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# COMPARISON IN ESTIMATING RESERVOIR LIFETIME BY UNIVERSAL SOIL LOSS EQUATION AND SITE OBSERVATION

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**ABSTRACT:** Sedimentation can severely limit the service lifetime and functionality of reservoirs. The application of the Universal Soil Loss Equation (USLE) requires validation of its accuracy and applicability despite its prevalence. This study compares reservoir lifetime predictions for the Leuwikeris Reservoir on the Citanduy River using the USLE model and the suspended load records from the field measurement. The comparison shows a reasonable similarity between the theoretical calculation and the factual observations in determining the amount of watershed soil loss and the reservoir lifetime. Although the validation is successful, USLE and the measurement technique have their specific limitations. In particular, the inability of USLE to consider both gully erosion together with sedimentation and the inability of the measurement technique in detecting bed load. Despite the limitations, these results are in line with previous studies which stated that the USLE model is generally feasible in estimating the quantity of reservoir-bound sediment.

***Keywords:*** *Reservoir sedimentation, Reservoir lifetime, USLE, Daily suspended sediment record, Validation*

## 1. INTRODUCTION

Reservoirs account for 20% of international power generation [1], therefore, their life becomes a fundamental issue to be studied [2]. River transports water and sediments, which are deposited on the reservoir bed, causing a decrease in capacity, which leads to its declining purpose as flood control, water supply, and electricity generator, and finally shortening the lifetime [3–5].

The service lifetime of the reservoir is generally calculated based on dead storage capacity. When sedimentation has filled the dead storage capacity, the service life is considered complete due to disruption of normal operation [6].

Therefore, sedimentation or siltation becomes a primary issue. All reservoirs are destined to deteriorate and fail due to excessive sedimentation unless they are carefully constructed and maintained. The large inflow of sediments compared to the capacity can reduce the useful life of the reservoir. The planning of the reservoir must consider the probable rate of sedimentation to determine whether the lifespan of the proposed reservoir will be sufficient to warrant its construction [7].

A large variety of erosion-sediment yield models are available in the literature. The most commonly used methods for the prediction of sediment yield are the universal soil loss equation (USLE) and the modified universal soil loss equation (MUSLE) [7].

The USLE method [8] computes the soil loss at a given site as a product of six major factors. This method has been indicated as the most commonly used regression model for predicting soil erosion [9]. The MUSLE was proposed by replacing the factor R in the USLE model with a runoff factor [10–11].

The quantity of land erosion is influenced by numerous variables, which are difficult to determine accurately. This makes land erosion quantification a complex analysis. For the prediction of sediment transport in rivers, some empirical probability distribution functions need to be used [12]. However, several variations of the previous methods and others for the prediction of sediment yield are available in the literature on soil science, hydrology, and water resources.

The increase in sediment deposits on the Pangsar Besar Soedirman Dam from 1988 to 2016 led to a decrease in the reservoir capacity. For over 28 years, the total capacity of the dam has dropped from 144 million $m^3$ to 33.2 million $m^3$ [13]. The reservoir sedimentation has decreased 18% of power plant production for 16 years of operation and ultimately reduced the service life of the dam, 19 years earlier than the original plan [14–15]. In the USA, sedimentations have decreased the lifetime of many reservoirs by 50 to 100 years [16]. These facts reveal the risk of reservoir sedimentation. Therefore, further studies must be conducted to understand the sedimentation processes in reservoirs.

This study aims to compare the sedimentation rate at Leuwikeris Reservoir, River Citanduy based on theoretical computation and field observation. The catchment area model is limited to only the upstream reach of the river until the dam structure. The reservoir is located in Cijeungjing District, Ciamis Regency, West Java Province, Indonesia as displayed in Fig.1.

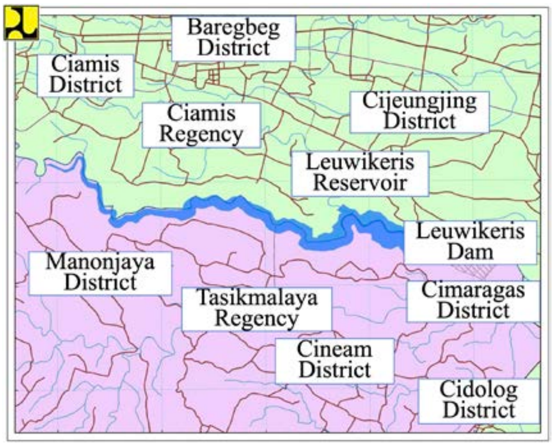


Fig.1 The map of Leuwikeris Dam and its surrounding [17]

The construction process of Leuwikeris Dam started in 2016 and has not yet been opened when this study is being carried out. Therefore, no investigation has been conducted on this particular location. The zoned dam with a central vertical clay core is intended to operate for 50 years with a dead storage capacity of 36.09 million $m^3$ [18]. The reservoir with a capacity of 81.44 million $m^3$ is designed to irrigate 11,950 hectares of crops, generate a 15 MW power supply, reduce 57 $m^3$/s of flood, and supply 0.085 $m^3$/s of water [17, 19].

Citanduy Watershed has a high erosion rate and a large number of sediment yields around 328,961-8,158,644 $m^3$ due to the silting of the river. Until 2012, the watershed erosion rate averaged 79.38 t/hectare/year or 28,962,668 t/year with potential river sedimentation of 2,360,327.47 t/year [20].

## 2. RESEARCH SIGNIFICANCE

The parameter of reservoir lifespan is important in determining its storage. This makes it necessary to estimate the quantity of sediment influx into the reservoir. The current practice is by USLE modeling, which is a popular approach worldwide. However, the question there is a concern about whether USLE is sufficiently accurate in forecasting sediment influx. Comparing the result of USLE with field measurement data is crucial in concluding its accuracy to estimate the quantity of reservoir-bound sediment. The successful validation by measurement data will promote USLE implementation and vice versa.

This paper does not only assess the validation between the theoretical model and the factual data, but it also investigates how the measurement technique's limitation affects the validation process. Numerous types of researches about USLE validation have been performed [21-22], but ta there is a lack of study on the relationship between the measurement technique's limitation and validation. For this reason, this paper also probes the issue.

## 3. METHOD

The initial estimation of reservoir sedimentation can be obtained from various empirical equations and charts. The USLE is used to estimate the reservoir sedimentation rate because it is the most common method. Subsequently, the theoretical soil loss will be compared with the suspended sediment transport data collected at the site.

### 3.1 Sediment Transport Rate Estimation

The USLE method estimates the long-term erosion rate on a land slope within a certain time based on rainfall pattern, soil type, topography, as well as land cover, and support. The method only predicts the amount of soil loss due to rainfall erosivity and concentrated flow, excluding wind erosion and agricultural development by humans.

To estimate the total erosion rate that occurs at the dam upstream, the calculated land erosion per hectare is multiplied by the area of the watershed to obtain the total annual land erosion. The formula is expressed in Eq. (1) [8].

$$A = R \times K \times LS \times C \times P \quad (1)$$

where:
A: the average amount of soil loss (t/ha/year)
R: rainfall erosivity (KJ/ha)
K: soil erodibility (t/ha/R)
LS : topographic factor (unitless)
C : land cover index (unitless)
P : support particle index (unitless)

#### *3.1.1 Rainfall Erosivity*

Rainfall erosivity (R) shows the relation between the kinetic energy (E) and maximum 30 minutes intensity ($I_{30}$) [23]. The estimation of the R factor is a complex process, which requires long-term data collection due to the limited precipitation data availability in a large part of the world [24].

Several methods are developed to calculate the annual rainfall erosivity factor based on an indirect relation with daily precipitation. Meanwhile, Eq (2) as expressed below was proposed to determine the rainfall erosivity according to an empirical study in Indonesia.

$$EI_{30} = 6.119P^{1.211} \times D^{-0.473} \times M^{0.526} \quad (2)$$

where:
$EI_{30}$ : rainfall erosivity (KJ/ha)
P : monthly rainfall (cm)
D : number of rain days in a month (day)
M : maximum rainfall in a month (cm)

Daily rainfall data of 2019 at the Cihonje, Cisayong, Cibeuerum, and Ciamis Kadipaten from the Citanduy watershed Hydrological Information System were used to calculate the rain erosivity. The location of the rain post and tributaries are shown in Fig.2.

Based on the distance between the available rain gauges and the tributaries, the rainfall at Ciamis is used for the calculation of erositivity in tributary number 1 because it is the nearest. Meanwhile, the rain gauges at Cibeureum, Cisayong, Cihonje, and Kadipaten are considered during the calculation of the rainfall erosivity at each tributary. These values are applied to calculate the amount of soil loss at tributaries 2-9, 10-15, 16-33, and 34-37, respectively.

*3.1.2 Soil Erodibility*

This parameter is highly sensitive to soil physical properties such as texture, organic matter composition, and the percentage of sand, silt, and clay [25]. The soil erodibility factor for various soil types is in [26] and [27].

Soil types in the study area consist of brown latosol, dark brown-red latosol, gray regosol and lithosol complex, red-brown Mediterranean and lithosol complex, an association of humus-gley and gray alluvial, and yellow-brown andosol [28–32].

*3.1.3 Topographic Factor*

The LS factor is analyzed based on the length (L) and the slope (S) of the topography. The slope length factor is an index between the erosion that occurs on the slope length and the 22 m long slope identically. Meanwhile, the slope factor is an index between the erosion that occurs on a slope and the gradient with a slope of 9% identically.

Since erosion can occur in the presence of runoff (overland flow), the length of the slope can be interpreted as that of the overland flow LS, which is calculated using Eq. (3) [33] with the contour data [28–30, 32].

$$LS = \left(\frac{L}{100}\right) \times \left(1.38 + 0.965\ S + 0.138\ S^2\right) \quad (3)$$

where:
LS : Topographic factor (LS)
L : Slope length (m)
S : Slope gradient (%)

The topography of the Citanduy watershed area includes mountainous areas in the north and the coast in the south, which border the Indian Ocean. In the middle part, there is a hilly area with an average slope of the land as follows (a) the eastern part (Cilacap and Ciamis Regencies) 0.20-14.11 %, (b) the middle part (Tasikmalaya Regency) 1.4 - 12.15 %, and (c) Western Part (Garut and Cianjur Regencies) 4.91 - 11.35 % [20].

*3.1.4 Land Cover Index*

The C factor ranges from 0 to 1, where a value of 1 indicates that the land is not covered and the surface is considered arid land, while zero shows that the land is covered and well protected [24]. Several studies have been carried out to determine the land cover management factor (C) for general situations. The land cover index for different types of land cover is in [34]. Most of the land in the study area is used as rice fields and dry land mixed with shrubs.

*3.1.5 Support Particle Index*

The P factor is defined as the impact of land use or agricultural systems on soil erosion. When there is no erosion control solution, the P-value can be assumed to be 1.0 [24].

The P factor adjusts the erosion potential due to runoff by considering the effects of contours and terracing [35].

The value of the P factor for various land conditions is stated in [34].

Land use affects erosion through land cover (C) and conservation index factor (P). Each type of land use has a different agricultural pattern that affects the value of the P coefficient. Most of the land in the study area is used as rice fields and dry agricultural land mixed with shrubs.

*3.1.6 Sediment Delivery Ratio*

The USLE only assumes the amount of soil moved on, not from, a field [36]. Therefore, the sediment delivery ratio needs to be considered in predicting the annual sediment yield in the river course.

Potential sedimentation is the process of transporting sediment from erosion to be deposited in certain places such as reservoirs. The actual amount of erosion that becomes sediment is influenced by the ratio between the volume of sediment from actual erosion and the volume that can settle in the reservoir, which is the Sediment Delivery Ratio (SDR). The SDR is affected by watershed area and can be formulated as expressed in Eq. (4).

$$SDR = \frac{S(1-0.8683A^{-0.2018})}{2(S+50n)} + 0.08683A^{-0.2018} \quad (4)$$

where:
SDR: Sediment delivery ratio (%)
A : Catchment area (ha)
n : Manning roughness coefficient

Estimation of the potential sediment rate that occurs in a watershed can be calculated using Eq. (5).

$$S\text{-}pot = E\text{-}Act \times SDR \quad (5)$$

where:
S-pot : Potential sedimentation

E-Act : Actual erosion
SDR : Sediment delivery ratio

### 3.2 Field Observation

The suspended sediment load data is important in the validation or calibration process of USLE analysis. The two observation stations available include Cirahong (-7.35 N, 108.36 E) and

Bojongsalawe (-7.36 N, 108.46 E). The Cirahong station is upstream of the reservoir inlet, while Bojongsalawe is downstream of the dam. The data were provided by the Citanduy River Authority (Balai Besar Wilayah Sungai Citanduy) and are accessible at bbwscitanduy.sdatelemetry.com.

The available sediment record is only 1 year long, which is obtained in 2019 (Fig.3 and 4). Therefore, the analysis will assume that the suspended sediment loads this year represents the normal hydraulic behavior of the Citanduy River.

## 4. RESULTS AND DISCUSSIONS

This study shows the estimated reservoir lifetime based on land erosion upstream of the dam using the USLE. It also compares the result of the USLE method with the suspended sediment load measured within the area.

The land erosion rate was derived by summing the application of Eq. (1) for all tributary yields A = 1,289.24 t/ha/year.

Since the watershed area is 63,405 hectares, the amount of the eroded soil is their multiplication, namely A total = 81,744,281 t/year.

USLE method estimates the soil loss from the catchment area, but not necessarily the amount of soil transported. Hence, the variable of sediment delivery ratio (SDR) needs to be determined. The computation of SDR by Eq. (4) is derived by applying an average slope (S) of 9.1 %, Manning coefficient (n) of 0.06, and catchment area of 63,405 hectares, the result is SDR = 2.27 %.

The multiplication of A and SDR (Eq. (5)) produces the amount of land erosion leaving the watershed. This shows that the eroded soil will move into the Leuwikeris Reservoir waterbody. Therefore, Eq. (5) represents the potential amount of sediment deposited on the reservoir bed.

Multiplying A total with SDR yields S-pot = 1,853,266.71 t/year. Assuming the sediment-specific gravity ($\gamma$) is 2.56, the volume of sediment transported into the reservoir is 723,932.31 $m^3$/year. The previous paragraph estimates the volume of solid particles displaced from the watershed and transported by the river into Leuwikeris Reservoir. However, this is not necessarily the volume of sediment occupying the storage. The displaced particles collectively settle at the reservoir bottom. The accumulated mass will contain pores among the particles. Subsequently, the reduction in the reservoir volume will be greater than the volume of displaced sediment. However, the relationship between them is hitherto difficult to determine. Hence, the rest of the analysis will assume the volume of sediment eroded from the watershed equals the volume of settled/deposited sediment.

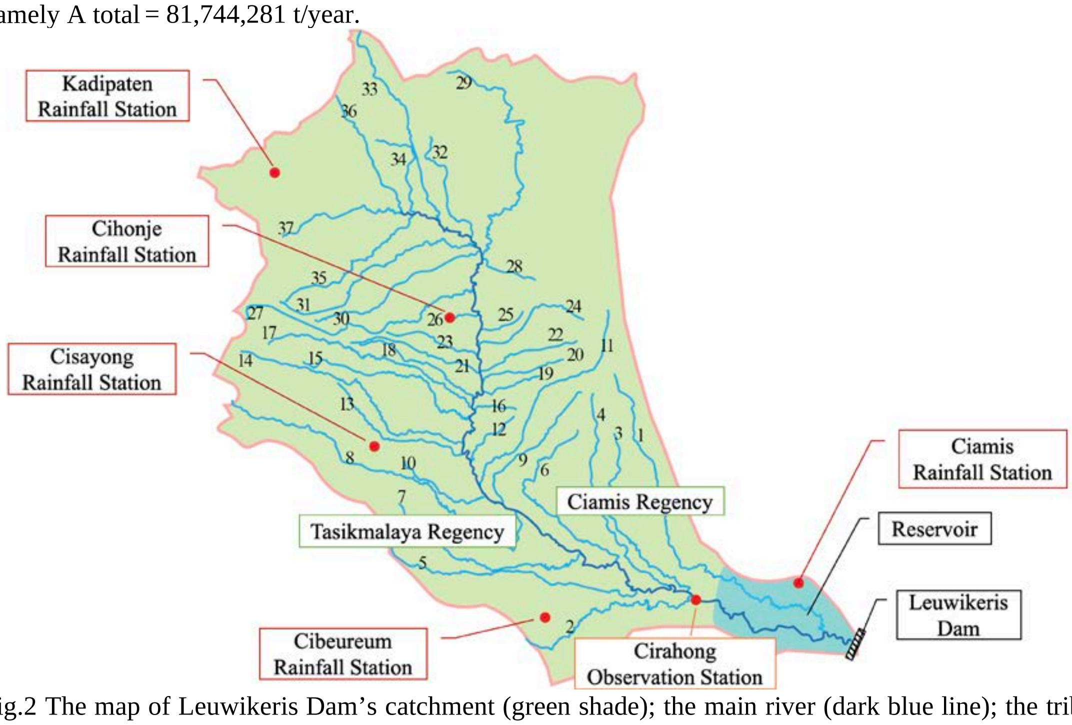


Fig.2 The map of Leuwikeris Dam's catchment (green shade); the main river (dark blue line); the tributaries (light blue line and numbered); the rainfall stations; and the suspended sediment observation station (red circle) [28–30, 32]

Since the dead storage capacity of Leuwikeris Reservoir is 36.09 million $m^3$, the lifetime of the reservoir can be forecasted by dividing the dead storage by the annual erosion rate, namely $36.09.10^6$ $m^3$/723,932.31 $m^3$/year = 49.85 years. The estimated lifetime is close to the reservoir lifespan estimated by the Ministry of Public Works and Housing of the Republic of Indonesia at 51.47 years, which was computed by the USLE method.

The next step is to forecast the amount of sediment in Leuwikeris Reservoir using the observed daily record of suspended sediment load Fig.4 and 5. The annual sediment load measured at Cirahong station is 401,990 t/year, while Bojongsalawe has 455,062 t/year. This showed that Bojongsalawe saw more sediment than Cirahong station because it lies downstream. This implies the greater the catchment area yields, the more transported sediment.

The result shows that the bulk density is 0.6 t/$m^3$, while the suspended sediment volumes are 723,932 $m^3$/year and 669,984 $m^3$/year at Cirahong and Bojongsalawe, respectively. Furthermore, these values are close to the soil loss calculated using the USLE by the Ministry of Public Works and Housing of the Republic of Indonesia or the authors, which are 701,250 $m^3$/year and 723,932 $m^3$/year, respectively.

The calculation of the Leuwikeris Reservoir lifetime using the USLE predicts that the reservoir will reach the end of its life after 49 years 10 months 7 days (49.853 years) from the time of operation. This is in line with the estimation results based on sediment transport data from the Citanduy Watershed Hydrological Information System at the Cirahong and Bojongsalawe observation stations. It also correlates with the erosion rate data on the water resources development pattern of Citanduy Watershed, which predicted that the reservoir lifetime will be completed after 53.867, 47.585, and 51.465 years, respectively. Before validating the USLE calculation with the recorded suspended sediment load, there is a need to consider the limitation of the method. This is because it only quantifies sediment from the catchment area, but not from gully or stream bank erosion [36]–[38]. The recapitulation of the estimation of reservoir lifetime from different approaches are shown in Table 1 and Fig. 5.

The sediment observed at Cirahong and Bojongsalawe is not exactly from the Citanduy watershed, but it can be mixed with the sediment from the bed and bank erosion of the Citanduy river and tributaries. Moreover, USLE failed to consider the deposition of eroded soil along the river.

The limitation also comes from the measurement technique. The calculation of reservoir lifetime considers the total load (bed load + suspended load) which enters the reservoir. However, bed load is significantly difficult to measure because it is a thin layer near the bed [39]. The estimation of sediment influx needs to depend on suspended load measurement, which is carried out by US DH-48.

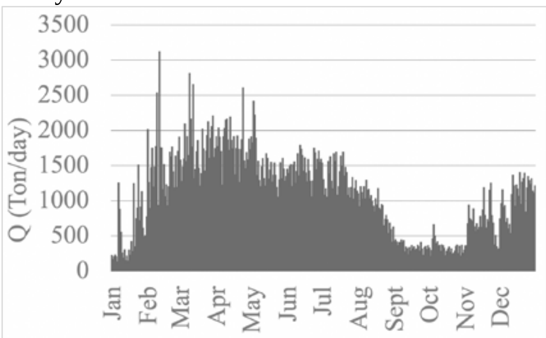


Fig.3 The record of suspended sediment load at Cirahong station in 2019 [40]

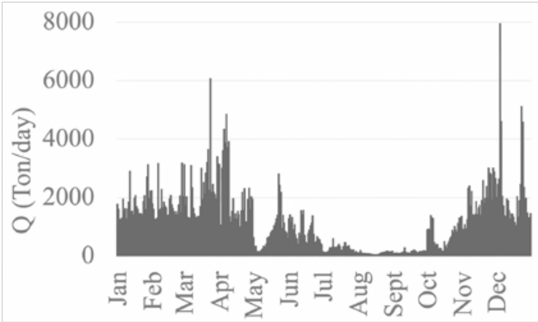


Fig.4 The record of suspended sediment load at Bojongsalawe station in 2019 [40]

Table 1 The reservoir lifetime estimation based on various approaches

| Reference | γ (t/$m^3$) | Sediment yield ($m^3$/year) | Lifetime (year) |
|---|---|---|---|
| USLE reference [1] * | 2.561 | 701,250 | 51.47 |
| USLE calculation [1] | 2.561 | 723,932 | 49.85 |
| Cirahong station [2] | 0.602 | 669,984 | 53.87 |
| Bojongsalawe station [2] | 0.602 | 758,436 | 47.59 |

** [20]*
*[1] Specific gravity*
*[2] Bulk density*

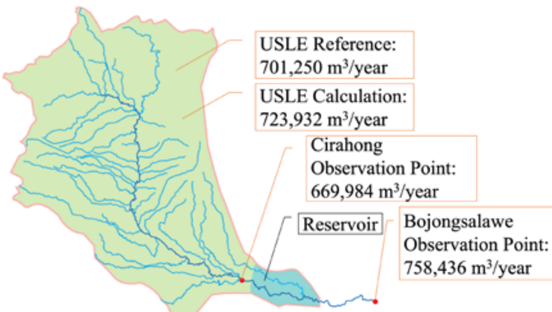


Fig. 5 The illustration of the sediment yield quantity based on various approaches

The quantity of land erosion computed by USLE should approximate the amount of sediment recorded during observation (Fig.5). The problems are USLE's limitation in considering erosion/deposition mechanism and the inability to precisely determine bed load. Despite these limitations, the USLE method performs accurately when validated with sediment measurement. The analysis in this study shows the agreement of eroded soil quantification by USLE calculation or by field observation. Meanwhile, results from previous reports concluded that the theoretical eroded soil quantity compares quite fairly with measurement data [37]. It also compares accurately with different measurement methods such as the paleolimnological records [41].

The fact that the validation compared quite fairly might come from the balancing of erosion and deposition along the rivers. The USLE does not consider gully erosion and sedimentation. When the amount of gully erosion and deposition are not different, they counterbalance each other. It implies that the USLE-calculated soil loss' quantity approximates the quantity of sediment entering the reservoir.

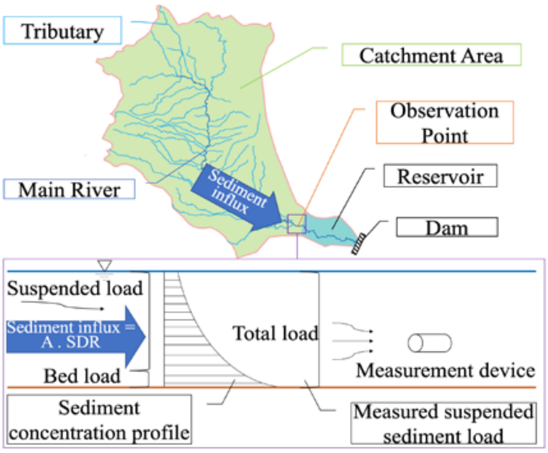


Fig. 6 The validation scheme of eroded soil quantity by field measurement

Furthermore, the suspended load tends to dominate total sediment transport [42]. This indicated that its measurement approaches the total load. This method justifies the use of US DH-48 in sampling the suspended load, which is in line with this study.

Note that the reservoir lifetime calculation in this paper assumes no change in the watershed's land use. Land use change will alter reservoir sedimentation [43–44]. Examples of land use change are urban sprawling and conversion from vegetation into a settlement or industrial area [45–46]. Such phenomena indeed occur here. The satellite imageries from various years reveal the land use change in the Citanduy watershed (Fig.7). The red line is the border of the watershed while the blue circle illustrates the converted area. In 1984, there was only a small area of settlement. In 2009, the area grew and another new settlement area emerged at its upstream. Both areas develop even larger as seen in the 2020 imagery. Consequently, the actual reservoir lifetime might differ from the calculation.

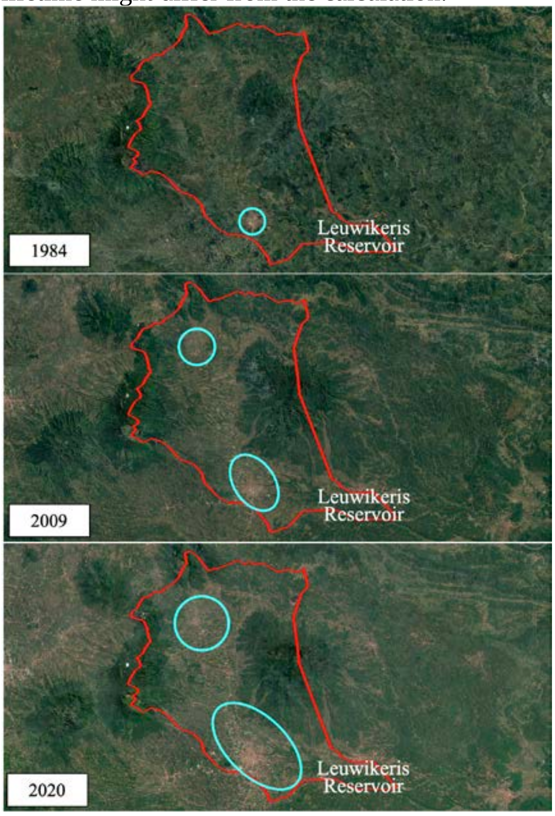


Fig.7 The land use development within the Citanduy catchment area

## 5. CONCLUSIONS

The sedimentation rate determines when the dead storage of the reservoir will be full and the end of its service life. The theoretical calculation using USLE and the field measurement data is in line with the reservoir lifetime prediction, which is approximately 50 years.

Validation is still necessary to ensure the accuracy of the theoretical erosion analysis. However, there is no perfectly accurate erosion model and measurement technique. This study signifies the agreement between suspended load field observation and USLE analysis despite of their shortcomings. There are many advancements required to improve both accuracies, but the finding in this case study indicates the feasibility of the combination.

## 6. ACKNOWLEDGMENTS

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