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# The eco-hydraulics base as flood mitigation to overcome erosion and sedimentation problems: A case study in the Lae Kombih River, Indonesia

Ziana Ziana[1, 2], Azmeri Azmeri[1, 2], Alfiansyah Yulianur[1, 2], Ella Meilianda[1), 2)]

[1)] Universitas Syiah Kuala, Doctoral Program, School of Engineering, Banda Aceh, 23111, Indonesia
[2)] Universitas Syiah Kuala, Department of Civil Engineering, Banda Aceh, 23111, Indonesia

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**Abstract:** Erosion and sedimentation have a very big influence on flooding. Floods are strongly influenced by land use and population activities that change the river's physical condition, including erosion and sedimentation. The river upstream was very steep, and the downstream was narrowing and meandering with high rainfall recorded. This study analyses erosion, sedimentation, and its handling using the eco-hydraulic base. The method involves input rainfall data, river hydraulics, land use, watershed area, and land cover. The analysis of hydrology, hydraulics, land use, flood discharge, and eco-hydraulic, inundation height, vegetation diameter, velocity reduced, and riverbank width measured in five bridges cross-sections along the river. The eco-hydraulic compares the width of existing riverbanks and design, high inundation, and the vegetation diameter to minimise flood discharge. Erosion in the right cliff is 22.73% and the left cliff is 37.04%, land erosion was 225.83 Mg·ha$^{-1}$·year$^{-1}$. The river's bottom is formed by rocks of 0.18–1.30 mm. The plantation land used around the Lae Kombih River grows mainly an oil palm with a diameter of 0.5–0.7 m. The riverbank design on 100 m for vegetation diameter of 0.1–1.0 m can retain flood discharge for five years return period up to 72.3%, resulting in discharge of 112.04209.43 m$^3$·s$^{-1}$. The largest erosion and sedimentation on the river border is Dusun Silak, so it is recommended to plant *Vetiveria zizanioides*, *Ipomoea carnea* and *Bambusoideae*. An inundation height of 0.9 m can be recommended to design an embankment to be used as flood mitigation.

**Keywords:** eco-hydraulics, erosion, riverbank, sedimentation, vegetation diameter

## INTRODUCTION

Generally, rivers contain sediments, depending on the topography, watershed shape, land cover, land use, and soil type. Flow energy is also has a major influence on the concentration of sediment load in the river. Sedimentation is also a major problem because rivers contain large volumes of sediments [Azmeri *et al.* 2022; Omran, Jaber 2017]. In the rainy season, the sediment load in the river increases due to an increase in flow discharge. Rainfall also increases sediment transport through watershed runoff, especially at the start of the rainy season [Mohammad *et al.* 2016]. Thus, problems related to aggregation and degradation in rivers are unavoidable. Aggradation reduces water handling capacity in rivers, causing flooding, while degradation damages the river structure due to riverbed decline. Therefore, a river sediment transport analysis is pivotal to optimise river management [Rafsanjani 2017]. Soil conservation planning is carried out by vegetative conservation measures, such as planting variations of cover crops and terraces can be done to prevent and minimise erosion [Herawati *et al.* 2018; Widiatiningsih *et al.* 2018].

Planting cover crops of a high growth rate is a good solution. Cover crops of a high growth rate can prevent soil erosion and provide more soil organic material than perennial crops, which need a longer time to cover soil surface [Zulkarnain *et al.* 2014].

In general, the prediction of sedimentation velocity can be based on sediment characteristics consisting of size, shape, specific weight, and fall velocity [Hambali, Apriyanti 2016]. Sedimentation reduces water velocity in a river so that suspended sediment settles. As sediment builds up in a river, the river gradually loses its ability to transport water. Over time, this deposition reduces the volume of the river [Kheder *et al.* 2014].

Sediment transport processes can change the topography of the river bed [Holmes 2010], and sedimentation is a key factor hindering river development and management. In addition, increased human activities, such as extensive watershed damage, also increase sediment deposition in rivers.

The eco-hydraulics method is an integrative river development method with an environmental perspective. This method defines a river as an open water system with interaction between flora and fauna, on the one hand, and hydraulics of water and sediment, on the other. The eco-hydraulic base uses the riverbank area for flood retention. As an ecological buffer, riverbanks are an important area for river sustainability.

The riverbank is an area on the left and right of the river affected or flooded by overflowing river water, both in a short and long period, which is a transitional area (ecotone) between the aquatic system and the terrestrial ecosystem [Onrizal 2005]. As ecotones, riverbanks play in important role as unique habitats for biota, regulating organic supply to aquatic systems. They are hydroclimate indicators, and have strong visual quality in creating different colours, variations and images, and creating wilderness experiences.

The eco-hydraulic method causes low water surface temperature, low wind velocity, low evaporation, living root zone, high ecosystem quality, high water supply, and long basin life. On the other hand, the pure hydraulic method leads to a high water table temperature, high wind velocity, high evaporation, and reduced basin life. Technically, the arrangement of river boundaries can be divided into four parts: width of the flood plain, width of the sliding zone, width of the ecological buffer zone, and the safety zone [Maryono 2007]. A flood plain is an area at the edge of a river inundated with water during a flood. Several terms are related to flood plains, including buffer strip, riparian zone, floodplain, and a corridor [Petersen *et al.* 1992]. These terms denote the area between the stream and the surrounding plains. Plants like trees, grasses, and shrubs or a mixture of various forms and types of vegetation planted along the left and right banks of the river are called riparian buffer strips or filter strips. Generally, the term used is the river green line.

A riparian buffer serves to preserve the function of the river by holding or capturing eroded soil (mud) as well as nutrients and chemicals, including pesticides, carried from the land on the left and right of the river and preventing them from entering the river. In addition, riparian buffers also stabilise riverbanks. Trees planted along the river also cool the river water, creating a good environment for various aquatic animals to grow.

Plant composition and structural patterns in aquatic and riparian vegetation show important indicators in depositing erosion [Ferrera, Aquiar 2006]. Therefore, the ecological approach to riverbanks is directed to play a role in the sedimentation process. In ecological river conservation activities, it is necessary to consider the types of plants and their resistance to wet and dry conditions. *Tamarix ramosissima*, *Baccharis salicifolia*, *Salix gooddingii*, *Populus fremontii*, and *Pluchea sericea* are resistant to salinity and waterlogging in the lower Colorado River [Vandersande *et al.* 2001].

In the sliding zone, the vegetation arrangement prevents cliff landslides. This arrangement is implemented by applying soil bioengineering to avoid erosion and slope collapse. This technique utilises local materials, as these are relatively cheap and easily available compared to conventional cliff protection techniques.

Soil bioengineering involves the use of live plants or pieces of plant materials together or partially to control erosion and soil displacement [Lammeranner *et al.* 2005]. Plants that can be used as riverbank protection in Indonesia are *Vetiveria zizanioides*, *Ipomoea carnea*, and *Bambusoideae* [Hanggari Sittadewi 2010]. The vegetation on the riverbanks affects the deposition process and prevents erosion [Sandercock *et al.* 2007]. Besides, planting vegetation on riverbanks could reduce the velocity and discharge of the river [Ziana *et al.* 2019].

The Lae Kombih River is one of the tributaries of the Alas-Singkil River, the largest river in the Aceh Province, Indonesia. The Lae Kombih River high rainfall leading to erosion and sedimentation. Since 1969, excessive logging has often occurred in the Subulussalam City, causing massive deforestation, overflowing of the river, and flash floods. From Gayo Lues to Southeast Aceh, the vegetation dominated by agriculture and plantations has changed. The Alas River also undergoes physical changes with sedimentation. Hence, a flood disaster is likely to occur because the absorption capacity of the area decreases when the rain intensity reaches its highest point. These circumstances requires some measures [Visit Aceh Darussalam 2013].

However, efforts to restore conservation functions may encounter resistance from residents who are comfortable with farming and gardening. Thus, solutions offered should consider the social impact. The restoration of conservation functions should be combined with efforts of economic value without neglecting the ecological function.

According to metrotvnews.com, on 30 November 2019, the flood occurred due to the overflow of the Lae Kombih River in Silak Hamlet, Subulussalam City. Tens of hectares of rice plantations were threatened with crop failure due to high flood inundation mixed with mud soaking the residents' rice fields. As a result, residents lost money because rice fields were flooded.

Human and natural factors impact the rivers. The river changes in the long term causing geomorphological changes. Factors include severe river bed or bank erosion, cross-sectional movement, and sedimentation [Haghiabi, Zaredehdasht 2012]. Investigation of river morphology describing river geometry, river bed shape, longitudinal profile, cross-section, and changes in river shape is one of the main topics in river engineering [Graf 1984; van Rijn 1993].

This study aims to analyse the magnitude of erosion and sedimentation rate in the Lae Kombih River and the eco-hydraulic handling. The results may include recommendations and valuable information for several agencies, such as BPBD, BPDAS, PUPR, BWS, and others, to optimise land use and overcome the problem of flooding in the Lae Kombih River area.

Several studies on river area management have been previously conducted. However, none integrated hydrology, ecology, hydraulics, and community participation. Instead, previous research only considered the hydraulic components of the river. Thus, the novelty of this study is the arrangement of river area management based on the eco-hydraulics integrating the ecological components, physical hydraulics process (erosion and sedimentation), and community participation in the management of river area, especially tributaries. Additionally, this study provides an alternative river area management that can be the basis for determining vegetation and the boundary of the riverbank for flood protection.

## MATERIALS AND METHODS

### MATERIALS

Locations for hydrometric measurements and sediment sampling were carried out from upstream to downstream at Sikelang bridge's I and II, Penanggalan, Silak, and Longkip. The area of the Lae Kombih sub-watershed is 603.27 $km^2$, with river length of 86.45 km. The study location can be seen in Figure 1. The research location observed in the Lae Kombih River was approximately 20.2 km.

Topographic data that can be accessed from Google Earth in 2007, 2016, 2019, and 2021 show no significant change over time. It may be due to a short time span. If we move far back, it seems that the elevation has not been released, so it follows the first one released, as seen in Figure 2, and the land use map of the Lae Kombih watershed as seen in Figure 3.

Field observations were conducted during site surveys, hydrometric measurements, and sampling of suspended load and bedload. Hydrometric measurements consisted of the river width, length, and depth, flow velocity, and discharge. Samples of the sediment were collected by an Ekman grab sampler, whereas suspended load was obtained using a plastic bottle.

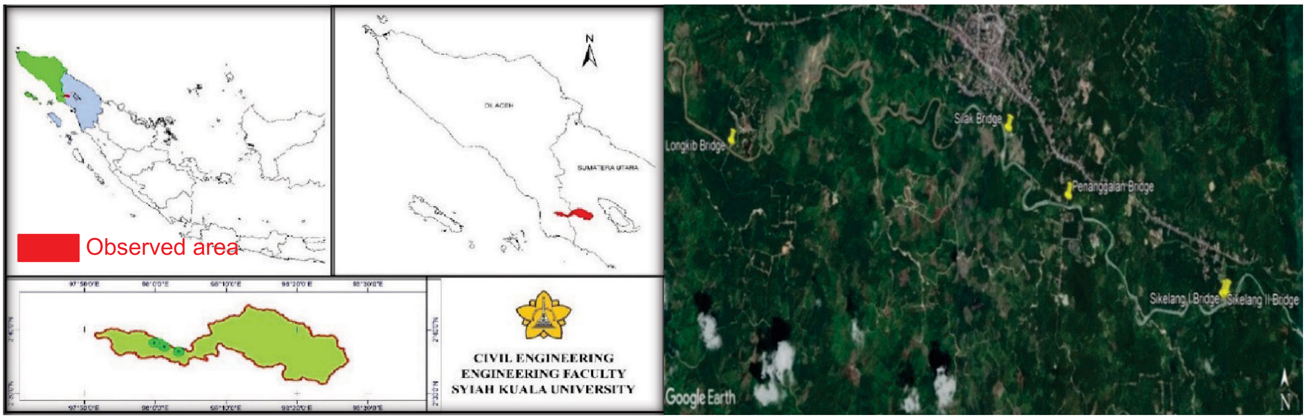


**Fig. 1.** Location map of the Lae Kombih River; location of 5 bridges on the Lae Kombih River; source: Syiah Kuala University and Google Earth

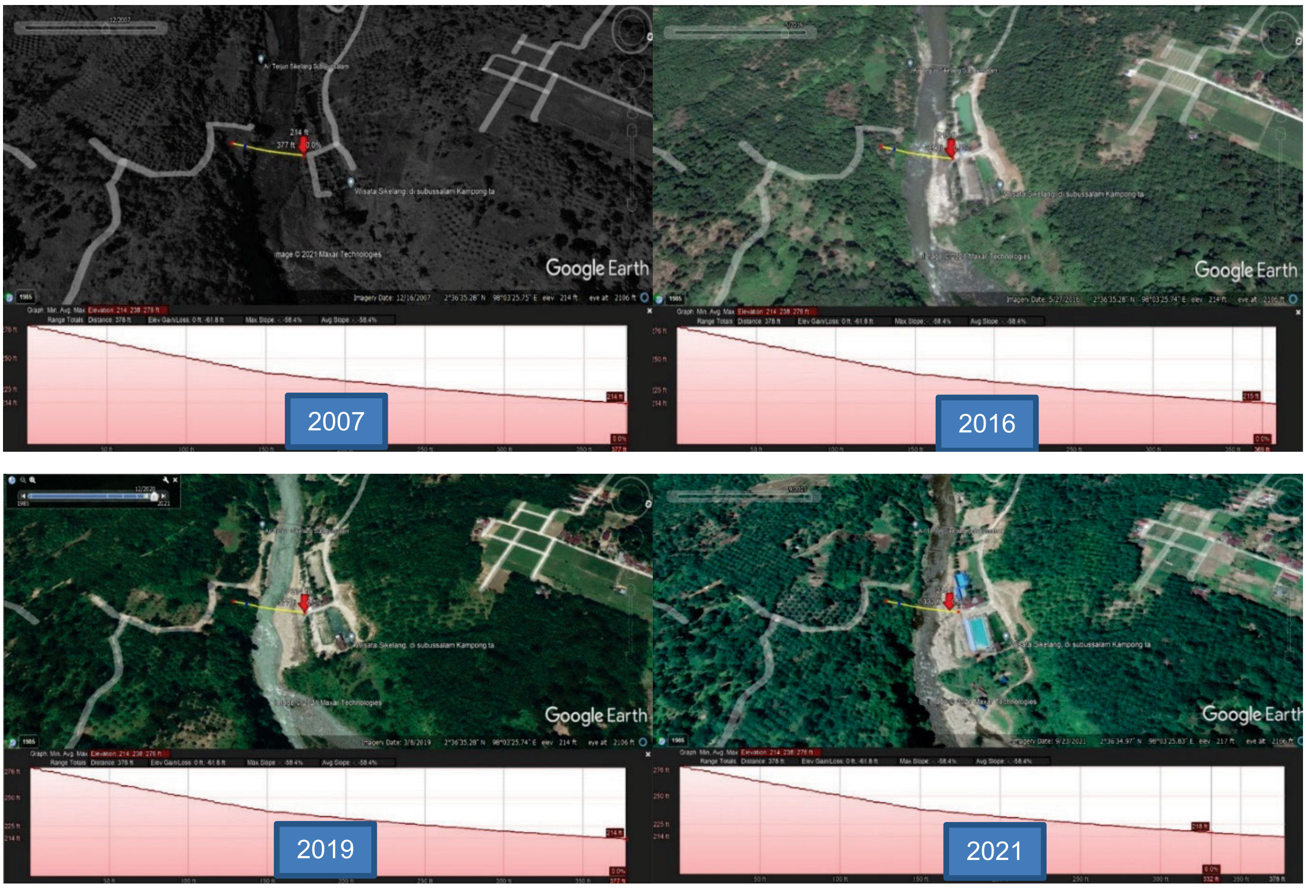


**Fig. 2.** Map of topography of the Lae Kombih River in 2007, 2016, 2019 and 2021; source: Google Earth

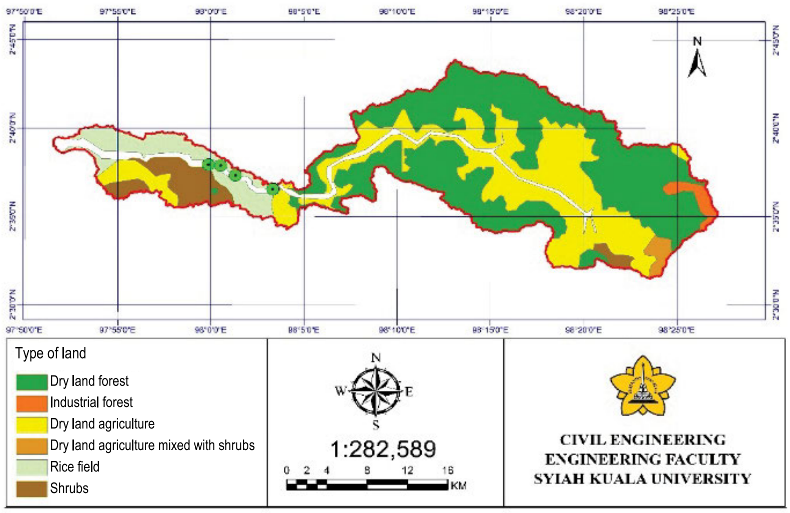


**Fig. 3.** Land use map of the Lae Kombih watershed; source: Syiah Kuala University

## METHODS

The study began by feeding rainfall data, river hydraulics conditions, land use on riverbanks, watershed area, and watershed land cover, followed by the analysis of hydrology, hydraulics, land use, flood discharge, and eco-hydraulic analysis with the output in the form of flood inundation height and vegetation diameter, and flood discharge and river velocity, which can be reduced before and after riverbank arrangement.

The first step involved field measurements which included the measurement of river cross-section ($B$), longitudinal cross-section ($L$), depth ($D$), current velocity ($v$), and discharge ($Q$). The measurement of current velocity ($v$) was carried out using a current meter and the one-point method, namely at a depth of $0.6D$ at $0.25L$; $0.5L$; and $0.75L$. The discharge calculation was done based on the middle section method.

The next step was the bedload collection using the Ekman Grab Sampler and basic sediment samples as follows: bedload sediment collection points were on the left, middle, and right of the river. The Grab Sampler must be free from dirt and other objects before use. The Grab Sampler should not be closed before you reach the bottom of the river.

The suspended load was directly collected using a 600 $cm^3$ plastic bottle. If the water discharge volume is high, the measured suspended load increases [Maulana *et al.* 2014]. High rainfall raises the river water discharge in the rainy season, so sediment collection was carried out three times. The stages in the implementation of sampling are described below.

Laboratory Research included the sieve analysis test conducted to determine the gradation (composition of grain size) of the sediment, the dominant grain size of the sediment in the tested sample, and the type of soil. After measuring the diameter of grains and the passing percentage, a graph was created to illustrate the relationship between them. Based on the graph, the grain size of the sediment can be obtained and the type of soil can be determined.

The falling velocity of the particles was tested using three samples of 20 g, each held at filter diameter 140 mm, and the test was carried out at a water level of 30 cm. The procedure for testing the velocity of falling particles is as follows: the tube is filled with a clear liquid; the test object is dropped from the top of the tube until it reaches the bottom of the tube; the time taken by the particle from the starting line to the finish line is calculated using a stopwatch and recorded, and the test is repeated three times.

The estimation of the rate of soil erosion has been carried out by many previous researchers. The Universal Soil Loss Equation (USLE) method has advantages over its simplicity and accuracy, so this empirical model is the most widely used method in Equation (1). The suspended load sample test was conducted to obtain the sediment content in the water (in $mg \cdot dm^{-3}$). This sediment content is also known as suspended load concentration. Parameters obtained from the results of laboratory tests, the magnitude of the bedload sediment ($Q_b$) and suspended sediment ($Q_s$) can be estimated. The amount of bedload sediment is calculated using the Duboys method in Equation (2), and the suspended sediment is calculated using the Lane and Kalinske method in Equation (4) because both methods use the same value of shear stress on the river bed.

The USLE (Universal Soil Loss Equation) method developed by Wischmeier and Smith [1978] is the most commonly used to estimate the magnitude of erosion. The USLE erosion prediction model uses the following empirical equation.

$$A = R \cdot K \cdot LS \cdot CP \tag{1}$$

where: $A$ = estimated total erosion ($Mg \cdot ha^{-1} \cdot y^{-1}$); $R$ = rain erosivity factor ($kJ \cdot ha^{-1}$); $K$ = soil erodibility factor (–); $LS$ = slope length factor (m); $C$ = land use factor (–); $P$ = conservation action factor.

Prediction of sediment transport is concerned with the estimated rate of sediment transport under steady uniform flow conditions [Hambali, Apriyanti 2016]. Many formulas can predict sediment transport, including the following Duboys equation.

$$Q_b = K\tau_0(\tau_0 - \tau_c) \tag{2}$$

$$\tau_c = C_f d'(\gamma_s - \gamma_w) \tag{3}$$

where: $Q_b$ = basic material transport rate per unit river width ($kg \cdot s^{-1} \cdot m^{-1}$, $lb \cdot s^{-1} \cdot m^{-1}$, $Mg \cdot day^{-1} \cdot m^{-1}$); $K$ = parameters of the particle size function ($m^3 \cdot kg^{-1} \cdot s^{-1}$); $C_f$ = friction coefficient;

$d'$ = layer thickness (m); $\gamma_s$ = weight of sediment grain volume (kg·m$^{-3}$); $\gamma_w$ = weight of water volume (kg·m$^{-3}$); $\tau_o$ = base shear stress (kg·m$^{-2}$); $\tau_c$ = critical tensile stress (kg·m$^{-2}$).

The suspended load was calculated using the Lane and Kalinske methods because both use the same shear stress value on the river bed. The suspended load can be calculated using the Lane and Kalinske method [SIMON, SENTÜRK 1977], as follows:

$$Q_S = Q \cdot C_a \cdot P_L \exp\frac{15wa}{DU^*} \quad (4)$$

$$a = 2D_{65} \quad (5)$$

where: $Q_S$ = suspended load transport (kg·s$^{-1}$·m$^{-1}$, lb·s$^{-1}$·m$^{-1}$, Mg·day$^{-1}$·m$^{-1}$); $Q$ = river discharge (m$^3$·s$^{-1}$, ft$^3$·s$^{-1}$); $C_a$ = concentration of suspended load (mg·dm$^{-3}$); $P_L$ = a function of $w/U^*$ and $n/D^{1/6}$; $w$ = velocity of fall (m·s$^{-1}$, ft·s$^{-1}$); $a$ = reference point of the base (mm, in); $U^*$ = shear velocity (m·s$^{-1}$, ft·s$^{-1}$); $D$ = depth of flow (m, in); and $D_{65}$ = diameter of sediment particles escapes 65% (mm, in).

After knowing the size of the bedload ($Q_b$) and the amount of suspended load ($Q_s$), the total sedimentation value can be calculated using Equation (6) [ENDYI *et al.* 2017].

$$S = Q_s + Q_b \quad (6)$$

where: $S$ = total sediment (kg·s$^{-1}$·m$^{-1}$, lb·s$^{-1}$·m$^{-1}$, Mg·day$^{-1}$·m$^{-1}$); $Q_s$ = suspended load (kg·s$^{-1}$·m$^{-1}$, lb·s$^{-1}$·m$^{-1}$, Mg·day$^{-1}$·m$^{-1}$); $Q_b$ = bedload sediment (kg·s$^{-1}$·m$^{-1}$, lb·s$^{-1}$·m$^{-1}$, Mg·day$^{-1}$·m$^{-1}$).

The influence of vegetation in the riverbank area on the water velocity and discharge is generated based on the following equation proposed by MERTEN [1989] in MARYONO [2017].

$$\frac{1}{\sqrt{\lambda}} = -2.03\log\left(12.27\frac{R}{K_s}\right) \quad (7)$$

$$K_s = C_b + 1.5d_p \quad (8)$$

$$C_v = 1.2 - 0.3\frac{B}{1000} + 0.06\left(\frac{B}{1000}\right)^{1.5} \quad (9)$$

$$B = \left(\frac{\alpha_x}{d_p} - 1\right)^2 \frac{\alpha_y}{d_p} \quad (10)$$

$$v = \left(\frac{1}{\lambda}8gRI\right)^{0.5} \quad (11)$$

where: $\lambda$ = coefficient of resistance; $K_s$ = roughness value; $C_v$ = vegetation composition coefficient; $b$ = riverbank width (m); $d_p$ = vegetation diameter (m); $B$ = vegetation parameter; $\alpha_x$ = transverse vegetation distance (m); $\alpha_y$ = distance between vegetation in longitudinal direction (m); $v$ = velocity (m·s$^{-1}$); $g$ = gravity (m·s$^{-2}$); $R$ = hydraulic radius (m); $I$ = river slope (–).

## RESULTS

In calculating the flood discharge using the unit hydrograph method, the flood discharge is the sum of surface runoff and base flow for several variations of the return period, as presented in Table 1 and Figure 4.

**Table 1.** Flood discharge with various return periods

| Return periods (years) | Direct runoff | Base flow | Flood discharge |
|---|---|---|---|
| | (m$^3$·s$^{-1}$) | | |
| 2 | 238.610 | 13.631 | 252.241 |
| 5 | 390.895 | 13.631 | 404.526 |
| 10 | 490.105 | 13.631 | 503.736 |
| 25 | 624.250 | 13.631 | 637.881 |
| 50 | 699.185 | 13.631 | 712.816 |
| 100 | 774.519 | 13.631 | 788.210 |

Source: own study.

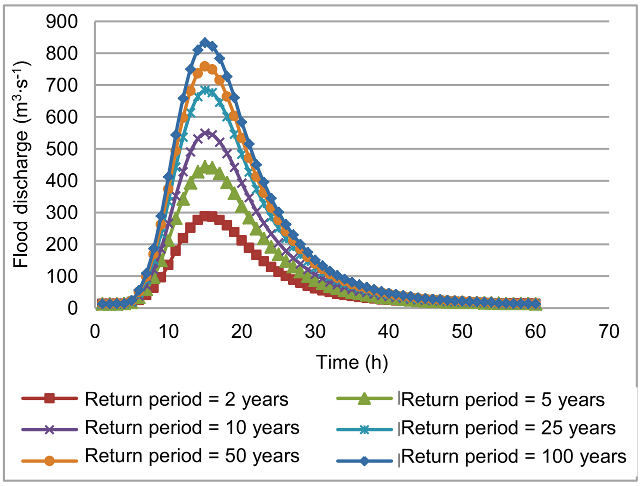


**Fig. 4.** Hydrograph for flood discharge with various return period; source: own study

Based on the hydrometric measurements, the discharge value was calculated using the middle section method. This measurement was carried out three times, and the average was based on discharge and average depth at each location are presented in Table 2.

**Table 2.** Discharge and average depth at each cross-section

| Cross-section | Depth (m) | Discharge (m$^3$·s$^{-1}$) |
|---|---|---|
| Sikelang I bridge | 0.78 | 24.340 |
| Sikelang II bridge | 0.98 | 33.525 |
| Penanggalan bridge | 0.48 | 23.411 |
| Silak bridge | 0.78 | 28.128 |
| Longkip bridge | 1.06 | 32.519 |

Source: own study.

Table 3 presents the area of land use in the Lae Kombih watershed from the map results.

Table 3 shows that the type of land cover dominating the Lae Kombih watershed area, which includes rice fields (8.10%), followed by forest type (49.55%), indicating that this ecosystem is relatively good. The erosion analysis results were obtained using the Universal Soil Loss Equation (USLE) method from the

**Table 3.** Area of different type of land cover in the Lae Kombih watershed

| Type of land cover | Area (ha) | Percentage |
|---|---|---|
| Dry land forest | 28,319.99 | 49.55 |
| Industrial plantation forest | 893.68 | 1.56 |
| Dryland agriculture | 18,930.93 | 33.12 |
| Mixed dry land agri-culture with shrub | 731.18 | 1.28 |
| Rice fields | 4,626.61 | 8.10 |
| Shrubs | 3,650.92 | 6.39 |
| **Total** | **57,153.31** | **100.00** |

Source: own study based on land use map.

multiplication of USLE factors, such as rain erosivity ($R$), soil erodibility ($K$), length, and slope ($LS$), plant management, and soil conservation ($CP$). Data fluctuations in the average monthly rainfall in 1980 – 2006 and the calculation of rain erosivity are presented in Table 4, slope length ($LS$) is presented in Table 5, and land use and conservation measures ($CP$) are calculated in Table 6.

Based on the values of these factors, the amount of erosion (A) can be calculated using the erosion USLE method (A) is 225.826 Mg·ha$^{-1}$·year$^{-1}$. It indicates a fairly large erosion so that it is necessary to prevent it by planting hard-rooted trees.

The condition of cliff erosion on the Lae Kombih River is a problem and causes land loss. The occurrence of cliff erosion is influenced by saturated soil conditions in the rainy season and causes an increase in the soil mass. Hence, the load on the soil increases, and landslides will occur. Erosion of riverbanks is also affected by water velocity, vegetation along the river bank, farming activities on the banks of the river, the depth and width of the river, river channel shape and soil texture [ASDAK 2007].

The condition of the cliffs of the Lae Kombih River is described by erosion and non-erosion. The occurrence of cliff erosion can be observed in two ways: based on the presence of tree roots that appear on the river bank [WALKER *et al.* 1992] and the absence of vegetation on the cliff. The observations at 65 reading points reveal that the erosion of the cliff at the left side of the river is smaller than at the right side. The cliff erosion along the river can be seen in detail in Figure 5.

The description of cliff erosion in Silak and Longkip hamlets occurs on the left and right sides of the river. The morphological condition of the river in this area with many meanders is the main factor causing cliff erosion. The morphological condition of the river that has a meander causes the water flow that leads to a certain area on the outside of the bend. In this condition, the water flow will try to move out so that the velocity of the water on the outside of the bend will be greater than on the inside. As a result, in rivers that have cliffs with unstable soil conditions, there will tend to be landslides on the cliffs on the outside of the river bend. This cliff slide process occurs due to a continuous scouring at the base of the cliff as a reaction to basic changes of the flow pattern at the bend [SUJATMOKO 2006].

In the Lae Kombih watershed area, uncontrolled population activities will impact changes in the physical condition of the river, especially in the form of erosion and sedimentation. The area prone to erosion is 2,283.14 ha (13.35%). Furthermore, along the river, there is also riverbank erosion. As a result of the erosion, excessive sedimentation occurs in the downstream area, where there is a narrowing of the river to a meter in size. This

**Table 4.** Rain erosivity ($R$) in the Lae Kombih watershed

| Parameter | Value in month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
| Monthly rainfall (mm) | 8.40 | 7.83 | 9.38 | 9.84 | 8.11 | 4.44 | 5.22 | 6.06 | 7.31 | 12.45 | 9.94 | 11.59 |
| $R$ (kJ·ha$^{-1}$) | 39.95 | 36.31 | 46.42 | 49.54 | 38.10 | 16.81 | 20.94 | 25.61 | 33.05 | 68.21 | 50.25 | 61.88 |
| **Σ*R* (kJ·ha$^{-1}$)** | **487.06** | | | | | | | | | | | |

Source: own study.

**Table 5.** Slope length and slope ($LS$) in the Lae Kombih watershed

| Slope class (%) (1) | Average slope in class (%) (2) | Area (km$^2$) (3) | Area : watershed area (4) | (2)·(4) |
|---|---|---|---|---|
| 0–5 | 2.5 | 71 | 0.152 | 0.381 |
| 5–20 | 12.5 | 156 | 0.335 | 4.185 |
| 20–40 | 30 | 216 | 0.464 | 13.906 |
| 40–60 | 50 | 10 | 0.021 | 1.073 |
| 60–100 | 80 | 13 | 0.028 | 2.232 |
| **Total** | | **466** | **1** | **21.776** |
| ***LS*** | | | | **3.1** |

Source: own study.

**Table 6.** Land use and conservation measures ($CP$) in the Lae Kombih watershed

| Type of land use (1) | *CP* value (2) | Area (km$^2$) (3) | Area : watershed area (4) | (2)·(4) |
|---|---|---|---|---|
| Field | 0.01 | 59 | 0.127 | 0.001 |
| Shrub | 0.30 | 26 | 0.056 | 0.017 |
| Secondary dryland forest | 0.01 | 180 | 0.386 | 0.004 |
| Open ground | 0.95 | 201 | 0.431 | 0.410 |
| **Total** | | 466 | 1 | **0.432** |

Source: own study.

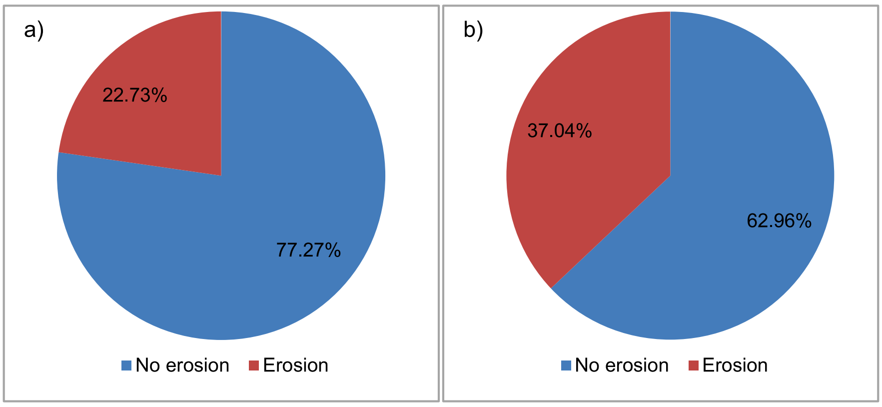


**Fig. 5.** River cliff conditions on the Lae Kombih River: a) riverbank right, b) riverbank left; source: own study

condition is further exacerbated by the unfavourable behaviour of the local community, which often throws garbage into the river. As a result, the river's carrying capacity is smaller, and floods often occur, especially in the Silak Hamlet, Penanggalan District.

Most of the observed cliff erosion events occurred in areas where the land use on the riverbanks was rice fields and gardens. In both types of land use, there is no structural protection of riverbanks. The riverbed is composed of material transported naturally by water flow and settling in certain areas. Forman and Gordon [1991] stated that riverbeds vary widely and often reflect hard bedrock. Rarely found flat parts. Sometimes the shape is wavy, sloping or both, and often deposited material is carried by the river (mud deposits). The bedrock strongly influences the thickness of the riverbed. The condition of the Lae Kombih riverbed varies from upstream to downstream. In the measuring area along the 20,200 m, the river bottom is formed by rocks (0.18–1.30 mm in size).

For the calculation of sediment discharge was determined using the Duboys method, whereas the diameter used was the median diameter ($D_{50}$). The sediment on the Sikelang II bridge cross-section had the largest average diameter, while the smallest was the sediment in the Longkip bridge. The average diameters can be seen in Table 7.

The results of the sieve analysis test showed that the sediment in the Sikelang II bridge cross-section had the largest average diameter of 1.3 mm, while the smallest was in the Longkip bridge cross-section (0.18 mm). The result of the test for the falling velocity of larger particles in the Sikelang II bridge cross-section was 0.00837 m·s$^{-1}$. In contrast, the Sikelang I, Penanggalan, Silak, and Longkip bridges cross-sections have lower falling velocity because of finer particles. The laboratory testing of suspended load samples indicated that the highest average sediment concentration was at the Longkip bridge (31 mg·dm$^{-3}$).

The largest sedimentation rate was in the Longkip bridge cross-section 20.9388 kg·s$^{-1}$·m$^{-1}$, and the smallest was in the Penanggalan bridge cross-sections 2.647 kg·s$^{-1}$·m$^{-1}$. The sediment rate can also be influenced by sediment sampling. Data on the velocity of falling particles in the five bridges measured can be seen in Table 8.

**Table 7.** Recapitulation of average $D_{50}$ value of sediments in the Lae Kombih River

| Location | $D_{50}$ (mm) in | | | Average $D_{50}$ (mm) |
|---|---|---|---|---|
| | left river | middle part | right river | |
| Sikelang I bridge | 0.360 | 0.900 | 0.360 | 0.540 |
| Sikelang II bridge | 1.900 | 1.200 | 0.800 | 1.300 |
| Penanggalan bridge | 0.140 | 0.600 | 0.150 | 0.297 |
| Silak bridge | 0.460 | 1.600 | 0.200 | 0.753 |
| Longkip bridge | 0.200 | 0.160 | 0.180 | 0.180 |

Source: own study.

**Table 8.** Data on the velocity of falling particles in the five bridges cross-sections measured

| Cross-section | Para-meter | Value in | | | |
|---|---|---|---|---|---|
| | | left river | middle part | right river | average |
| Sikelang I bridge | $H$ (m) | 0.3 | 0.3 | 0.3 | 0.3 |
| | $t$ (s) | 74.31 | 44.34 | 60.16 | 59.6 |
| | $w$ (m·s$^{-1}$) | 0.00404 | 0.00677 | 0.00499 | 0.00526 |
| Sikelang II bridge | $H$ (m) | 0.3 | 0.3 | 0.3 | 0.3 |
| | $t$ (s) | 25.88 | 42.1 | 47 | 83.65 |
| | $w$ (m·s$^{-1}$) | 0.01159 | 0.00713 | 0.00638 | 0.00837 |
| Penangga-lan bridge | $H$ (m) | 0.3 | 0.3 | 0.3 | 0.3 |
| | $t$ (s) | 98.17 | 52.86 | 88.88 | 79.97 |
| | $w$ (m·s$^{-1}$) | 0.00306 | 0.00568 | 0.00338 | 0.00404 |
| Silak bridge | $H$ (m) | 0.3 | 0.3 | 0.3 | 0.3 |
| | $t$ (s) | 57.27 | 35.49 | 75.24 | 56 |
| | $w$ (m·s$^{-1}$) | 0.00524 | 0.00845 | 0.00399 | 0.00589 |
| Longkip bridge | $H$ (m) | 0.3 | 0.3 | 0.3 | 0.3 |
| | $t$ (s) | 80.45 | 86.89 | 82.22 | 83.18 |
| | $w$ (m·s$^{-1}$) | 0.00373 | 0.00345 | 0.00365 | 0.00361 |

Explanations: $H$ = fall height, $t$ = time, $W$ = fall velocity.
Source: own study.

Based on the calculation results of all sediment samples in Table 9, it can be seen that the rate of bedload from the upstream and middle of the river decreases. However, the rate of bedload in the downstream river increases. This finding is influenced by the diameter of the sediment ($D_{50}$) and the depth of the river ($D$). Table 9 also indicates that the rate of suspended load from the upstream, middle, and downstream rivers increases because the influence of sediment concentration ($C_a$) is becoming higher downstream.

**Table 9.** Suspended load in the Lae Kombih River

| Cross-section | Load (kg·s$^{-1}$·m$^{-1}$) | | |
|---|---|---|---|
| | $Q_b$ | $Q_s$ | $S$ |
| Sikelang I bridge | 4.679 | 0.00512 | 4.6841 |
| Sikelang II bridge | 4.105 | 0.00657 | 4.1116 |
| Penanggalan bridge | 2.638 | 0.00903 | 2.6470 |
| Silak bridge | 3.501 | 0.01304 | 3.5140 |
| Longkip bridge | 20.901 | 0.03778 | 20.9388 |

Explanations: $Q_b$ = bedload discharge, $Q_s$ = suspended load discharge, $S$ = total load.
Source: own study.

Based on the Regulation of the Minister of Public Works and Public Housing Number 28/Prt/M/2015 concerning Stipulation of River Border Lines and Lake Border Lines, namely the border of a large river without embankments outside urban areas is determined to be at least 100 m from the left and right border of the riverbed.

The Lae Kombih River eco-hydraulic calculation was carried out by comparing two riverbank designs: the width of the riverbank in the river existing natural conditions and the planned riverbank width of 100 m on the left and right of the river.

The eco-hydraulic riverbanks grow the vegetation that has an economic value to the community. The appropriate vegetation is the one with a diameter of 0.1 m to 1.0 m and a height exceeding the planned inundation height. The economic benefits of the eco-hydraulic concept can be seen from the improvement of community welfare due to reduced flood hazards and proper use of land along river banks. The calculation eco-hydraulic parameters in the Silak bridge cross-section is shown in Table 10.

**Table 10.** Discharge of eco hydraulics for the return period of five years and $Q$ flood = 404.526 m$^3$·s$^{-1}$ Silak bridge cross-section

| Vegetation diameter (m) | $\alpha x$ and $\alpha y$ | Vegetation parameter $B$ | Vegetation coefficient $Cv$ | Roughness $K_s$ | Cross-sectional area (m$^2$) | Hydraulics radius (m) | Roughness coefficient $\lambda$ | Velocity (m·s$^{-1}$) | $Q_{eco\text{-}hydraulic}$ | Result | $\Delta Q$ (m$^3$·s$^{-1}$) | Reduction (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Riverbank's width 50.7 m, inundation height 2.7 m** | | | | | | | | | | | | |
| 0.0 | 0 | 0 | 0 | 0 | 238.923 | 2.384 | 0 | 1.693 | 404.526 | | | |
| 0.1 | 1 | 810 | 1.00074 | 50.888 | 226.479 | 2.260 | 3.489 | 0.295 | 66.738 | safe | 333.788 | 83.502 |
| 0.2 | 2 | 810 | 1.00074 | 51.038 | 226.479 | 2.260 | 3.456 | 0.296 | 67.061 | safe | 333.464 | 83.422 |
| 0.3 | 3 | 810 | 1.00074 | 51.188 | 226.479 | 2.260 | 3.423 | 0.298 | 67.384 | safe | 337.142 | 83.342 |
| 0.4 | 4 | 810 | 1.00074 | 51.338 | 226.479 | 2.260 | 3.390 | 0.299 | 67.706 | safe | 336.820 | 83.263 |
| 0.5 | 5 | 810 | 1.00074 | 51.488 | 226.479 | 2.260 | 3.358 | 0.300 | 68.026 | safe | 336.499 | 83.184 |
| 0.6 | 6 | 810 | 1.00074 | 51.638 | 226.479 | 2.260 | 3.327 | 0.302 | 68.346 | safe | 336.180 | 83.105 |
| 0.7 | 7 | 810 | 1.00074 | 51.788 | 226.479 | 2.260 | 3.296 | 0.303 | 68.665 | safe | 335.861 | 83.026 |
| 0.8 | 8 | 810 | 1.00074 | 51.938 | 226.479 | 2.260 | 3.266 | 0.305 | 68.983 | safe | 335.543 | 82.947 |
| 0.9 | 9 | 810 | 1.00074 | 52.088 | 226.479 | 2.260 | 3.236 | 0.306 | 69.300 | safe | 335.226 | 82.869 |
| 1.0 | 10 | 810 | 1.00074 | 52.238 | 226.479 | 2.260 | 3.207 | 0.307 | 69.616 | safe | 334.910 | 82.791 |
| **Riverbank's width 100.0 m, inundation height 0.9 m** | | | | | | | | | | | | |
| 0.0 | 0 | 0 | 0 | 0 | 324.052 | 1.320 | 0 | 1.248 | 404.526 | | | |
| 0.1 | 1 | 810 | 1.00074 | 100.224 | 307.672 | 1.253 | 0.366 | 0.677 | 208.432 | safe | 196.094 | 48.475 |
| 0.2 | 2 | 810 | 1.00074 | 100.374 | 307.492 | 1.253 | 0.365 | 0.678 | 208.480 | safe | 196.046 | 48.463 |
| 0.3 | 3 | 810 | 1.00074 | 100.524 | 307.312 | 1.252 | 0.365 | 0.679 | 208.528 | safe | 195.998 | 48.451 |
| 0.4 | 4 | 810 | 1.00074 | 100.674 | 303.892 | 1.238 | 0.360 | 0.679 | 206.441 | safe | 198.085 | 48.967 |
| 0.5 | 5 | 810 | 1.00074 | 100.824 | 306.952 | 1.251 | 0.363 | 0.680 | 208.622 | safe | 195.905 | 48.428 |
| 0.6 | 6 | 810 | 1.00074 | 100.974 | 306.772 | 1.250 | 0.362 | 0.680 | 208.668 | safe | 195.859 | 48.417 |
| 0.7 | 7 | 810 | 1.00074 | 101.124 | 307.672 | 1.253 | 0.363 | 0.681 | 209.426 | safe | 195.100 | 48.229 |
| 0.8 | 8 | 810 | 1.00074 | 101.274 | 306.772 | 1.250 | 0.361 | 0.681 | 208.996 | safe | 195.530 | 48.336 |
| 0.9 | 9 | 810 | 1.00074 | 101.424 | 306.232 | 1.248 | 0.360 | 0.682 | 208.803 | safe | 195.724 | 48.383 |
| 1.0 | 10 | 810 | 1.00074 | 101.574 | 306.052 | 1.247 | 0.359 | 0.682 | 208.847 | safe | 195.680 | 48.373 |

Explanations: $Q_{eco\text{-}hydraulic}$ = discharge before and after eco-hydraulic arrangement.
Source: own study.

Table 10 shows that the eco-hydraulic design of the existing Silak bank with an inundation height of 2.7 m resulted in the smallest discharge of 66.74 m$^3$·s$^{-1}$ for vegetation with a diameter of 0.1 m and the largest discharge of 69.62 m$^3$·s$^{-1}$ for vegetation with a diameter of 1.0 m. This design can withstand flood discharges up to 83.5%. Meanwhile, the eco-hydraulic design on the bank is 100 m with an inundation height of 0.9 m, resulting in the smallest discharge of 206.44 m$^3$·s$^{-1}$, for vegetation with a diameter of 0.4 m, and the largest discharge of 209.43 m$^3$·s$^{-1}$ for vegetation with a diameter of 0.7 m. This design can withstand flood discharges up to 49.0%.

Based on the overall results from observations in five bridges' cross-sections on the Lae Kombih River, we have obtained the following: designs with existing banks for vegetation with a diameter of 0.1–1.0 m can retain flood discharge for a 5-year return period up to 82.8–94.4% with inundation heights that occur 1.1–2.7 m, where the resulting flood discharge is 22.75–104.14 m$^3$·s$^{-1}$.

Based on observations in five cross-sections on the Lae Kombih River, the eco-hydraulic design on a 100 m design bank for vegetation with a diameter of 0.1–1.0 m can retain flood discharge for a 5-year return period up to 48.2–72.3% with an inundation height of 0.3–0.9 m, where flood discharge the resulting 112.04–209.43 m$^3$·s$^{-1}$. Based on the height of the inundation and the resulting flow rate, an eco-hydraulic design with a design bank width of 100 m was used.

The most significant land function in the Lae Kombih watershed is dryland forest of 28,319.99 ha, while the minor land function is dryland agriculture mixed with shrubs and industrial plantations, 731.18 and 893.68 ha respectively. The 2019 inundation flood had the same inundation area as the $Q_5$ inundation flood, with an area of 2,286.02 ha. Rice fields are the most significant area affected by flooding in all return period flood discharges.

## DISCUSSION

In his previous research, PERTIWI [2011] conducted an eco-hydraulic analysis by optimising the width of riverbanks and selecting the right vegetation diameter that can reduce flooding.

The eco-hydraulic analysis carried out by the author is to compare the width of the existing bank and the width of the bank, which is set at 100 m from the flood elevation around the inundation area, the height of the flood inundation, determine the diameter of the vegetation and the distance between vegetation that is in accordance with the plant canopy and can reduce the velocity and discharge. This study also looks at the erosion conditions in the watershed and on the river bank, as well as sedimentation in the river and the results of cross-sectional photos of rivers in 2007, 2016, 2019 and 2021.

Arrangement of riverbanks with the eco-hydraulic concept, namely by planting plants in accordance with vegetation that have economic value for the community. Suitable vegetation is vegetation with a diameter of 0.1 m to 1.0 m and exceeds the planned inundation height. The economic benefits of the eco-hydraulic concept can be seen from the increase in community welfare due to reduced flood hazards and proper land use on riverbanks.

The land around the Lae Kombih River is generally use for oil palm plantations. This plant is suitable for use as an application of the eco-hydraulic concept with a stem diameter of 0.5–0.7 m and has high economic value. The research results on 15-year-old oil palm plantations in Kalianta, Riau show that fluctuations in the groundwater level in oil palm plantations are influenced by rainfall, and the groundwater level tends to be constant. The decrease in groundwater level actually occurs in residential areas, as well as open areas that lack vegetation. Palm oil plants also have a canopy with the same rainwater-holding capacity (interception) as forest plants (21.23% of the total rain). Meanwhile, the ability of mature oil palm canopies to hold water is much higher than that of food crop ecosystems [PASARIBU *et al.* 2012]. This interception capability can certainly reduce water loss due to runoff and damage to soil structure due to erosion. Another study conducted by HARAHAP [1997] in Gunung Tua, North Sumatra, found that soil in oil palm plantations had a lower bulk density (g·cm$^{-3}$) than fallow soil (without plants). Oil palm plantations generally have higher organic C, percentage of available water, and increased soil pore space to store more water than fallow soil.

Another plant that also grows on the banks of the river is bamboo. A well-cultivated clump of 60 cm diameter bamboo plants can be used for eco-hydraulic applications. This plant is also of high economic value. Bamboo is used as a building material and by small handicraft industry. In addition, newly grown trees (bamboo shoots) are used as vegetables. Bamboo is also used in the community's social life, for example, in traditional wedding and funeral ceremonies. In protecting river ecology, bamboo can also function as a cliff erosion protection.

Various fruit plants that can be cultivated on riverbanks and have economic value for the community, for example jackfruit (*Artocarpus heterophyllus*), breadfruit (*Artocarpus altilis*), mango (*Mangifera sp.*), and coconut (*Cocos nucifera*). These plants have a diameter between 0.10–0.25 m and height 2–3 m.

The results showed that the bedload rate in the upstream and middle of the river decreased, but the bedload rate downstream of the river increased. It is influenced by the characteristics of the watershed, the shape of the watershed, the depth of the river, the diameter of the sediment, and the concentration of the sediment.

Based on the field survey results, the condition of the river that experienced the most severe erosion and sedimentation on the river bank was in the hamlet of Silak, so it was recommended to plant *Vetiveria zizanioides* (vetiver grass), *Ipomoea carnea* and *Bambusoideae*. This type of vegetation was chosen to take into account the velocity of the water. Groups of grass (*Gramineae*) and water spinach (*Convolvulaceae*) which are flexible, can be used for cliff protection at high current velocity, while they have brittle properties (breaks easily) at low velocity. While planting this vegetation, initial protection is needed until the vegetation grows and has strong roots before being exposed to flooding or relatively strong currents. It is very good if these are planted in the middle of the dry season or the end of the rainy season so that it is strong enough to withstand the energy of the flow of water in the next rainy season.

The combination of bamboo construction, vetiver grass, and coral are suitable for sites with the following conditions: water velocity during flooding is less than 1.5 m·s$^{-1}$, floodwater carries a lot of suspended sediment, and the riverbed is not composed of gravel. Bamboo stems are planted vertically in locations where cliffs are threatened with scouring. Horizontal transverse bars are installed and tied to vertical bars as reinforcement. Twigs are inserted between the vertical stems, creating a porous box that can retain floodwater and bind sediment. Once the sediment has formed, *Ipomoea carnea* or vetiver grass is planted [Hanggari Sittadewi 2010] Furthermore, mentioned plants will grow strong and irregular, overlapping and intertwined, to speed up the process. The new sediment at the foot of the riverbank is relatively stable and resistant to scouring. *Bambusoideae*, *Ipomoea carnea*, and vetiver plants can be seen in Photo 1.

priate actions in river management. Government intervention in providing regulations, increasing community institutional capacity, monitoring, and evaluation can be intensified so that flood control programs can take place in a sustainable, participatory, and beneficial manner for the community.

Forest restoration is one way to deal with climate change and another effort is to improve riverbanks, especially in the upper reaches, by planting large trees to absorb more water into the soil and prevent erosion and sedimentation in rivers, as well as maintain river ecosystems.

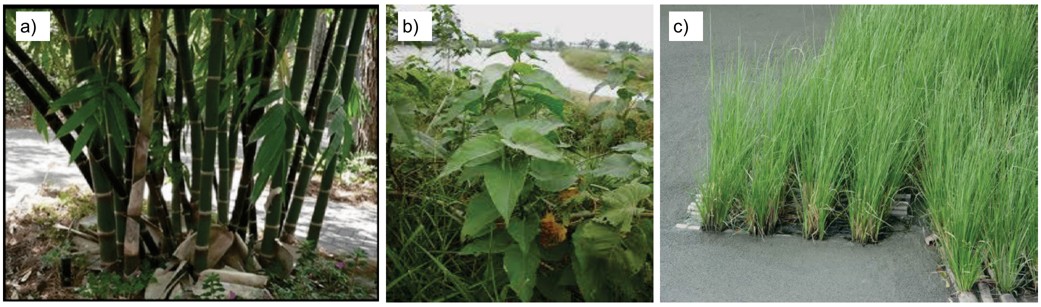


**Photo 1.** Plants used in riverbank's reinforcement: a) *Bambusoideae*, b) *Ipomoea carnea*, c) *Vetiveria zizanioides*; source: Repository of Syiah Kuala University

## CONCLUSIONS

Based on the results of the eco-hydraulic analysis, it was found that the reduction value of river flood discharge at the Silak Village was 48.2% from the previous riverbank arrangement. The vegetation land use around the Lae Kombih River was generally planted with oil palm trees with a diameter of 0.5–0.7 m and has a high economic value.

For water conservation in river management, the right vegetation type must also be considered depending on land conditions. The land use vegetation around the Lae Kombih River is generally in the form of oil palm trees. In implementing eco-hydraulic in the field, awareness, understanding, and participation of the community and government will determine its function and purpose. One alternative to reduce sedimentation is to plant bamboo on riverbanks. Clumps of bamboo plants with a diameter of 0.6 m that are well-cultivated can be used to apply the eco-hydraulic method.

An eco-hydraulic river can be developed by considering river meandering patterns and the incidence of erosion and sedimentation. Thus, once a model of cliff protection due to erosion is determined, the river morphology can be maintained. In addition, for water conservation in river management, the right type of vegetation should also be taken into account according to the condition of the land along the riverbank. To develop eco-hydraulic-based river management policies, it is necessary to have a river management policy that provides legal certainty for the Regional Government and the community. This is supported by regulations regarding the width of river borders, allotment of river border areas, and land use arrangements on riverbanks. This policy should be adapted to flood conditions in rivers in Indonesia and integrated into the General Spatial Plan.

Community participation in river management can be increased by increasing awareness and knowledge about appro-

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