.68	Changed	8
4	Cropland	Woods - Grass combination	17.7	4.64	Changed	4
5	Barren land	Cropland	7.8	2.06	Changed	7
6	Barren land	Barren land	2.2	0.59	Unchanged	-
7	Barren land	Woods	0.7	0.18	Changed	12
8	Barren land	Woods - Grass combination	3	0.8	Changed	11
9	Woods	Cropland	14.3	3.76	Changed	5
10	Woods	Barren land	8.5	2.26	Changed	6
11	Woods	Woods	95.8	25.18	Unchanged	-
12	Woods	Woods - Grass combination	35.5	9.33	Changed	1
13	Woods - Grass combination	Cropland	30.1	7.9	Changed	2
14	Woods - Grass combination	Barren land	3.8	1	Changed	10
15	Woods - Grass	Woods	21.6	5.68	Changed	3

	combination					
16	Woods - Grass combination	Woods - Grass combination	23	6.04	Unchanged	-

Table 4: LULCC between 2008 and 2021.

The study depicts the change in runoff caused solely due to change in land-use distribution of the watershed within a span of 13 years. An increase of 2.38%, 1.59%, 1.65% and 2.16% respectively in runoff in June, July, August and September of 2021 was observed with respect to the corresponding values in of 2008 (Figure 11).

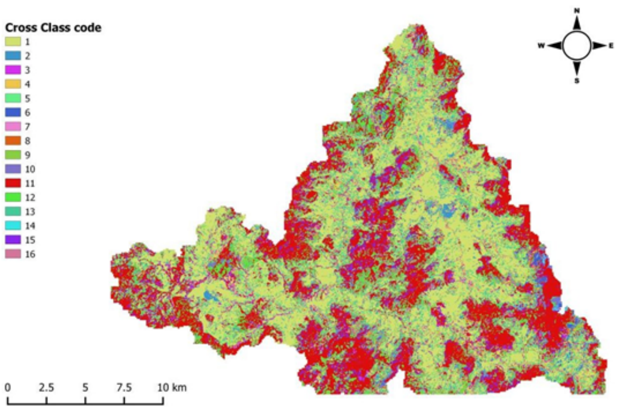


Figure 11: Cross class code distribution for land-use change.

Runoff

The month of July receives the highest amount of rainfall followed by August, September and June. Runoff for each month was calculated using the SCS-CN model using Equation 6. An increase of 2.38%, 1.59%, 1.65% and 2.16% respectively in runoff in June, July, August and September of 2021 was observed with respect to the corresponding values in of 2008.

Since all variables related to runoff calculation using SCS-CN method in the watershed had been kept constant other than the land-use, it can be concluded that the change in runoff caused in 2021 can solely be attributed to the change in land-use happening within the watershed between 2008 and 2021. Table 5 shows the calculated values of runoff using Equation 6 and percentage change that occurred between 2008 and 2021 (Table 5).

Precipitation (mm)	June	July	August	September
Mean runoff depth 2008 (mm)	212.28	346.19	332	228.41
	144.33	269.77	256.22	159.1
Runoff range 2008 (mm)	76.99-193.99	181.09-327.43	169.3-313.3	88.45-210.03
Mean Runoff depth 2021 (mm)	147.74	274.08	260.45	162.54
Runoff range 2021 (mm)	76.99-193.99	181.09-327.43	169.3-313.3	88.45-210.03
% change in runoff	2.38	1.59	1.65	2.16

Table 5: Runoff depth for 2008 and 2021.

Conclusion

Given the current trend of land-use change, the watershed runoff is bound to increase in the forthcoming years since areas with high CN values such as barren lands are increasing, and their expansion is being compensated by the areas of low CN values such as forest lands. One should avoid conversion of least runoff potential areas such as dense woods to activities inducing barren lands such as mining, since this increases the runoff condition immensely and so are the losses due to runoff increased.

It is evident that land-use patterns are moving towards higher runoff distribution, and based on prediction of depleting precipitation levels it is a critical time to start investing upon activities to harvest the available rainwater, and make minimal losses as runoff else it is bound to adversely impact the water dependent sectors, primarily agriculture.

Additionally trends such as expansion trends of agricultural lands due to increasing food demand in the society caused by the population surge are in a way inevitable and needs to happen in order to prevent Malthusian fears from coming true.

Land-use is indeed a dynamic factor when observed over a decadal time scale for many areas just like the study area and for such areas it is suggested that when runoff forecasting is done using the SCS-CN model for longer time spans, the land-use forecasting be necessarily carried out based on the historic land-use trends of the watershed. This would enhance the accuracy of the runoff forecast estimates and further help in planning and designing of suitable hydraulic structures for storage and recharge purposes.

Furthermore, accurately planning out water harvesting and runoff control structures such as check dams, contour bunds, contour trenching etc. would help increase resilience of agriculture and allied sectors against climate change and would also decrease their dependency over rain water for irrigation.

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