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Land Use Optimization in Asahan Watershed with Linear Programming and SWAT Model

Ahmad Dany Sunandar [a]*, Endang Suhendang[b], Hendrayanto[c], I Nengah Surati Jaya[d], Marimin[e]

[a] *Forestry Research and Development Institute of AekNauli, km 10,4 SibagandingParapat, North Sumatra, Indonesia, Post Graduate Student in Bogor Agricultural University (IPB)*

[b,c] *Forest Management Department, Bogor Agricultural University (IPB), Bogor, Indonesia*

[e] *Agricultural industry technology Department, Bogor Agricultural University (IPB), Bogor, Indonesia*

[a]*Email: sunandar_dany@yahoo.com*

[b]*Email: e_suhendang@yahoo.com*

[c] *Email: hendrayanto@gmail.com*

[d]*Email: suratijaya@yahoo.com*

[e]*Email: marimin07@yahoo.com*

Abstract

Erosion occurring within a watershed can threaten land use sustainability through land quality degradation. To minimize erosion in Asahan Watershed, this study employs land use optimization technique through linear program and spatial optimization. Optimization wasapplied to minimize erosion with a number of constraints and taking the land's economic value into consideration. Spatial optimization uses the query method based on land capability category to obtain a combination of optimal land use area to be simulated using the SWAT model. Results indicate that to minimize erosion, there is a large change in forested land area, increased plantation and rice field areas, reduced dry farm land areas, and barren land soil and shrubs converted into other vegetated areas. These changes can reduce erosion without reducing water yield in the SWAT model simulation.

.***Keywords:*** Erosion; Asahan Watershed; Land use optimization; SWAT model; linear programming.

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* Corresponding author.

E-mail address: sunandar_dany@yahoo.com.

1. Introduction

Watershed is a space that may be supposed as a processor that processes inputs (rainfall) to a wide range of outputs. The major output expected from a watershed is the water output usable to people inhabiting the area to meet their various needs, aside from erosion being another output. A watershed's land use will have impacts on the water and erosion it produces [1, 2]. On the one hand, presence of land cover vegetation such as forests or mixed gardens will reduce the water output as they consume more water for transpiration. On the other hand, they also contribute to erosion reduction. Among a variety of land use types, agricultural land use is the largest erosion-producing factor [3, 4, 5,6]. Population growth also triggers land use change and agricultural land expansion, as an implication of meeting people need's for food, which may potentially trigger surface flow and erosion increase. Several factors causing erosion are inappropriate agricultural practices, deforestation, land abandonment and forest fire [7].

Land use and cover are both the factors most affecting surface flow and erosion intensity and frequency [8]. There are many research in land use change impacts on decreasing run off and soil erosion, some of them are: land cover type effect in various land uses [9], land use and cover types effects to erosion [10, 4]. Land cover vegetation presence plays significant roles in reducing surface flow velocity [11] and erosion as vegetation is a shell or supporting layer between atmosphere and soil [12], and land cover in the form of forest is an effective controller to reduce erosion [6, 13, 14, 15]. Erosions occurring in undisturbed natural forests are also considered an indicator in assessing erosions in other land uses [16] and forest management activities [17, 18]. However, the more percentage of forest area in a watershed, the less water is produced by the watershed due to the intense evapotranspiration [19]. Such water output reduction definitely affects the downstream area's other land uses because trees and other forest vegetation generally consume more water and, given the fact that water resources are limited, they become competitors to other water users in the downstream area, such as farmlands, industries and households [3].

Water output and erosion in a land use can be estimated using hydrological model approach. One of the hydrological models commonly used and applied to estimate land use surface flow and erosion rates is Soil and Water Assessment Tool (SWAT). This is a physic-based hydrological model for continuous occurrences, developed to predict practical management change impacts on water, sediment and chemicals from farm wastes in a vast and complex watershed with a wide range of soil types, land uses, and land management in a long term [20]. SWAT can also make simulation to identify surface and underground flows, erosion and chemical movement in a watershed.

Asahan Watershed is one of North Sumatera Province priority watersheds based on Minister of Forestry Decree No. 328/Menhut-II/2009. As a developing area, particularly due to massive farm and plantation areas, the land use changes such as settlement, farmland and plantation area expansion, as well as land cover changes from vegetated to non-vegetated conditions, will change the water output and river water discharge [21], increase the surface flow [22] having impacts on the erosion rate increase [23], hence leading to the land productivity decrease. Although there is no data on actual erosion occurring in Asahan Watershed, but to illustrate, sedimentation in Asahan River Estuary in 2013 reached 331,924 cubic meters per month [24]. To ensure water availability and minimize erosion, land use approach can be done through various land use combination in the Asahan watershed. Land use optimization for watershed level can help decision makers determine the best land use combination for conservation of watershed functions without sacrificing economic values that can be obtained from the available land use [25].

This research's optimization model development is meant to obtain the most appropriate land use, aiming primarily at minimizing erosion without decreasing its water yield. This optimization was performed using linear programing with a variety of constraint functions based on the existing land use conditions.

2. Materials and Methods

2.1. Research location

This research took place in Asahan Watershed (99.03-99.96°E 2.40-3.04°E) in August-December 2013. The research site is presented by Figure 1. Asahan Watershed area based on the delineation result is 2,833.86 km^2, where the major river is 170 km length. The watershed has steep topography around the upstream part, but becomes plainer to the middle and downstream parts, with elevation ranging from 0 to 2,100 m a.s.l. The primary land uses are dominated by dry land agriculture, oil palm plantations and rubber fields as the area's main commodity. The annual rainfall varies between 1,924 and 3,406 mm (according to 1985-2010 data).

The Upstream Asahan Watershed border Toba Lake water catchment and it empties into Malacca Strait, with the major river of 170 km length. The primary land uses in Asahan Watershed are dry land farms and plantations. The mainly practiced dry land farms are rain-fed rice fields (particularly at the upstream region), seasonal farming, coffee and horticultures. As for the plantation types, the dominant commodities are oil palm (including those managed by private companies, State-Owned Enterprises (BUMN), and community) and rubber. The remaining dry land forest cover only appears at the watershed upstream part with an area of 46,757 hectares (16.50% of the watershed total area). This forest area has been fragmented instead of forming one single intact forest block, and administratively belongs to three local government territories, which are Toba Samosir, Asahan and Simalungun Districts.

The land use data employed in this research is 2010 Landsat image interpretation result dividing the land uses into 11 classes. Information on the soil types and attributes (number of layers, each layer thickness, soil bulk density and fraction) were obtained from the Research Centre for Soil and Agroclimate (Puslittanak) based on the reconnaissance scale soil map and other data from observation, i.e. soil bulk density, number of layers, each layer thickness and soil fraction). The climatic data (daily rainfall, daily maximum-minimum temperatures, relative humidity, duration of sunlight exposure and average daily wind velocity) were obtained from Meteorology, Geophysics and Climatology Agency for the stations located in Asahan Watershed. The calibration and validation process comparative data are the watershed river discharge data (the data is available covering 1990-2010 period, except for 2004 and 2008), obtained from Medan River Region II Centre and Irrigation Research and Development Department of Ministry of Public Work.

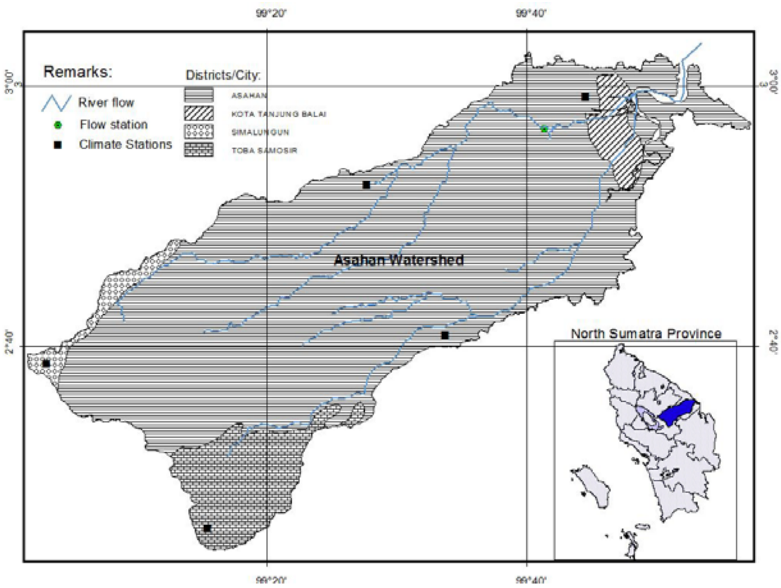

Fig. 1. Research location

2.2. Land Capacity Classification

Land capacity classification is a form of systematic land assessment in which land components are systematically classified into several categories based on the properties constituting potential or constraint to its sustainable use [12]. Land capacity assessment criteria are based on the properties mentioned in Table 1 below.

Table 1. Land capacity classification criteria

Constraint Factor	Land Capacity Class							
	I	II	III	IV	V	VI	VII	VIII
Slope	A	B	C	D	E	F	G	H
Erosion Sensitivity	E_1,E_2	E_3	E_4,E_5	E_6	(1)	(1)	(1)	(1)
Erosion Level	A_0	A_1	A_2	A_3	(2)	A_4	A_5	(1)
Soil Depth	k_0	k_1	k_2	k_3	(1)	(1)	(1)	(1)
Soil Texture	$t_1t_2t_3$	$t_1t_2t_3$	$t_1t_2t_3t_4$	$t_1t_2t_3t_4$	(1)	$t_1t_2t_3t_4$	$t_1t_2t_3t_4$	t_5
Permeability	P_2P_3	P_2P_3	P_2P_3	P_2P_3	P_1	(1)	(1)	P_5
Drainage	d_1	d_2	d_3	d_4	d_5	(2)	(2)	d_0
Gravel/rock	b_0	b_0	b_1	b_2	b_3	(1)	(1)	b_4
Flood potential	O_0	O_1	O_2	O_3	O_4	(2)	(2)	(1)

Source: [12]; Note: (1) may possess random properties; (2) not applicable

The land capacity classification in this research applies geographic information system by overlaying soil maps with erosion map resulted from SWAT model where scoring is previously performed on each constraint factor. The greater the value is, the greater the constraint factor will be, thus the land capacity becomes reduced (approaching the capacity class VIII). The relationship between land capacity class and land use intensity and types is presented in Table 2.

Lands with capacity class I has no constraint factor to vegetation, and the higher the class, the more constraint factors will exist. Lands from capacity classes I to IV are suitable for agricultural crops, pasture, grassland and forest. As for those from classes V to VIII, they are more suitable for grassland, pasture, forest and other natural vegetation rather than for agricultural uses. And more particularly for the class VIII, they must be left on their natural conditions [26].

Table 2. Relationship between land capacity class and land use intensity and types

Land Use	Land Capacity Class							
	I	II	III	IV	V	VI	VII	VIII
Forest :								
Protection Forest/nature reserve	■	■	■	■	■	■	■	■
Limited Production Forest	■	■	■	■	■	■	■	
Pasture:								
Limited	■	■	■	■	■	■	■	
Moderate	■	■	■	■	■	■		
Intensive	■	■	■	■	■			
Agriculture:								
Limited	■	■	■	■				
Moderate	■	■	■					
Intensive	■	■						
Highly Intensive	■							

2.3. SWAT model simulation

To obtain data on Asahan Watershed's water yield and erosion level, SWAT model is applied. The SWAT model applied in this research has been calibrated and validated. The calibration process generated an NSE value of 0.88 with R^2= 0.89, while the validation process generated an NSE value of 0.5 with R^2=0.55, where this value falls under the category of 'sufficient' [27]. The calibrated parameters are as mentioned in Table 1. The produced land use scenario is then applied in SWAT. The climate data employed are those from 1985-1991, and the data extraction was carried out for the same year (1990). For erosion calculation, C value and Manning roughness (OV_N) are adjusted referring to [28]. The extracted data are the water yield (mm/year) and erosion (ton/hectare/year).

2.4. Optimization model

Before optimization was applied, value for each bond was calculated. Land value and tolerable soil loss (TSL) can be seen in Table 3 and 4 and erosion for each land use was showed in Figure 2. Land value was calculated based on average land productivity of oil palm, rubber plant and coconut plant and its price in local market. TSL value was calculated based on Hammer's method [29] with soil use age of 200 years.

Table 3. Land value for dry farm land, plantation and paddy field

Land use	Land value (Rp/hectare/year)
Dry farm land	3 503 919
Plantation	24 001 250
Paddy field	21 148 842

Table 4. Tolerable Soil Loss (TSL) in Asahan Watershed (ton/hectare/year)

No	Soil Type (PPT Classification)	TSL
1	Aluvial	50.76
2	HidromorfKelabu	45.56
3	KompleksPodsolikCoklatdanLatosol	57.29
4	PodsolikMerahkuningLatosoldanLitosol	58.59
5	Latosol	42.44
6	PodsolikMerahKuningdanLatosol	63.34
7	OrganosoldanGlei Humus	38.90
8	PodsolikCoklatdankelabu	48.31
9	PodsolikMerah	84.40
10	PodsolikMerahKuning	65.21
11	RegosoldanLatosol	64.17

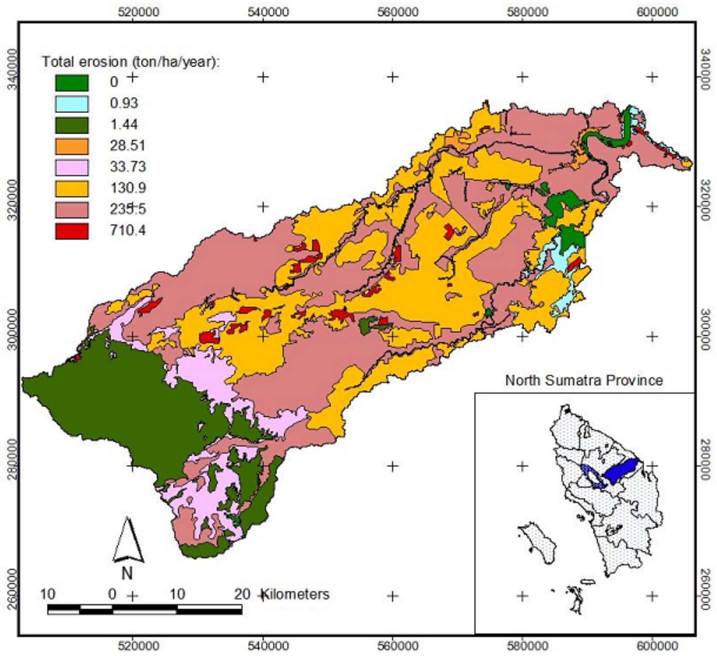

Fig. 2. Erosion in asahan watershed (SWAT model simulation result)

The optimization applies linear programming where the objective function is to minimize erosion:

$$\text{Min } Z=\sum_{j=1}^{n} cjXi\,,\ where j=1,2,\ldots,n$$

with the constraint functions as follow:

Table 5. Constraint functions used in linear programming

No	Constraint Functions	Explanation
1	$\sum_{i=1}^{n} A_{i1} = \sum_{i=1}^{n} A_{i2}$	The total area of each land use must be equal to the watershed area.
2	$X_{3(2)} \geq X_{3(1)}$	Urban area can be larger from actual with maximum 10% area addition
3	$X_{1(2)} \geq X_{1(1)}$	Forest land area after optimization can be larger then actual
4	$X_{7(2)} \geq X_{7(1)}$	Paddy field can be larger then before
5	$\text{Erosion}_{\ i(2)} \geq 0$	Erosion from each land use is positive but minimizing to zero
6	$\sum_{i=1}^{n} Erosion_i \leq \text{TSL}$	Total soil loss after optimization should not over the limit (TSL)
7	$\text{WY}_{\ i(2)} \geq 0$	Water yield from each land use should be positive
8	$I_{i(2)} \geq I_{i(1)}$	Land value after optimization should not reduce then before (based on year 2013price in North Sumatra province)
9	$Xi \geq 0$	Every land use area should be positive

The income constraint approach is as follow. Income is calculated from land productivity average multiplied by the commodity value in one year, and the land use to calculate is dry land farming, rice field and plantation. Land value calculation for dry land farming is made from the average production of corn, cassava and nuts as the primary commodities. As for plantation, it is calculated from oil palm and rubber value (owned by community, government or private) as the primary commodities. The commodities' productivity and values are calculated based on the data issued by North Sumatera Utara Statistical Board [30]. And as for the other values of land uses, the following assumptions apply.

1. Forest value is considered 0 as they are protection forests and no permanent activities are carried out for harvesting forest products, both in dry land and wet land (mangrove conservation) forests.
2. Value of rice field must be greater than settlement land use to prevent from rice field decrease.
3. Other uses' values (raw, are considered 0 due to no production activities, shrubs, bare soil and water body.

The optimization model is developed using SOLVER extension on Microsoft Excel 2010 software. Spatial reference from linear programming optimization result which do not have spatial reference was done by using query methods [31] based on its land capability and new optimized land use is a result. This new land use was simulated into SWAT model to estimate water yield and erosion in the watershed.

3. Result and Discussion

According to the Landsat image analysis, Asahan Watershed 2010 land uses is presented by Figure 3. Dry land farming, plantation and dry land forest are the dominating land uses in the watershed. According to [30], the primary plantation commodities from this area are oil palm, rubber and coconut (copra). As for the farmland, the primary commodities are cassava, corn, nuts and sweet potato. These are made basis to the determination of land values and uses for dry land farming and plantation. Each land use area is presented by Table 6.

Table 6. Area of each Asahan Watershed land use

No	Land use	Area (ha)	Percentage (%)
1	Dry land forest	47 803	16.82
2	Wet land forest	462	0.23
3	Urban area	2 601	0.91
4	Plantation	77 867	30.01
5	Dry farm land	118 767	39.71
6	Swamp	222	0.08
7	Paddy field	3 313	1.16
8	Shrubs	21 163	7.42
9	Barren land	5 040	1.65
10	Water body	2 923	1.02
11	Vegetated swamp	2 816	0.99

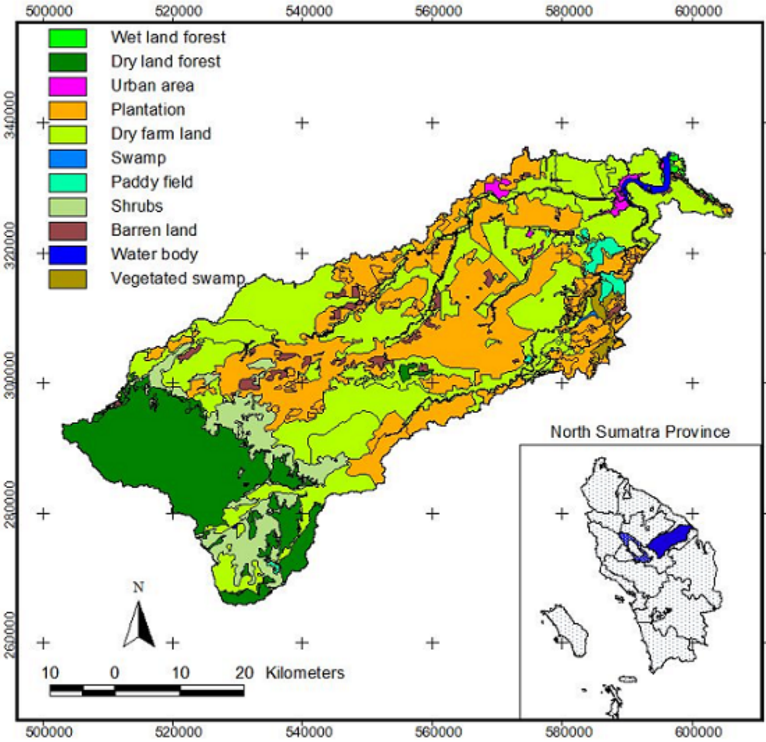

Fig. 3.Asahan Watershed 2010 land use distribution

According to the SWAT simulation result, Asahan Watershed water output and erosion from each land cover is as presented in Table 7. This calculation is made for the same year (2010) from each land use to generalize the incoming rainfall.

Table 7. Water yield (mm) and sediment (tonne/ha/year) from SWAT simulation

Year	Water Yield	Sediment
1990	818	35
2002	1,089	62
2010	1,092	53

Detail of the optimization result is presented in Table 8. Based on the result, it is known that the land use types changeable are plantation, dry land farming, swamp, bush and barren land. Being the largest land use type in Asahan Watershed, dry land farming can still be extensified while plantation, to the contrary, may potentially reduce. Barren land area reduction is expected to reduce erosion by converting into agricultural land. This can also lever up the land economic value. Such also applies to bush area that can be converted into agricultural land, hence it's increasing values and controlled land erosion by applying land conservation techniques in agricultural lands. For use of swamp area, the optimization result area is greater than the actual size, indicating the importance of water catchments to accommodate water excess during wet seasons to allow flood risk reduction and water storage during the dry ones. Erosion reduction by estimate compared to actual erosion by linear program is 4.05 tons/hectare/year from 30.38 tons/hectare/year to 26.33 tons/hectare/year.

Table 8. Actual land use area and optimization result

Land Use	Actual		Linear Program Optimization		Spatial Optimization	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Dryland Forest	47 803	17.07	47 803	17.07	47 803	17.07
Wetland Forest	462	0.16	462	0.16	462	0.16
Settlement	2 601	0.93	2 601	0.93	2 648	0.95
Plantation	77 867	27.80	74 584	26.63	74 610	26.64
Dryland Agriculture	118 767	42.41	141 254	50.44	141 198	50.42
Swamp	222	0.08	997	0.36	995	0.36
Rice field	3 313	1.18	3 313	1.18	3 313	1.18
Bush	21 163	7.56	6 224	2.22	6 208	2.22
Barren land	5 040	1.80	-	0.00	-	0.00
Vegetated swamp	2 816	1.01	2 816	1.01	2 816	1.01

To obtain spatial optimization from linear program optimization results, the first indication is to overlay land use with land capability category to obtain combination between land use and land capability as presented in Table 2. Based on Table 2 above the optimum land area based on linear program results can be adjusted to convert into spatially data through query. Overlay between land capability categories and land use produced 58 land units.

Complete optimization results are presented on Table 9. Based on optimization results it is evident that land use that can be changed is forest, plantations, dry land farming, swamps, shrubs, and bare soil. Forest area from optimization results increased by 48,139 hectares or became 34.26% of the total watershed area. Dry land farms from optimization results were smaller than actual data, which decreased 25,757 hectares or decreased to 22.69% from its initial area. This reduction in farmlands is expected to reduce the occurring erosion because it concurs with [32, 4, 5] who stated that farm lands are the largest contributors to erosion from various land uses and therefore based on this optimization, agriculture land area decreased. It is the same case for bare soil, in which its land optimization is zero because bare soil is a source of erosion, as well as shrubs which value became zero. Reduction of dry land farm area is, from the watershed conservation view, is to reduce erosion rate due to high erosion levels which will reduce land productivity and increase production costs, can potentially increase chemical pollution from chemical fertilizer applications, and reduce the land's economic value.

Increased land use from optimization results are forest, plantation, and rice fields. Forest area increase is due to the relatively lower erosion levels in forests compared to those of other land use categories. Increase in plantation area is due to its relatively larger land value compared to dry land farms and smaller erosion level, meanwhile rice field area increased due to its minimum erosion levels. Changes in the areas of these various land use categories result in reduced erosion of 1.83 tons/ha/year based on calculations using the linear program.

Increased area for a number of land use categories by reduction of other land use areas is not always acceptable. Decreased farmland area from optimization results will cause loss of community income. Therefore one alternative solution is to implement agroforestry in farmlands. According to [2], agroforestry can maintain hydrological functions of protected forests and provide a source of livelihoods for communities. In addition, agroforestry system can also maintain slope stability [13] in relatively steep areas. Agroforestry can provide multiple benefits by maintaining the land's hydrological functions, reduce erosion rate, as well as provide income for the communities.

Table 9. Actual and optimised land use areas

Land Use	Actual		Linear Program Optimization		Spatial Optimization	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Dryland Forest	47,803	17.07	95,942	34.26	96,131	34.14
Wetland Forest	462	0.16	461	0.16	462	0.16
Settlement	2,601	0.93	2,601	0.93	2,658	0.94
Plantation	77,867	27.80	80,583	28.77	80,719	28.66
Dryland Agriculture	118,767	42.41	93,009	33.21	92,618	32.89
Swamp	222	0.08	143	0.05	189	0.07
Rice field	3,313	1.18	4,499	1.61	4,497	1.60
Bush	21,163	7.56	0	0.00	0	0.00
Bare soil	5,040	1.80	0	0.00	0	0.00
Vegetated swamp	2,816	1.01	2,816	1.01	2,816	1.01

Plantation area increase from optimization results is in accordance with tendencies occurring in Asahan Watershed, especially in Asahan District in which plantation areas are increasing along with increasing plantation commodity prices. According to [34], oil palm plantation area in Indonesia increase by 3.1 million hectares from 4.7 million hectares in 2001 to 7.8 million hectares in 2011. Based on data from the North Sumatra Province Statistical Bureau [30], core plantation area in Asahan District covered 18,584 hectares for oil palm, 70,796 hectares for rubber, 24,473 hectares for coconut, and 3,977 hectares for cocoa. For rice fields, additional land area to anticipate growing food demands in line with population growth and within the Asahan District Regional Spatial Plan (RTRW) was planned by adding more than 7,500 hectares new rice fields [35].

As presented on Table 10, there are differences in optimization result areas with that of the linear program through spatial optimization. This is because for spatial optimization, polygon area was previously determined from overlay results between land use and land capability category. For spatial optimization, land use change from actual to optimization results are done by taking land capability class into account referring to [12] in which land with category V-VIII capabilities are not suitable for agriculture or plantations are more suitable for forestation. In its implementation, when these changes occur in farmlands afforestation can be applied through agroforestry or mixed plantations to ensure the hydrological functions of the land.

These spatial optimization results are then applied to a SWAT model to understand changes in erosion and water yield. The result is a difference between actual land use and optimization results which is presented in Table 11. Simulation results show that there is a difference in water yield in which under actual conditions, water yield and erosion are 1,091.83 mm/year and 52.81tons/ha/year, respectively. The values after optimization are 1,092.52 mm/year for water yield and erosion level decreased to 27.95 tons/ha/year. This 47% decrease in erosion is due to increased effective forest area which is minimized erosion [36, 37]. On the other hand, decreased erosion does not only impact water yield results in which based on SWAT simulation, water yield from spatial optimization only decreased by 1.32 mm/year. Optimization results for land use with spatial referenceis presented on Figure 4.

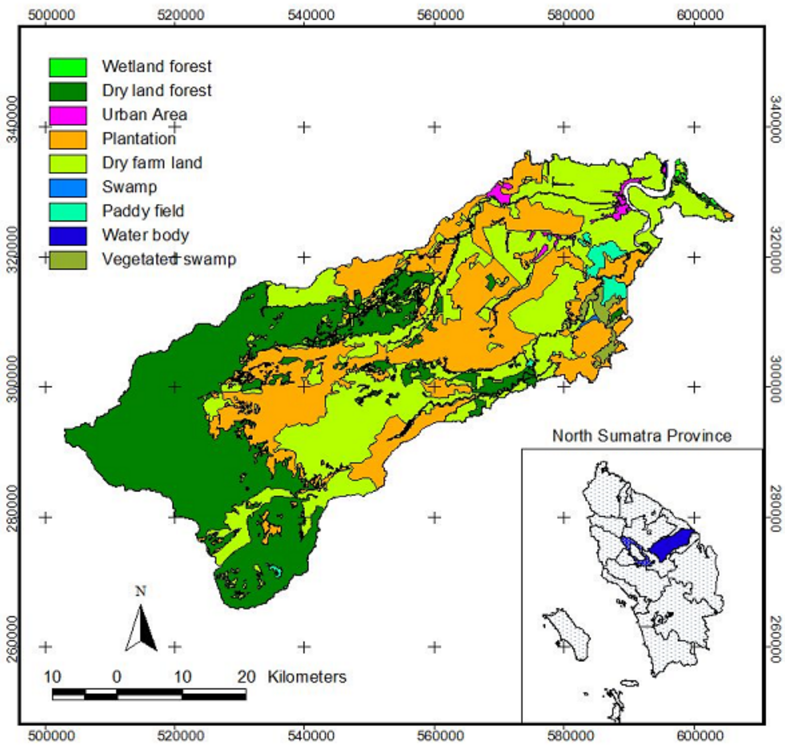

Fig. 4. Optimal land use in Asahan watershed

4. Conclusion

Minimizing erosion in Asahan Watershed land use can be done through optimization approach using linear program and query method to develop spatial optimization of these results. Optimization results for Asahan Watershed indicate that erosion can be reduced by increasing forest area, reducing dry land farm areas, and increasing plantation areas by eliminating barren land and shrubs. These land use areas change can reduce erosion without decreasing water yield and economic land value of the land. Forest area increase can be done through agroforestry, especially in areas with land capability categories that are not suitable for farmlands.

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