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ASSESSING SOIL EROSION IN BIREUEN DISTRICT ACEH USING USLE AND GIS MODELS

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ABSTRACT

Intensive land use in various fields allows land degradation to occur. One form of land degradation is soil erosion. This research aims to get an overview of the distribution of soil erosion in Bireuen Regency on various land uses. This research uses a descriptive survey research method with the Universal Soil Loss Equation (USLE) method approach and Geographic Information Systems. This research was conducted from June to August 2024, and the research area covered 17 sub-districts in the Bireuen district. To generate erosion distribution, data such as 10-year rainfall, land use type and soil biophysics were used. These data were obtained from BMKG, the World Rainfall Data Centre (CHRIPS), the Geospatial Information Agency, and DEMNAS. The data was then analyzed using the USLE equation and Arc GIS.10.8 software. The results of data analysis obtained that the distribution of soil erosion rates in Bireuen Regency consists of 0-20 tonnes/ha/year covering 84,297 ha, 20-60 tonnes/ha/year covering 41,327.34 ha, 60-180 tonnes/ha/year covering 32,954.82 ha, 180-480 tonnes/ha/year covering 17050.34 ha, and > 480 tonnes/ha/year covering 3,502.48 ha. Based on the classification of erosion hazard classes, the Bireuen Regency area has erosion at a very light-heavy level. The government and other stakeholders must apply sufficient soil conservation technology to produce sustainable land use.

Keywords: GIS; land use; soil erosion; USLE.

INTRODUCTION

Economic growth and increased development accompanied by population growth have resulted in land exploitation. Land utilization that does not follow land capability and suitability causes a more significant potential for land damage (Bashit, 2019). One common form of land damage is soil erosion (Satriawan et al., 2021), known as soil loss caused by the interaction of rainfall, soil, vegetation cover, slope/land morphology, and human activities (Satriawan & Fuady, 2015). Globally, soil loss due to erosion has rapidly increased land degradation (Sartori et al., 2019). Reduced crop yields, decreased surface water quality, and changed drainage channels can result from soil loss on agricultural land. (Kumarasinghe, 2021). Soil erosion is estimated at 12-15 hectares per year, which translates to an annual surface soil loss of 0.90-0.95 mm (Koirala et al., 2019), while (Pham et al., 2018) put the erosion rate in natural forests in Vietnam at 19 tonnes/ha/year. This escalation in soil loss is becoming more prominent as variations of climatic change and land use continue to increase (García et al., 2021).

Erosion is caused by agricultural practices that do not follow soil and water conservation standards, and erosion will impact the surrounding areas. It will cause sedimentation in downstream areas, which reduces the storage capacity of reservoirs and rivers or can even cause flooding in downstream areas (Ilhamni et al., 2023), reduce soil productivity, and damage ecosystems in highlands and mountains (Singh & Panda, 2017; Benavidez et al., 2018). According to Hossain et al. (2020) and Bindraban et al. (2012), increasing erosion has caused food production and livelihood problems.

Bireuen Regency has an area of approximately 1,798.25 km2, 17 sub-districts, 609 villages, and a population of 443,874 people (BPS, 2023). Bireuen Regency's population growth is increasing, accompanied by increased land use. This follows data on residential land use from the Regional Development Planning Agency (BAPPEDA), which states that in 2012, residential land of 11.47 km2 increased to 67.34 km2 in 2022. Landslides, floods, and erosion have been recorded in several areas of Bireuen Regency, identifying discrepancies between land use and land capability.

Efforts to control soil erosion can be made by analyzing the spatial distribution and rate of erosion using a modeling approach. One key element for modeling soil erosion is a precise earth's surface representation and investigating erosion hazard levels to calculate and predict soil particle loss (Efthimiou et al., 2017). Moreover, the erosion hazard classification and the risk assessment caused by erosion can be conducted at local, national, or global scales (Ilhamni et al., 2023; Lasaiba et al., 2023; Terranova et al., 2009; da Silva et al., 2011). Several models have been created to evaluate erosion resulting from on-site observations and statistical analyses. The Universal Soil Loss Equation (USLE) model is one of the most widely recognized models ((Wischmeier & Smith, 1978; Fiener et al., 2020). Together with the erodibility (K), erosivity (R), slope, and slope length (LS) factors, the cover management factor, also known as the C-factor, is the most significant of the USLE variables in terms of the sensitivity of the estimated soil loss and plays a significant role in controlling soil erosion(Prasuhn, 2022).

Numerous scholars have discussed integrating USLE and Geographic Information Systems (GIS) with remote sensing. Soil erosion over broad areas can be described by combining these two modeling systems(El Jazouli et al., 2017), Determine the amount of soil loss(Devatha et al., 2015), classify erosion hazard levels (Chen et al., 2021), and assemble data to calculate soil loss(Thakuriah, 2023). Using the USLE model and GIS, the analysis results can be presented through thematic maps in various scales and formats (Kardhana et al., 2024). The problem in this study is how the level and distribution of soil erosion in Bireuen Regency, which is one of the factors that cause critical land in order to plan control efforts to ensure the sustainability of land resources in this area. This research aims to get an overview of the distribution of soil erosion in Bireuen Regency on various land uses.

MATERIALS AND METHODS

This research was conducted within the Bireuen District of Aceh Province. This research was carried out from June to August 2024, and the research area covered 17 sub-districts in the Bireuen district. This study used the USLE method established by Wischmeier and Smith (1978) and a Geographic Information System (GIS) technique to assess an area's long-term erosion vulnerability. The primary purpose of this technique is to spatially forecast the degree of erosion susceptibility derived from the overlaying of feature data for land use, slope, and soil type in shape file (SHP) format.

The data used is divided into two types based on its source: primary and secondary. While primary data is obtained from field observations, including observations of the entire Bireuen Regency area and its documentation, secondary data is the data obtained from relevant agencies, including satellite imagery, offices within the scope of the Bireuen Regency Government, literature books, literature studies, scientific journals and the results of previous research reports (Table 1).

Table 1: Research data types and requirements

No	Type of Data	Data Source
1	Administrative Area of Bireuen Regency	- Inageoportal - BAPPEDA Kab. Bireuen
2	Slope and Length	- DEMNAS
3	Rainfall (2013-2023)	- CHRIPS - BMKG
4.	Soil Type	- Badan Informasi Geospasial (BIG)
5	Land cover	- RTRW Kab. Bireuen - Earth Explorer USGS
6	Function Area	- Dinas Lingkungan Hidup dan Kehutanan (DLHK) Kab. Bireuen

The tools used in this research are divided into 2 (two): tools used during field observations and data processing. Field observation tools consist of GPS and Digital Camera, while tools for data processing consist of Arc.GIS 10.8 software, Google Earth Pro, Global Mapper, and Microsoft Exel 2020.

Determination of the amount of erosion (Ton/Ha/Year) (A) using the Universal Soil Loss Equation (USLE) Model, which requires analysis of erosion-determining parameters, consisting of rainfall Erosivity (R), Soil Erodibility (K), Length and slope (LS), Land cover and management (CP), as follows:

$$A = R \times K \times L \times S \times CP \qquad (1)$$

Description: A : The amount of soil lost; R: Erosivity; K : Erodibility; LS : Length and slope; CP : Plant management (vegetation)/land cover.

Rainfall erosivity parameters are calculated from 10 years of rainfall data from the BMKG and CHRIPS websites. Rainfall erosivity data analysis using the Bols equation (Bols, 1978), as follows:

$$R = 6.119\ (CH)^{1.21}\ (HH)^{-0.47}\ (CHmax)^{0.53} \qquad (2)$$

Where: R is the rainfall erosivity, CH is the rainfall on a monthly basis, HH is the frequency of rainy days, and CHmax is the highest rainfall in a specified month.

The soil erodibility assessment refers to the types of soils found in Bireuen Regency and is classified based on (Dangler & El-Swaify, 1976) (Table 2).

Table 2. Soil erodibility index value (K)

No	Soil Type	Index K
1	Andisol (Hydrudans)	0.07
2	Andisol (Hapludans)	0.28
3	Inceptisol	0.23
4	Ultisol	0.16
5	Oxisol	0.03
6	Entisol	0.19
7	Alfisol	0.20
8	Vertisol	0.27

The slope factor (LS) was investigated by extracting the DEM of the research location into the slope using ArcGIS 10.8 software with the help of Slope tools. The slope was reclassified into five classes: flat slopes with slopes ranging from 0-8%, gentle slopes with slopes of 8-15%, moderately steep slopes with slopes of 15-25%, steep slopes with slopes of 25-45%, and very steep slopes with slopes >45%. Furthermore, the calculation of LS follows the formula LS = $(\text{flow acc.} \times \text{map resolution}/22.13)^{0.4} \times (\sin \text{slope}/0.0896)^{1.4}$ (Andriyanto & Suprayogo, 2015).

C and P variables, identified as CP factors in this study, defined the impact of conservation and vegetation management techniques on soil erosion control. The reference value for specific land use types was used to calculate the CP factor value(Table 3).

Table 3. Vegetation management (C) and control practice (P) index value

No	Land Use Type	Index CP
1	Secondary Dryland Forest	0.010
2	Plantation Forest	0.050
3	Shrubs	0.300
4	Settlements	0.950
5	Open Land	0.950
6	Water Body	0.001
7	Dryland Agriculture	0.280
8	Mixed dryland agriculture	0.190
9	Rice Field	0.014

RESULTS AND DISCUSSION

The Distribution of Soil Erosion in Bireuen Regency on Various Land Uses

1. Erosivity of Rainfall (R)

The erosivity factors include rainfall, the number of days with rain, and the 24-hour maximum rainfall, calculated from CHRIPS and BMKG Malikussaleh data. Through the variables of total rainfall, intensity, and distribution, rainfall strongly influences erosion. Rainfall erosivity, in turn, influenced the intensity of raindrop influence on the soil's surface, soil particle separation, the volume of surface runoffs generated, and erosion-induced damage. The erosivity values of this study were computed using rainfall data from the preceding ten years and the Bols formula (2013-2023) (Romdania & Herison, 2023). The annual erosivity values at the study site were 788.16 to 1520 mm/month based on ten years of monthly rainfall data. Considering that 52% of Bireuen Regency consists of moderately steep slope hills, the topography has the potential to cause more significant erosion. This is in line with the results made by (Lasaiba et al., 2023), who looked at the Wairutung watershed of Ambon Island, a hilly and steep-sloped area characterized by a significant level of erosivity. This is in line with (Zhao et al., 2021) research, which showed that at lower rainfall intensities, erosion will decrease, but at longer slopes, erosion will increase. In these circumstances, runoff and erosion will rise if ground cover is not there to protect the soil.2. Soil Erodibility (K)

Soil erodibility (K) illustrates soil's susceptibility to erosion. The soil's sensitivity to erosion is influenced by its water-absorbing capacity and resistance to external detriment. The soil type conditions at the study site consist of six different soil types, according to the 1:50,000 Scale Soil Map. These soil types are classified based on their components and soil physical and chemical properties. Table 4 shows the following soil classifications: Andisol, Entisol, Inceptisol (Aquepts), Oxisol, Alfisol, and Inceptisol. In addition, GIS analysis shows that the soil types consist of Entisols (12,428.5 ha), Inceptisols (Aquepts) 28,282.02 ha, Inceptisols (92,720.77 ha), Alfisols (3303.8 ha), Oxisols (3434.2 ha) and Andosols (30.49 ha). The soil types Inceptisol (Aquepts) and Inceptisol, with a K value of 0.23, are the soil types with the highest erodibility values (86.30% of the total area), but the soil type Andosol, with a K value of 0.28, does not significantly affect the USLE erosion values.

Table 4. Distribution of soil types and soil Erodibility (K) values in Bireuen District

No	Soil Types	Value of K	Area (ha)	Percentage (%)
1	Entisol	0.19	12.428,50	8,86
2	Inceptisol (Aquepts)	0.23	28.282,10	20,17
3	Inceptisol	0.23	92.720,77	66,13
4	Alfisol	0.20	3.303,80	2,36
5	Oksisol	0.03	3.434,19	2,45
6	Andosol	0.28	30,49	0,02

According to research by Olaniya et al. (2020), a high soil erodibility value will cause the soil's ability to erode higher. Different types of soil have different levels of erodibility and susceptibility to erosion. If the soil can withstand heavy rainfall, the likelihood of erosion will be reduced, and vice versa. Soils with low erodibility and high erosion resistance are more susceptible to erosion (Satriawan & Fuady, 2015). According to (Fauzi et al., 2024), Inceptisol soil type has the highest erodibility value due to the lower permeability factor than other soil types. Soil permeability concerning erosion is related to the infiltration rate because the capacity of the soil infiltration rate determines the amount of water that will flow on the surface as surface flow.

3. Slope and Length Factor (LS)

Topographic factors that affect the amount of soil eroded are slope and slope length. Slope steepness and slope length affect erosion through runoff, which increases with slope length. Since LS values are high in areas where streams converge, soil erosion is expected to be higher in regions where such convergence occurs. Slope affects surface runoff velocity, having a significant impact on erosion. Slope values, surface runoff volume, and erosion risk will reduce the likelihood of infiltration or water seepage into the soil. LS values were provided from the Digital Elevation Model (DEM) data extraction, resulting in 5 slope classes at the study site. According to the results of GIS analysis, flat slopes have the largest area of 55,015.26 ha, followed by moderately steep (35,087.34 ha), gentle (30,747.93 ha), steep (30,325.94 ha), and very steep (27,957.35 ha) slope classes (Table 5). This indicates that the cumulative soil loss after rainfall increases with the slope gradient with varying rainfall intensities, with more pronounced loss observed on steeper slopes. The degree of soil erosion increased as the slope's inclination increased, as reported by Koirala et al. (2019) in five different slopes.

The topographic variables most influencing runoff and erosion are slope and slope length. The slope determines the speed at which runoff moves soil particles that are destroyed by rainwater blows, while the length of the slope determines how much soil particles are carried away by surface runoff. Huang et al. (2020) stated that erosion will increase along with the length and inclination of the slope. Land surfaces with steeper slope thresholds enhance surface flow velocity and increase the water's energy to displace material; hence, more soil is exposed to rainfall impact. As a result, the land surface can become steeper, which will multiply the erosion rate. This is due to the high level of slope, which causes surface flow to run faster than usual, which causes the amount of water entering the soil to decrease. Related to this, Dewi et al. (2024) stated that low levels of conservation on land with moderately steep - very steep topography can lead to an increase in several effects, including reduced infiltration capacity, increased velocity, and surface flow, enhanced flow energy of surface transport, as well as intensified erosion.

Table 5. Distribution of LS values in Bireuen Regency

No	Slopes	Value of LS	Area (ha)	Percentage (%)
1	0 - 8 % (Flat)	0.4	55.015,26	30,71
2	8 - 15 % (Ramps)	1.4	30.747,93	17,16
3	15 - 25 % (Slightly Steep)	3.1	35.087,34	19,59
4	25 - 40% (Steep)	6.8	30.325,94	16,93
5	> 40% (Extremely Steep)	9.5	27.957,35	15,61

4. Land use factor (CP)

Land use is the next factor affecting erosion in terms of defending the land surface from damage. The vegetation characteristics covering the soil and the land use type form the conservation direction (CP). GIS analysis was used to establish land use type distribution to measure the CP factor value. The results of the land use analysis in Bireuen District showed 17 different land use types with their respective CP values (Table 6).

Table 6. Vegetation and soil management value factors (CP)

No	Land Cover	Value of CP	Area (ha)	Percentage (%)
1	Parking area and field	0.950	8.10	0.005
2	Industrial and commercial buildings	0.950	51.25	0.030
3	Volcanic sand beach	0.950	181.80	0.100
4	Forest	0.010	69.344.93	38.570
5	Mixed gardens	0.190	54.324.24	30.220
6	Other freshwater ponds	0.001	8.04	0.004
7	Open Land	0.950	617.52	0.300
8	Estate	0.280	18.022.74	10.030
9	Settlements	0.950	6.734.89	3.750
10	Mining	0.950	4.69	0.003
11	Inland swamp	0.300	274.74	0.150
12	Rice fields with continuous paddy	0.014	16.793.79	9.340
13	Shrubs	0.300	7.178.36	3.990
14	Rivers	0.001	1.162.15	0.650
15	Fish/shrimp farms	0.001	4.900.86	2.730
16	Another water body	0.001	163.51	0.090
17	Irrigation reservoir	0.001	4.64	0.003

Table 6 shows that the highest CP value of 0.95 is found in the land use of settlements, mining, parking areas, industrial buildings, volcanic coastal expanses, and open land. Then, land use such as shrubs, mixed gardens, plantations, and inland swamps have a reasonably high CP value of 0.19 - 0.3. This is because land use in the plantation sector in Bireuen Regency rarely applies soil and water conservation systems. So, if this CP factor is combined with the steep slope factor (LS), it will cause a significant erosion potential. However, in contrast to forest land use, continuous rice fields, water bodies, ponds, and irrigation reservoirs, low CP values (0.001 - 0.0143) are obtained. This land use has a capacity large enough to retain rainwater due to its thick canopy, density, deep roots, and designation as a water reservoir.

According to research conducted by Gao et al. (2020), because vegetation keeps raindrops from hitting the soil surface directly.it contributes significantly to erosion. This means that the force required to erode the soil is reduced. It must be considered when studying how vegetation affects land cover, canopy height, and canopy density, which impact raindrops falling on the soil surface. In addition, plant roots play an important role in expanding soil porosity and aggregate stabilization. In addition, Ahmad et al. (2020) stated that garden land use and open land together significantly influence soil erosion velocity.

5. Erosion Value in Bireuen District

Based on the results of erosion prediction calculations using the USLE method, soil erosion varies significantly, between 0 - 3156.78 tonnes/ha/year (Figure 1). The outcomes of the data analysis obtained that the distribution of soil erosion rates in Bireuen Regency consists of 0-20 tonnes/ha/year covering 84,297 ha, 20-60 tonnes/ha/year covering 41,327.34 ha, 60-180 tonnes/ha/year covering 32,954.82 ha, 180-480 tonnes/ha/year covering 17050.34 ha, and > 480 tonnes/ha/year covering 3,502.48 ha. Based on the classification of erosion hazard, the Bireuen Regency area has erosion at a very light-heavy level (Figure 2).

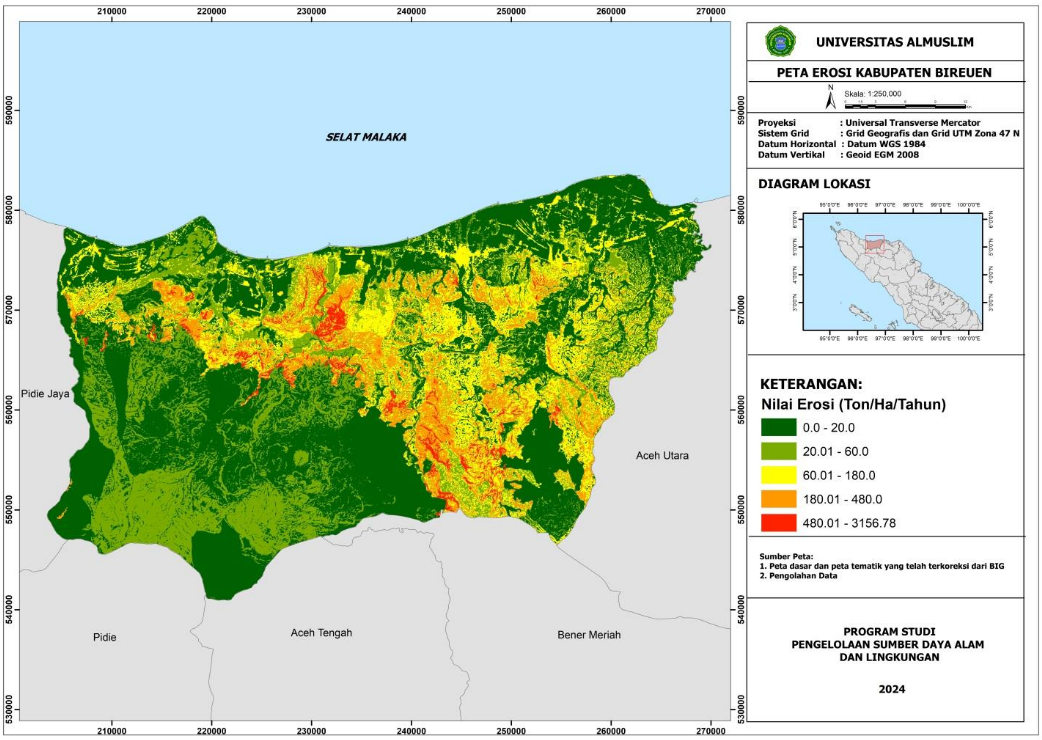

Figure 1. Predicted values of soil erosion in Bireuen District, Aceh Province.

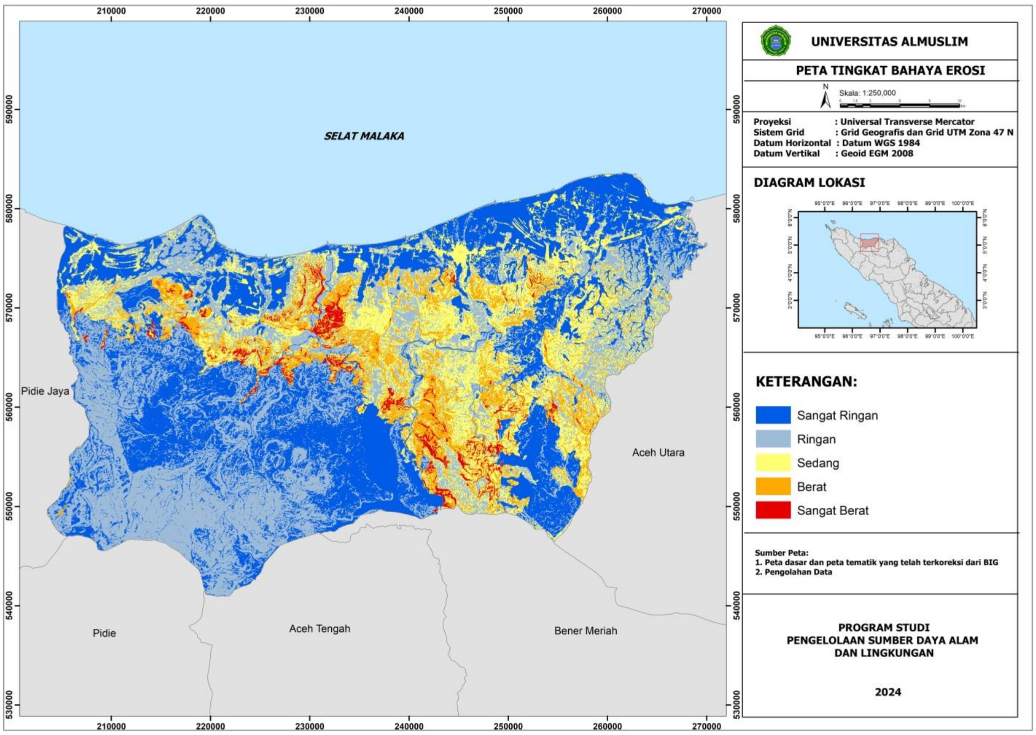

Figure 2. Classification of erosion in Bireuen District

The government and other stakeholders must apply sufficient soil conservation technology to produce sustainable land use. Erosion rate estimation is an important tool for planning land conservation. If erosion rates can be identified, suitable land use and conservation strategies can be designed to avoid further land deterioration and make the land productive and sustainable. To anticipate or minimize the erosion rate on the land, it is necessary to practice conservation to reduce the erosion rate, such as planting with lanes cutting slopes or keeping them in line with contour lines. In addition, it can also be done by selecting plant species with a minor factor (C) value to minimize the erosion rate.

CONCLUSIONS AND SUGGESTION

Erosion occurs due to the interaction between rainfall, length and slope, and vegetation conditions developed on land managed by humans. Bireuen District of Aceh Province, with various biophysical characteristics of the region and the distribution of existing land use, causes variations in the amount of soil eroded based on USLE calculations. In this area, the soil erosion that occurs is in the cluster: Very Light (0-20 tonnes/ha/year), Light (20.01-60 tonnes/ha/year), Medium (60.01 - 180 tonnes/ha/year), Heavy (180.01 - 480 tonnes/ha/year) and Very Heavy (480.01 - 3158.78 tonnes/ha/year). To prevent the increasing status of land criticality in Bireuen District, Aceh Province, it is necessary to determine the level of erosion tolerance. In addition, it is necessary to regulate land use by applying soil conservation principles in every cultivation activity.

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