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OPTIMIZATION OF LAND USE TO REDUCE SURFACE RUNOFF AND EROSION IN KURANJI WATERSHED

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ABSTRACT: Changes in land cover in the Kuranji watershed (22,460 hectares) increased very rapidly along with the increase in the number of people using land due to the impact of the September 2009 earthquake. Therefore, an appropriate land use model is needed so that surface runoff and erosion can be reduced. This study aims to determine the value of surface runoff using rational methods and soil erosion using a modified universal soil loss equation model based on land units with a total of 22 samples and to determine land cover optimization using the Spatial Multi Criteria analysis (SMCA) technique. Scenario determination is also based on maps of conservation, protected areas, and cultivation as well as the spatial plan of Padang City. The results showed that erosion that exceeded the tolerance limit was found in 5 samples. A site with mixed gardens and a very steep slope had an erosion rate of 16.60 tonne/hectares/year, and an erosion rate at settlements area with a slightly steep slope of is12.53 tonne/hectares/year, mixed gardens with a steep slope of 8.57 tonne/hectares/year. The settlements with a flat slope of 19.43 tonne/hectares/year, and 17.85 tonne/hectares/year. The optimal way to reduce erosion is to convert 0.83% of shrubs and 4.51% of mixed gardens located on steep/very steep slopes into conservation areas and protected forests; thus, erosion can be reduced by up to 70-80%; while the built-up area (settlement area, industrial area, etc.) is developed on a flat slope.

Keywords: Land cover, Land use, Erosion, Planning

1. INTRODUCTION

Watershed management is a conservation area method aimed at realizing the sustainability and harmony of ecosystems and increasing the sustainable use of natural resources for humans, producing many benefits without reducing environmental quality.

A problem in the management of watershed areas that is very prominent is the excessive use of natural resources which results in changes in land use. Changes in land use are generally caused by human activities to meet the needs of life and efforts to improve the economy.

Based on the analysis of Quickbird satellite imagery in 2007, Google Earth for 2009-2015, SAS Planet (ArcGIS Imagery) in 2018, land-use changes occurred massively in the Kuranji watershed in Padang City. Such as the conversion of land functions from agricultural land and mixed gardens to developed land, increasing residential areas, reducing forest areas for agricultural use, and mixed gardens. Illegal logging activities that have increased since 1980 have also greatly changed the condition of forests into agricultural land and mixed gardens. This has an impact on the hydrology of the area.

The Kuranji watershed is the largest in the city of Padang and has the potential to be used as a direction for urban development. In particular, the utilization of the central part of the Kuranji watershed leads to the upstream watershed. Based on the analysis of satellite imagery for 2009-2018, the central part of the watershed has changed land use of 46.67 hectares from paddy fields to developed land.

The increase of land-use changes is in line with the rise of population growth, also due to the impact of the earthquake on 30 September 2009. It is proven that based on the analysis of Padang Municipality in Numbers data from 2010-2017 there has been an increase in the population of the central Kuranji watershed by 32,729 people with a population growth rate of 4.95%[1,2].

The increase in population is thought to be due to the 2009 earthquake that hit the city of Padang and the threat of the megathrust that would trigger a tsunami wave. There have been efforts to encourage people who are in the red zone of the threat of tsunami waves, especially those on the coast of Padang City, to move to a safer location. So that the central part of the Kuranji watershed experiences high population pressure.

Due to the threat of megathrust which is predicted to hit the city of Padang after the earthquake in 2009 and based on the Regional Regulation of Padang City no. 10/2011, city development is directed to the eastern part of the city. In the City Planning of Padang City year 2010-2030, it is stated that one of the directions for spatial development in the Kuranji watershed is to direct the development of new tertiary institutions and supporting facilities to the Limau Manis area. These supporting facilities include trade and services as well as residential housing. Meanwhile, government offices, private offices, trade, and business areas were allocated at the Air Pacah area. As a result, the need for land increases significantly in the central Kuranji watershed.

The problems in the Kuranji watershed can also be seen from community activities in managing forest resources such as illegal logging in the upstream watershed, which is protected and conservation forests. Based on an analysis of satellite images for the last 11 years (2007-2018), the former illegal logging area was identified as 198.01 hectares spread over 162 locations; which consists of 118.17 hectares in a protected forest, 16.74 hectares in conservation areas, and 63.10 hectares in other land use. The occurrence of illegal logging has resulted in no more vegetation to protect the soil surface. So that the soil is easily eroded. Fiantis [3] explained that the reduction in the number of forest areas in the Kuranji watershed every year from 1994 to 2002 was 209.30 hectares/year. From this change, only 5.56 hectares of forest land were converted to agroforestry. Human settlements and agricultural land have increased by 0.99% and 0.38%.

The above problems have explained that land-use changes in the Kuranji watershed impact environmental quality degradation, such as erosion and sedimentation. Erosion and sedimentation occur due to high surface runoff and reduced soil infiltration. Based on these problems, it is necessary to restore and maintain the watershed area to remain sustainable. One of the efforts that should be done is by optimizing land use to reduce surface runoff and erosion.

This research has two objectives. The first is to predict the amount of runoff using the rational method and erosion using the Modified Universal Soil Loss Equation (MUSLE). Second, determine land cover optimization using Spatial Multi Criteria Analysis (SMCA) technique. Spatial analysis is one of the techniques used to explore multi-criteria data from a spatial perspective so that new information will be obtained from existing data. Spatial Multi Criteria Analysis (SMCA) is a method used to facilitate the optimization of land cover at the Kuranji watershed. In this study, optimization of land cover was carried out by looking at the value of surface runoff, erosion, and morphometric characteristics that occurred due to changes in land cover in the Kuranji watershed.

2. RESEARCH SIGNIFICANCE

The increase in population in the Kuranji watershed has resulted in changes in land cover. This increase in population was due to the aftermath of the 2009 earthquake and the potential for a large megathrust earthquake that would trigger a tsunami wave. The impact caused by the increase in population is the occurrence of illegal logging and changes in land cover to agricultural areas in the upstream watershed, which should have been protected areas. In the middle part of the watershed, there is a change in mixed gardens to a slightly steep slope into a residential area. Likewise, rice fields have also changed into residential areas. Changes on a large scale will have an impact on high runoff, erosion, and flooding. Changes in land cover may occur but must be environmentally sound, so that surface runoff and erosion can be reduced and floods do not occur. For this reason, an appropriate land use optimization model is needed so that environmental impacts can be reduced.

3. MATERIALS AND METHOD

3.1 Research Location

The Kuranji watershed is located in Padang City, West Sumatra Province, Indonesia. This area has a maximum elevation of 1,860 meters above sea level with an annual rainfall of more than 5,054 mm. This watershed has an area of 22,469.55 hectares. Based on geographical position, the Kuranji watershed is located between $100^0$21'18,84" E - $100^0$33'52,87" E and $0^0$47'23,36" S - $0^0$56'13,71" S. This research was conducted from November 2019 to March 2020. The research location can be seen in Fig. 1.

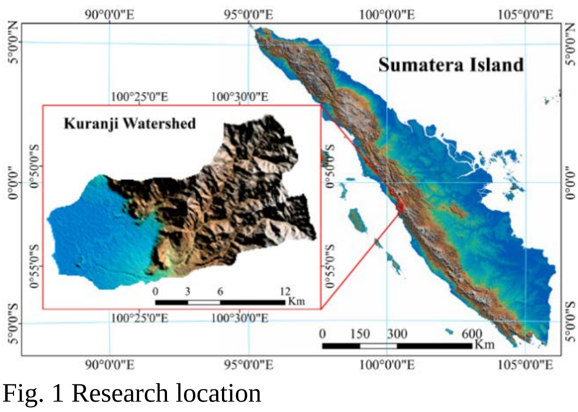

Fig. 1 Research location

3.2 Materials

This research was conducted at the Kuranji watershed in the city of Padang, West Sumatra Province. The first research objective was to predict erosion using MUSLE. The rainfall used is the highest daily rainfall in 10 years, from 2009-2018 amounting to 97.75 mm/day which comes from Gunung Nago. Predicting surface runoff using the SCS (Soil Conservation Service) curve number (CN) method. Determination of the peak discharge was conducted using a rational method.

Determination of erosion samples based on land unit maps (Lu), namely the overlay between slope maps, soil type maps, and land cover maps. Slope map derived from the DEM map with a spatial resolution of 15x15 meters. Slope maps consist of flat (A), gentle (B), rather steep (C), steep (D), and very steep (E), details can be seen in Fig. 2.

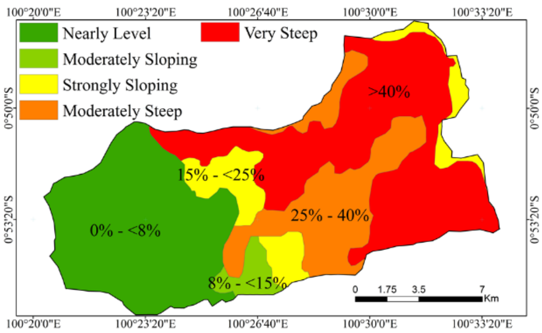

Fig. 2 Slope conditions in the Kuranji Watershed

Soil maps at a scale of 1: 250,000 consisting of inceptisol (EPT) and Entisol (Ent) soils. For more details, the location of soil sampling can be seen on the land unit map in Fig. 3. Explanation of sampling can also be seen in Table 1 (Lu).

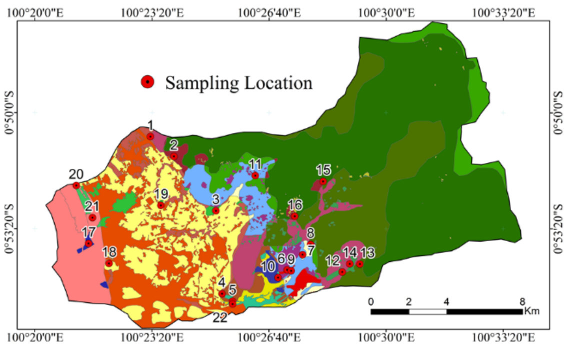

Fig. 3 Map of Land Units in The Kuranji Watershed

Land cover map analysis from SAS Planet (Arc-GIS Imagery) satellite imagery in 2018 with a spatial resolution of 20x20 meters. The land cover map consists of forest (Frs), mixed gardens (Mg), rice fields (Rf), scrub (Sc), and settlements (Slm). Each variation of land units (Lu) was taken 1 soil sample with a sample size of 22 (number of samples). The tools used are GPS and ArcGIS 10.6.1.

The second research objective is to create a land cover model based on the value of erosion. If the erosion value is large and exceeds the tolerance limit, a land cover change scenario is carried out. The scenario is also based on the existence of conservation, protected, and cultivation areas. The city planning of Padang City year 2010-2030 is also a reference in scenario creation. The land cover scenario from 0 to 4.0 represents the existing land cover condition.

3.3 Method

The MUSLE equation with the formula:

$$Sed' = 11.8 (Q_{surf} \times q_{peak})^{0.56} \times K \times LS \times C \times P \quad (1)$$

where :
Sed′: sediment yield from HRU (tonne);
Q_{surf}: total runoff volume (mm)/hectares;
q_{peak} : peak discharge (m3/s);
K : soil erodibility factor;
LS : topographic factors of length and slope;
C : land cover by plants;
P : supporting factors for conservation actions;

The surface flow equation uses the SCS (Soil Conservation Service) curve number (CN) method with the formula:

$$Qsurf = ((Rday - 0.2S)^2)/((Rday + 0.8S)) \quad (2a)$$

$$S = 25.4\ 100/CN - 10 \quad (2b)$$

where:
Q_{surf} : total runoff on day 1 (mm);
Rday : amount of rainfall on the day (mm);
S : retention parameter (mm);
CN : curve number

Calculating the peak discharge using the rational method with the formula:

$$q_{peak} = 0.277\ C.I.A \quad (3a)$$

$$I = R/25 \times (24/Tc)^{2/3} \quad (3b)$$

$$Tc = (0.869 \times L^3)^{0.385}/H \quad (3c)$$

where :
q_{peak} : maximum surface runoff rate/peak discharge (m3/s);
A : area of the watershed (km2);
I : intensity of rain maximum (mm/hour);
C : runoff coefficient;
R : rain a day (mm);
Tc : time of concentration (hours);
L : length of the main river (km);
H : height difference (highest point - lowest point) in the watershed (m).

Determination of C value (runoff coefficient) is determined by dividing surface runoff by rainfall.

Table 1. The Value of Runoff and Erosion Under Existing Conditions

No Spl	Lu	Q m^3	RM m^3/Sec	K	LS	CP	E tonne/ha/yr	T tonne/ha/yr
1	Ept-A-Mg	308550.49	554103.24	0.23	2.82	0.20	3.18	10.07
2	Ept-E-Mg	141634.35	358279.87	0.21	24.78	0.20	16.60	8.94
3	Ept-A-Sc	136416.08	350826.76	0.13	2.20	0.30	1.30	11.89
4	Ept-B-Slm	92040.28	281446.36	0.15	4.41	1.00	8.27	12.98
5	Ept-B-Kc	149003.86	368602.78	0.11	5.55	0.20	2.04	11.84
6	Ept-C-Sc	170257.55	397180.18	0.15	9.45	0.30	7.38	12.90
7	Ept-C-Swh	74380.74	249796.23	0.18	9.45	0.02	0.37	9.87
8	Ept-C-Frs	423430.78	661555.30	0.07	7.57	0.01	0.07	9.26
9	Ept-C-Slm	92911.45	282935.07	0.15	6.52	1.00	12.53	12.05
10	Ept-B-Sc	98319.36	292042.37	0.15	5.10	0.30	3.07	10.12
11	Ept-C-Mg	634394.23	829639.00	0.18	5.87	0.20	7.96	10.83
12	Ept-D-Sc	117595.91	322840.22	0.13	9.45	0.30	5.36	9.67
13	Ept-D-Frs	1317591.63	1249238.21	0.07	18.62	0.00	0.07	7.49
14	Ept-D- Mg	574695.46	784970.16	0.12	10.37	0.20	8.57	8.42
15	Ept-E-Frs	3534634.71	2170905.59	0.06	20.10	0.001	0.11	9.71
16	Ept-E-Sc	28931.96	147210.78	0.20	18.24	0.30	7.33	9.79
17	Ent-A-Mg	22770.90	128736.28	0.09	1.55	0.50	0.39	9.04
18	Ept-A-Swh	2057312.78	1603305.11	0.21	1.55	0.00	0.09	10.38
19	Ept-A-Slm	1965379.74	1562780.64	0.18	1.55	1.00	19.43	12.04
20	Ent-A-Sc	27982.36	144485.16	0.11	1.55	0.30	0.34	7.84
21	Ent-A-Slm	1070534.79	1112101.52	0.23	1.55	1.00	17.85	10.03
22	Ept-B-Swh	109052.32	309487.81	0.14	5.55	0.00	0.04	9.02

The optimization scenario model uses the SMCA technique. In this study, there are 5 land cover change scenarios, where scenario 0 is the existing condition. Scenarios 1-4 are based on the SMCA model using overlay analysis techniques such as slope maps, land cover maps, soil maps, river flow density maps, forest area maps, erosion values , and morphometric characteristics of the Kuranji watershed. For each map, an overlay analysis was performed, and to determine the land cover change scenario model, an analysis of the erosion value and the morphometric characteristic values of the Kuranji watershed was also carried out. So that it can be determined the appropriate land cover in the area. Based on the data used, the criteria that were changed were only land cover, while the other criteria were fixed.

4. RESULT AND DISCUSSION

4.1 Surface Runoff and Erosion

The Kuranji watershed consists of 22 land units that have varying erosion values (E). The erosion value that exceeds the tolerable erosion (T) is found in samples 2, 9, 14, 19, and 21. The highest erosion value on the built-up area is found in sample 19 (Ent-A-Pmk), which is 19.43 tonne/hectares/year, with an amount of surface runoff (Q) of 1,965,379.74 m^3. The highest erosion value on land that has vegetation is found in sample 2 (Ept-E-Kc), which is 16.60 tonne/hectares/year, with a total surface runoff of 141,634.35 m^3. The total erosion generated in scenario 0 is 122.36 tonne/hectares/year. The high level of erosion is due to the presence of logged-over shrubs in protected and conservation forest areas. This high erosion causes critical land because high water runoff will cause the land to be degraded. According to Istijono [4]**,** forest reduction results in critical land and has an impact on landslides, especially on steep slopes. Scenario 0 results in a high peak flow rate of 712.87 m^3/sec and the potential for flooding. This is also confirmed that the Kuranji watershed has the potential for flooding due to low infiltration [5]. Details can be seen in Table 1.

The high level of erosion in sample 19 built land is due to the high surface runoff the erosivity of rainfall (RM) and soil erodibility (K). Even though sample 19 is on flat and long slopes and low slopes (LS), erosion is still large because it is a largely residential area with crop management values (C) and soil conservation measures (P) abbreviated as CP.

Sample 2 with mixed garden land cover has high erosion. Supposedly, land cover that has vegetation will produce low erosion. The high level of erosion is caused by topographic factors which represent the influence of the length and slope (LS) with a value of 24.78. In line with this, Li [6] explain that erosion occurs due to surface runoff, and erosion increases when the slope conditions get steeper. Added by Liu [7] increased rainfall and slope resulted in runoff and erosion increasing rapidly and getting bigger.

Low erosion values are generally found in forest land cover. Even though the RM and LS values are high, erosion is still low, because forests have dense vegetation and can reduce splash erosion due to rainfall kinetic energy. As in sample 15 (Ept-E-Htn), the resulting erosion is 0.11 tonne/hectares/ year. Even though this area is on a steep slope, the erosion that occurs is still minor. This is due to the low erodibility and CP values of 0.001.

Zema [8] argues that forest vegetation can reduce 45% of the total rainfall that falls in the watershed area. Huang [9] added that forests can reduce sediment runoff, run-off, and soil erosion.

The low erosion in forest areas is because forest areas have high organic matter. Organic matter can improve soil structure, increase infiltration and increase soil erodibility so that erosion is reduced. Zeng [10] added that organic matter can improve soil aggregate so that the soil is not prone to erosion. Also added by Anderson [11] that the infiltration rate has a positive correlation with soil organic matter. The greater the amount of organic matter in the soil, the more infiltration increases. According to Zhao [12], the high content of soil organic matter can give the form of irregular aggregate pores, this is what makes the infiltration bigger.

It can be concluded that forest areas can reduce rainfall kinetic energy which can damage the soil surface so that soil aggregate damage does not occur. Infiltration persists, runoff and erosion are small.

4.2 Optimization of Land Use

The scenario approach carried out in the Kuranji watershed uses the SMCA model based on the value of land unit erosion. The value of erosion in land units is the basis for optimizing land cover so that the amount of erosion and surface runoff can be reduced. The determination of this scenario is also based on the value of erosion in each land unit, whether it exceeds the tolerance limit or has an erosion value that is classified as high.

Determination of the scenario also looks at the status of forest areas that are in protected areas, conservation areas, or other use areas (APL). If it is in conservation and protected area, the area must be reforested. If it is in an APL or cultivated area, it can be directed to become a mixed garden and settlement. The level of the slope is also a reference in determining residential areas. Cultivation areas that are on slopes above 15% are used as mixed gardens and below 15% can be used as residential areas. The consideration of the designation of residential areas is also based on the Regional Regulation of the City of Padang No. 10 of the year 2011 which states that the development of Padang City is directed towards the east. Vogdrup-Schmidt [13] explained that the multi-criteria spatial approach is a decision-making tool and can show the most suitable areas. Adiat [14] added that the spatial model of GIS-based decision-making can produce accurate and reliable predictions if the criteria used are coherent. Van Haaren [15] added that GIS-based SCMA can assess large geographic areas and display the results on a map. For more details, the scenario in the Kuranji watershed is described below.

Scenario 0 is the land cover by current conditions (Fig. 3). Scenario 1 increases the forest area by 38.91 hectares or 0.17% slope E on logged scrubland in conservation areas (Sc to Frs E). Increase forest area by 147.13 hectares or 0.65% slope D on logged scrubland in protected forest areas (Sc to Frs D) with annual crops or MPTS (Multi Purposes Trees Species). Increase density in the mixed garden (Mg +) by 190.49 hectares or 0.85% slope E on mixed garden land. Spatially it can be seen in Fig. 4.

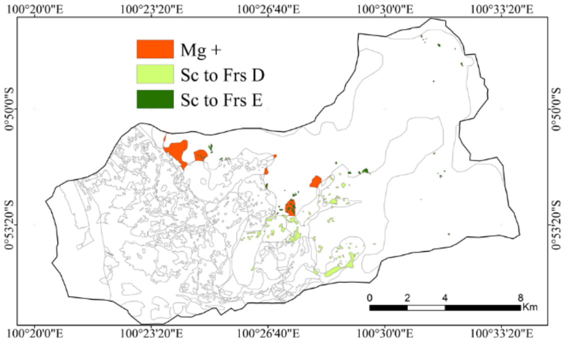

Fig. 4 Scenario 1 land cover change

Scenario 2 continues from scenario 1 and there is an added part, namely increasing the area of mixed gardens by 563.64 hectares or 2.51% slopes C, B, and A on scrubland in the cultivated area. Spatially it can be seen in Fig. 5.

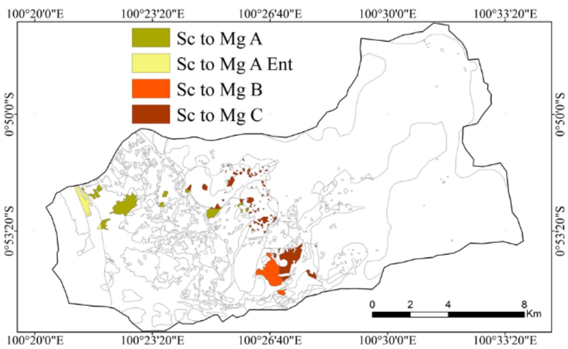

Fig. 5 Scenario 2 land cover change

Scenario 3 continues from scenario 2, but there are changes, namely increasing the residential area by 350.62 hectares or 1.56%, 227.61 hectares or 1.01% slope A and 123.01 hectares or 0.55% slope B on land shrubs located in the cultivated area. Spatially it can be seen in Fig. 6.

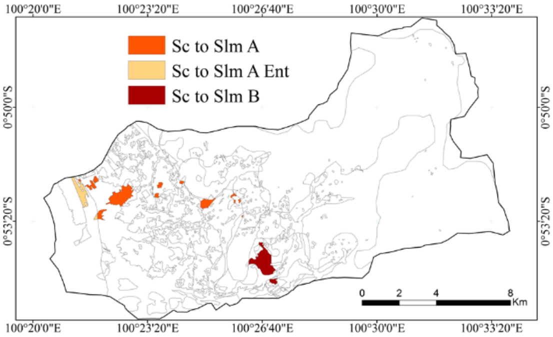

Fig. 6 Scenario 3 land cover change

Scenario 4 continues from scenario 3, but there are changes, namely increasing the area of mixed gardens by 123.01 hectares or 0.55% slope B on scrubland in the cultivated area. Spatially it can be seen in Fig. 7.

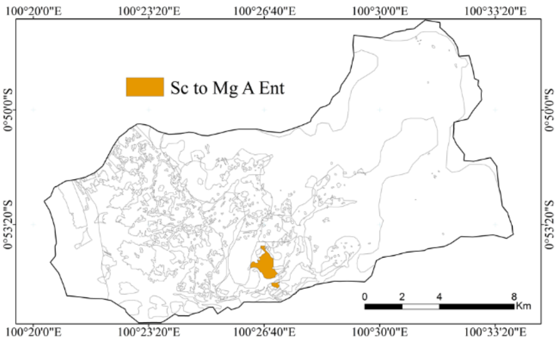

Fig. 7 Scenario 4 land cover change

Scenario 1, the land cover that changes is the mixed garden sample 2 by increasing the density of the mixed garden. Erosion generated from 16.60 tonne/hectares/year to 8 tonne/hectares/year. Shrubs in protected and conservation areas (samples 12 and 16) were turned into forest, from the erosion of 5.36 and 7.33 tonne/hectares/year to 0.01 and 0.02 tonne/hectares/year. According to Appraisal [16], soil that has vegetation cover can reduce erosion. The total erosion generated in scenario 1 is 98.87 tonne/hectares/year and the runoff is reduced by 65,504.12 m^3 or 0.5%. The peak discharge is reduced by 31.42 m^3/sec or 4.10%.

Scenario 2 is a continuation of scenario 1 but there are additions, namely by changing the cover of shrubs in the cultivated area (samples 3, 6, 10, and 20) into mixed gardens. So that the erosion value from 12.08 tonne/hectares/year to 11.78 tonne/ hectares/year. The total erosion generated in scenario 2 is 90.54 tonne/hectares/year and the runoff is reduced by 89,589.70 m^3 or 0.68%. The peak discharge is reduced by 35.83 m^3/sec or 5.02% from scenario 0.

Scenario 3 is a continuation of scenario 2. But in the mixed garden with sulfur A and B, the designation is changed for settlement found in samples 3,10 and 20. Erosion generated from 4.71 tonne/hectares/year to 15.65 tonne/hectares/year. The total erosion produced in scenario 3 is 05.79 tonne/hectares/year and the runoff is reduced by 63,664.70 m^3 or 0.49%. The peak discharge is reduced by 21.16 m^3/sec or 3.06% from scenario 0.

Scenario 4 is also a continuation of scenario 3. However, the settlement slope B in sample 10 is converted into a mixed garden. So that the resulting erosion from 9.98 to 0.96 tonne/hectares/year. The total erosion produced in scenario 4 is 96.61 tonne/ hectares/year. The surface flow is reduced by 69,182.50 m^3 or 0.53%. The peak discharge is reduced by 23.26 m^3/sec or 3.26%.

For more details on the trend of land cover change, which is divided into 4 scenarios that affect the value of erosion and surface runoff, it can be seen in Fig. 8.

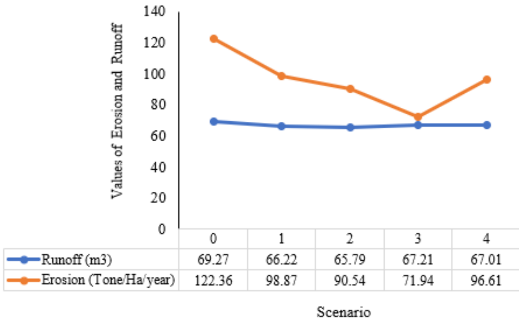

Fig. 8 Trends in the erosion and runoff values of changing scenarios.

Scenario 0, namely the existing conditions produce the highest erosion and surface runoff values than other scenarios. After optimizing land cover by converting former illegal logging shrubs in conservation and protected areas into forests, as well as increasing the density of mixed gardens, the value of erosion and runoff is reduced. According to Chaidar [17], reforestation in forest areas can reduce soil erosion.

In scenario 3, the change of shrubs into settlements area on flat slopes causes the erosion value to decrease but the development of settlements area on steep slopes will result in increased erosion values and runoff coefficients. In scenario 3, it is also seen that the runoff coefficient does not change significantly. Scenario 3 is by the spatial plan for the city of Padang in 2010 -2030, namely the area of the settlement will be developed to the east of the city. Based on the analysis, it is found that scenario 3 is suitable for regional development because it will not cause environmental degradation. Scenario 2 produces a higher erosion value than scenario 3. This is due to the increasing density of mixed gardens on steep slopes so the potential for erosion is higher because runoff on steep slopes is very fast carrying large volumes of water.

5. CONCLUSION

The high runoff and erosion in the Kuranji watershed are dominated by low-density residential land cover, shrubs, and mixed gardens. The total erosion in the current condition (scenario 0) is 122.36 tonne/hectare/year. After modeling, in scenario 1 the erosion becomes 98.87 tonne/hectare/year, surface runoff is reduced by 0.50%, and peak discharge is reduced by 4.10%. Scenario 2 erosion becomes 90.54 tonne/hectare/year, surface runoff is reduced by 0.68%, and peak discharge is reduced by 5.02%. Scenario 3 erosion becomes 71.94 tonne/hectare/year, surface runoff is reduced by 0.49%, and peak discharge is reduced by 3.06%. In Scenario 4, erosion is 96.61 tonne/hectare/year, surface runoff is reduced by 0.53% and peak discharge is reduced by 3.26%. Built-up areas (residential and industrial areas) should be developed in areas with flat slopes because the erosion value is smaller than in areas with steep slopes. The optimization result that is suitable for the settlements area is scenario 3 because the erosion value is smaller than scenarios 1, 2, and 4. Scenarios 1, 2, and 4, that have steep slopes should be used as environmental buffer zones (vegetation areas and protected forests).

6. ACKNOWLEDGMENTS

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