Journal of Natural Resources and Environmental Management
https://doi.org/10.29244/jpsl.16.5.644

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Comparative Delineation Methods and Ecological Quality Assessment of Riparian Zones in the Downstream Ayung River, Bali

I Kade Alfian Kusuma Wirayuda[a], I Putu Gede Eka Handrayana Putra[a] , Made Dendy Pratama[b], Moh Saifulloh[c]

[a] Department of Aquatic Resources Management, Faculty of Marine Science and Fisheries, Udayana University
[b] Department of Aquaculture, Faculty of Marine Science and Fisheries, Udayana University
[c] Department of Marine Sciences, Faculty of Marine Science and Fisheries, Udayana University

Article History
Received 03 August 2025
Revised 05 July 2026
Accepted 30 July 2026

Keywords
land cover, remote sensing, riparian quality index, riparian zone

ABSTRACT

Riparian zones are transitional areas between aquatic and terrestrial ecosystems. They play a very important ecological role in both ecosystems. The accuracy of ecological assessments of riparian zones fundamentally depends on how riparian boundaries are delineated. Current policies rely on strict, fixed buffer zones, which lead to generalization. This study evaluates how boundary sensitivity affects the Riparian Strip Quality Index (RSQI). This study compares three delineation methods (Upland Terrace, Fixed-width buffer, and slope-based) in the downstream Ayung River, Bali. Statistical analysis indicated that the delineation method affected the ecological assessment outcomes (η^2 = 0.49). The fixed-width buffer delineation method tends to underestimate riparian quality by including non-contributing built-up areas (27.23%). In contrast, the Upland Terrace method shows more ecologically representative results and has no significant score difference with slope-based delineation (Wilcoxon Z = -0.75). RSQI evaluations showed significant spatial variability. It also indicated local degradation in urbanized segments (RSQI dropping to 50.09–59.77 in Segments 1 and 5), and pristine environmental quality where segments are dominated by natural vegetation (RSQI = 94.41 in Segment 9). These findings show the disadvantages of current regulations that use a generalized delineation method. To improve urban river management, policymakers need to consider a transition to geomorphology-based boundary delineations and carry out targeted restoration in degraded areas.

Introduction

Rivers are lotic ecosystems with high dynamics and are important to the hydrological cycle. They are formed by physical processes such as erosion, sedimentation, inundation, and interactions between groundwater and surface water. The riverine ecological conditions are strongly influenced by river morphology and the catchment characteristics, including riparian zones along the riverbanks [1,2]. The riparian zone is a transition area that links aquatic or wetland ecosystems with the surrounding terrestrial land. This area is typically defined by vegetation along the riverbanks that forms a natural boundary between the two systems [3–5]. This zone supports diverse species, habitats, and ecological processes, and provides important ecosystem services, such as filtering pollutants before they enter the rivers [6–8]. Vegetation performs multiple interlinked functions that trap water and sediment, moderate increases in water temperature, provide habitat for flora and fauna, regulate energy and nutrient cycling, buffer pollutants, and shape the local microclimate, thereby contributing to greater plant resilience along with biodiversity [2,6]. Although riparian vegetation has morphological, physiological, and reproductive traits that enable adaptation to humid and flood-prone conditions, the riparian zone remains an ecosystem highly vulnerable to hydrological processes, geomorphological changes, and anthropogenic encroachment [4,7,8].

Corresponding Author: I Kade Alfian Kusuma Wirayuda alfiankusuma@unud.ac.id Department of Aquatic Resources Management, Udayana University, Denpasar City, Bali, Indonesia.

Anthropogenic activities in developing countries have affected the functions and condition of river ecosystems. The existence of Built-up structures and riparian vegetation loss can inhibit natural filtration, leading to increased pollution and loss of fluvial biodiversity. River restoration and management strategies are needed to enhance the resilience of river ecosystems and improve their aesthetic value [9]. Analyzing the ecological quality of riparian zones is a crucial first step toward managing and restoring riverine riparian areas. To quantify this ecological condition, several methods are available for estimating riparian zone quality, including the Riparian Strip Quality Index (RSQI). The RSQI assesses the quality of riparian zones by analyzing their land cover [10,11].

Land cover monitoring can be carried out using remote-sensing approaches. This approach is one of the effective methods for observing riparian zones across large areas [12]. Various remote sensing techniques are available for mapping riparian vegetation, including Unmanned Aerial Vehicles (UAVs), LiDAR, and satellite imagery [13]. Riparian zone quality assessment is necessary to supportriver ecosystem management. However, the accuracy of these assessments relies on the delineation of the riparian boundary. The initial stage in the RSQI analysis is calculating the land-cover percentages. Researchers must define the extent of the riparian buffer as the area to be identified. Any inaccuracy or bias in drawing this boundary will affect the proportion of land cover classes analyzed within the GIS environment, leading to a misinterpretation of the ecological quality assessment.

There are several methods to determine riparian zone boundaries. The fixed-width buffer method is the most common method applied, which generates a uniform distance from the riverbank across all terrain features [14,15]. Although computationally simple, this method frequently disregards geomorphological realities. Conversely, Topography-based methods identify functional riparian zones based on slope breaks and valley confinement, delivering a more hydrologically relevant delineation [16,17]. Difference in the delineation method affected the land cover proportions in each river area and led to different Riparian Quality Index (RSQI) scores. Although the RSQI has been widely used as a riparian condition assessment tool, there is still little research that focuses on the potential bias caused by differences in delineation methods. Previous ecological assessments have predominantly evaluated the RSQI using a single, static boundary approach. Consequently, a substantial gap remains in the riparian sensitivity condition indices and delineation methods, which may lead to bias and misinterpretation of the actual riparian conditions.

The application of these delineation methods is limited and segmented by local riverine characteristics. The diverse characteristics of rivers are one of the challenges in applying delineation methods, especially in Southeast Asia, which has unique urban characteristics. Rivers in these regions have dynamic morphological features that are significantly influenced by tropical climatic conditions. Moreover, anthropogenic pressure from dense residential encroachment along the riverbank is a major challenge in riparian zone management. However, regulations regarding riparian zone boundaries usually apply a standard fixed-width buffer method. It is often adopted from Western frameworks with flatter topographies, which are spatially irrelevant, impractical, and ecologically misaligned when applied to highly constrained landscapes, typically in tropical regions. Bali's rivers exhibit varying morphological heterogeneity from upstream to downstream. The application of a fixed-width and regulatory approach to complex area characteristics can introduce accuracy bias in riparian zone delineation results.

The Ayung River is one such tropical hydrological challenge. As the largest watershed in Bali, it covers 306,149 km² and comprises seven subbasins [18,19]. This river flows from Bangli Regency into Padang Galak Beach (Denpasar City), spanning a total length of 71.791 km [19–21]. Research conducted by Eryani [20] found that the Ayung watershed is predominantly covered by forest (49.72%). However, in the downstream areas (sub-basins 5, 6, and 7), the land cover is dominated by residential settlements. Previous studies have also highlighted the poor water quality in the downstream section of the Ayung River, particularly in Denpasar City, which has the highest population density in Bali. Therefore, evaluating the true ecological state of constrained rivers requires an entirely new understanding of the way boundary definitions dictate ecological scores. To address this gap, this study comprehensively compared spatial delineation methods and their direct impact on ecological quality assessments downstream of the Ayung River. Specifically, this study attempts to (1) compare the riparian boundaries and land cover proportions produced by different delineation methods, (2) measure the effect of different delineation methods on the final RSQI assessment score, and (3) evaluate how these methodological discrepancies influence urban river management decisions and spatial planning strategies.

Materials and Methods

Study Area

This study was conducted in the Ayung River area, focusing on the Denpasar City region (Figure 1). According to Indonesian Central Bureau of Statistics (BPS) [22], this city has a recorded population of approximately 725,314 people, excluding tourists and non-permanent residents. Urbanization has driven land cover conversion along the Ayung River in Denpasar. The riverbank has been transformed from natural cover into concrete structures. Therefore, this study focused on the riparian zone along the downstream of the Ayung River within Denpasar City. The study area was determined from the Ayung Watershed, which was analyzed through watershed analysis utilizing a Digital Elevation Model (DEM). In addition, river extraction was conducted to generate flow. Consequently, we compared the extraction results with the river network data from the Indonesian Geospatial Information Agency and World Imagery satellite images to obtain the most accurate representation of the actual field conditions in the study area.

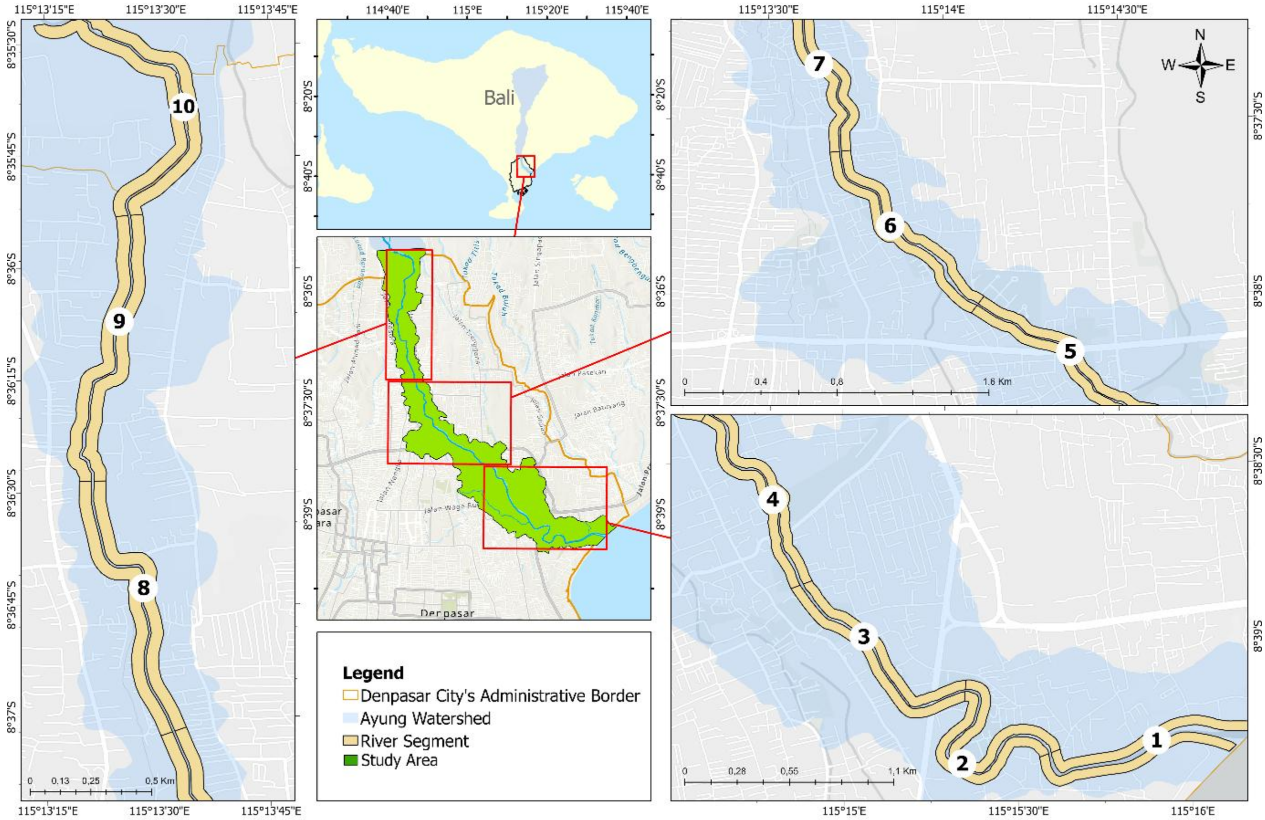

Figure 1. Geographical layout of the study area, located in the downstream region of the Ayung River, Bali. The river corridor is divided into 10 distinct spatial segments to map and analyze localized conditions within the riparian corridor. This segmentation serves as the fundamental basis for identifying spatial variations in ecological degradation.

Data and Methodological Framework

This study used both geospatial and field-observation data. Remote-sensing data were used to delineate and analyze the riparian zone conditions. Field surveys were conducted to validate the remote sensing analysis results. We used the Digital Elevation Model from the Indonesian Geospatial Information Agency (DEMNAS) to map watersheds, extract river channels and delineate the riparian zone. This data has a horizontal resolution of 0.27 arcseconds (8.25 m) and a higher vertical resolution than the SRTM. High-resolution ESRI World Imagery (2023) was used for vegetation mapping. Other spatial data, such as the administrative boundaries of Denpasar City and river network data, were used to define the areas of interest. All spatial datasets were standardized and projected to the Universal Transverse Mercator (UTM) Zone 50S coordinate system using the World Geodetic System (WGS) 1984 datum to ensure highly accurate geometric and area calculations. Spatial processing, DEM analysis, and digitization were performed using ArcGIS Pro 3.0.0.

The fundamental methodological framework is illustrated in Figure 2 to provide a comprehensive overview of the research stages. This study fundamentally approaches riparian delineation using three distinct methods: slope-based, Upland Terrace, and fixed-width. Concurrently, land cover mapping was conducted via on-screen digitization and validated through an accuracy assessment. The land cover proportions within each boundary were extracted to compute the RSQI. Statistical analysis was applied to identify the differences in RSQI scores among the delineation methods.

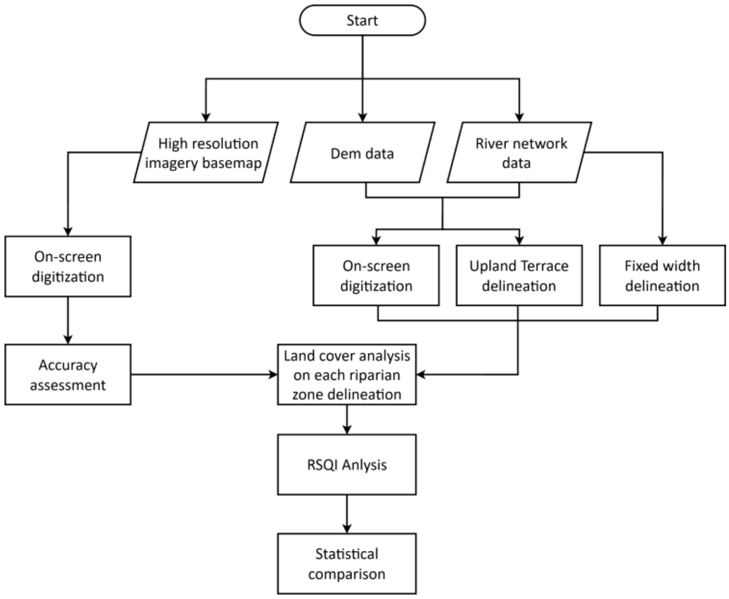

Figure 2. Flowchart of the spatial analysis framework to evaluate riparian ecological quality by comparing three different delineation methods. The diagram illustrates the step-by-step integration of spatial data to calculate the RSQI and verify the sensitivity of ecological scores to different spatial boundaries.

Riparian Zone Delineation Method

In this study, we applied three methods to delineate riparian zones: Upland Terrace Analysis, a fixed-width buffer of 50 m, and slope-based delineation. Upland Terrace Analysis is an approach used to delineate riparian zones based on a river's topographic profile. There are four distinct zones within the riparian zone. The first zone extends from the top of the toe zone to the bank zone and is predominantly dominated by aquatic plant species, such as reeds, characterized by flexible stems and spreading root systems. The next zone, known as the bank zone, extends from the edge of the channel to the upper limit of the overbank zone and is typically dominated by small to medium-sized shrubs. The transitional zone lies between the overbank zone and the flood-prone area, whereas the upland zone is generally covered by woody vegetation and tall trees [23] . However, Dodds [24] described terrestrial (upland) boundaries as typically defined by variations in topography, vegetation structure, and decreasing soil moisture levels. Consequently, the riparian zone boundary can be characterized by a diminishing presence of hygrophilous or mesophyte vegetation. This boundary is known as the "brown line," which is an area predominantly occupied by woodland vegetation. The woodland riparian zone begins at the upland edge adjacent to the active channel (green land) and extends outward to the brown line. Steep-banked rivers often exhibit narrow riparian and riparian woodland zones.

Recent conceptualizations, which adopt the foundational valley classifications introduced by Verry [25], define the terrestrial boundaries of riparian zones through multidimensional physical and ecological gradients, which are heavily dependent on the valley setting and topography [24]. As shown in Figure 3, highly confined streams typically have steep lateral slopes (>50%) and V-shaped valleys, which strictly limit lateral riparian expansion [26]. In contrast, rivers with moderate slopes (15-50%) form U-shaped valleys with distinct and recognizable floodplains and terraces, supporting a broader riparian ecotone [24,25,27]. Furthermore, on unrestricted rivers located within plain geoforms with very gentle valley slopes (<15%), the functional riparian boundary is primarily determined by flood recurrence intervals and channel bankfull width [28], differentiating between wider main channels (>3 m) and narrower tributaries (<3 m).

According to De Sosa [29] who delineated riparian zones using a GIS-based topographic approach, combining DEM and contour data with supporting datasets such as aerial photography and river network maps. In this study, we attempted a similar approach, albeit with several adjustments to the delineation technique. We performed a digital cross-sectional analysis of river profiles using DEMNAS (Digital Elevation Model from the Indonesian Geospatial Information Agency). According to Irene [30] , DEMNAS has a coefficient of determination (R^2) of 0.963, indicating a high level of agreement with the terrestrial surveys. DEMNAS has a relatively high resolution of 0.27 arc-seconds, making it suitable for surface analysis in areas of limited spatial extent compared with lower-resolution DEMs. The DEMNAS exhibits a root mean square error of 2.237 m and a vertical accuracy of 3.679 m [31]. The application of these data to a relatively localized spatial scale can introduce elevation bias during the boundary delineation process. To mitigate the inherent vertical error and improve the detailed transitions between elevation pixels, we applied a focal smoothing process to the DEM data prior to the cross-sectional analysis. Although alternative high-resolution data, such as UAV photogrammetry, provide more detailed topographic information, DEMNAS was selected for its computational efficiency, considering the relatively large study area of the Ayung River. The use of UAVs involves prohibitive costs and a complex flight-permit process. Therefore, DEMNAS was chosen as an initial and practical standard for mesoscale geomorphological mapping.

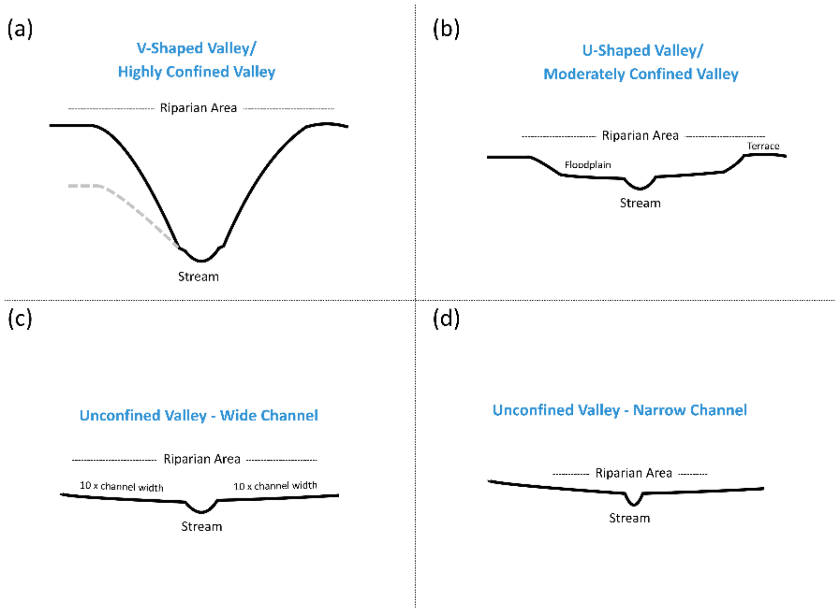

Figure 3. Topographical cross-sections defining the structural limits of riparian zones across (a) highly confined, (b) moderately confined, (c) unconfined wide, and (d) unconfined narrow valley types. It visually shows that a river's functional riparian extent depends on local terrain. It shows that an accurate ecological assessment requires a geomorphologically based boundary delineation.

We created digital transects across the river line with a transect length of 300 m and a distance of 15 m for each transect. We adjusted this distance to the length of the river in the study area and considered the detail and effectiveness of the transect to delineate the upland terrace. The digital cross-section methods previously utilized by Petikas [32] generated transects with a spacing of 12.5 m. We analyzed the elevation profile to obtain an overview of the river topography, followed by making points of the upland terrace section on the left and right sides of the river to mark the delineation boundary. To minimize bias during this manual point-selection process, the identifications were standardized and systematically placed at the edge of the flat terrace immediately after the first major break in slope (topographic inflection) in the elevation profile. This specific placement represents an abrupt functional transition from an active, steep riverbank to a stable upland terrace. Based on the river valley type [24,25,27,28], the shape of the Ayung River valley is dominated by Type I with a slope of >5%. After the profile elevation analysis, a digitization process was conducted by connecting the points of the upland terrace boundary markers that had previously been made to produce the riparian zone delineation line. In this process, additional criteria were applied, namely the minimum distance from the river to the riparian zone boundary was 100 ft (30m) by creating a 30-meter buffer on both sides of the river (Figure 3).

Manual or semi-automatic boundary analysis can lead to spatial uncertainty in the delineation process, particularly with the Upland Terrace method. Although digital transects were created at 15-meter intervals, the interpolation of boundary lines between these points remains an estimate (Figure 4). Local geomorphological features within these gaps may go undetected, resulting in minor spatial deviations from the actual functional boundaries of the habitat. However, these minor spatial errors are negligible compared to the massive spatial generalizations and geomorphological ignorance inherent in the standard fixed-width buffer method.

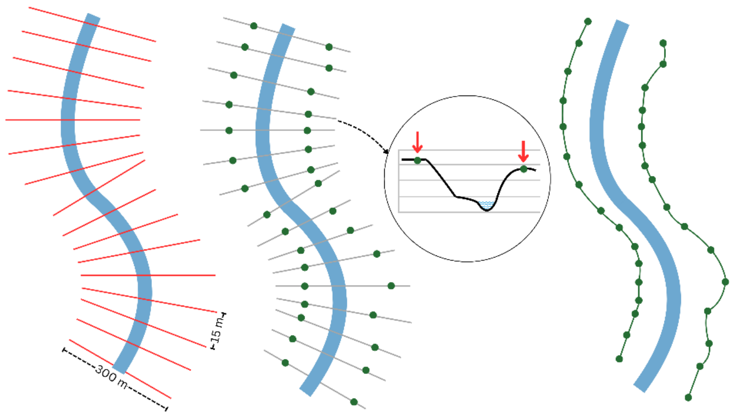

Figure 4. Upland Terrace delineation workflow to map the functional riparian corridor by capturing local topographic variations. The extraction of terrace edge points from 300 m digital transects spaced at 15 m intervals uses elevation cross-sections to identify the precise boundaries of the riverbanks that conform to the valley terrain.

In addition to the Upland Terrace Analysis method using cross-sectional analysis, we utilized several alternative delineation techniques to identify riparian zones, including fixed-width buffer and slope-based methods. There are varying perspectives on the appropriate buffer widths for riparian zone delineation. However, several studies suggest that an effective width ranges from 5 to over 100 m, depending on the buffer's ecological function [14,15]. In this study, we adopted a 50-meter buffer based on the recommendation of Peterjohn and Correll [33], as integrated into the recent conceptual framework for nitrogen buffering by De Sosa et al. [29] for agricultural purposes, a method also applied by Fandino [11][30] in their multi-method delineation of riparian zones. Although the study area is highly urbanized, this buffer zone was selected because the Ayung River corridor still contains patches of agricultural land where the nutrient buffering function remains ecologically relevant. This is particularly important becaause the Ayung River Basin in Denpasar exhibits a fairly high heterogeneity of land cover.

In addition, we deliberately applied the agricultural standard as a rigid baseline benchmark. This allowed us to explicitly compare and evaluate the performance of conventional and generalized metrics against dynamic and topography-based methods. Furthermore, Cole et al. [14,15] and Lind et al. [14,15] recommend riparian buffer widths ranging from approximately 5 to 30 m for water quality protection from nutrient input, whereas wider buffers from 10 to more than 100 m are recommended for aquatic wildlife habitat conservation. Therefore, we applied a 50-meter buffer on both sides of the river. A slope-based delineation approach was applied by Susetyo et al. [31] utilizing LiDAR technology to analyze Riparian Buffer Zones (RBZ) based on recommendations from the South Carolina Forestry RBZ guidelines. According to Eishoeei [34], riparian buffer zones are divided into primary and secondary zones. The primary zone represents the minimum required width of the riparian zone across all slope gradients, extending 40 ft (12 m) from the riverbank. The secondary zone is not added for slopes less than 5%, but is necessary for slopes of 5% or greater. The maximum total buffer width based on the slope was 48 m, consisting of a 12-meter primary zone and a 36-meter secondary zone.

Slope gradients were analyzed within a 30-meter buffer zone on both sides of the river. The slope percentage was determined using the "Focal Statistics" tool, which computes values based on the surrounding (neighborhood) cell data. The river slope was classified according to the Riparian Buffer Zone (RBZ) classification. This method divides the buffer into primary (minimum) and secondary (additional) buffers. A primary buffer of 12 m was applied across all slope gradients. However, the secondary buffer width scales with terrain steepness. No secondary buffer was used for flat terrain with a slope of less than 5%. However, secondary buffers were added for slope ranges of 5-20%, 21-40%, and those exceeding 40%, by 12 m, 24 m, and 36 m, respectively. This variable-width approach ensures that steeper riverbanks receive a wider buffer to mitigate higher erosion and runoff risks.

Riparian zone vegetation mapping

Riparian zone vegetation mapping was conducted using an onscreen digitization method. Although this manual approach is highly time-intensive, it is considered the most accurate method for interpreting land cover from high-resolution imagery. This was necessary because of the narrow extent of the study area, which requires high spatial precision for detailed land cover mapping within the riparian zone. We used a high-resolution World Imagery map from Esri as a basemap to produce a vector map, which was then clipped based on the three delineated riparian zone boundaries. The land cover within each riparian zone was classified following the land cover categories defined by Gyimah et al. [35], which categorize land cover into forest, grassland and shrubs, agricultural land, bare land, and built-up areas. Despite its high accuracy, this digitization method still has a small chance of uncertainty owing to operator subjectivity, such as ambiguity in interpreting edge-effect zones (mixed pixels) or areas covered by buildings or cloud shadows. To mitigate this uncertainty and maintain consistency, the digitization process was performed by a single observer. We applied the fundamental elements of visual image interpretation, such as tone, color, texture, pattern, and shape, to accurately distinguish between specific vegetation types and built-up boundaries. Specifically, on-screen digitization was performed at a fixed, constant zoom scale of 1:500 to ensure uniform spatial detail and prevent multiscale generalization bias. In addition, data updates for freely accessible high-resolution imagery tend to be delayed (1–5 years), which can lead to discrepancies between interpretation and current conditions. Therefore, this study conducted accuracy calculations to assess whether the results of image interpretation were still relevant to the current conditions.

Accuracy Assessment

Riparian areas are dynamic zones that are highly influenced by the dynamics of river water. Therefore, it is essential to validate the vegetation map within the riparian zone to assess its accuracy, compare it with current field conditions, and evaluate uncertainty in land cover classification. Misclassification errors, such as distinguishing between natural vegetation and agricultural boundaries, can introduce sensitivity bias into subsequent ecological scores. To measure this uncertainty, the accuracy was assessed using an error (confusion) matrix, which served as the basis for calculating the Kappa Accuracy. According to Islami et al. [36], a Kappa Accuracy value greater than 81% indicates that the image interpretation results are accurate. The error matrix classes were divided into five main categories: forest, grassland and shrubs, bare land, agricultural, and built-up. To ensure a proportional and statistically valid sample size, observation points were distributed using a stratified random sampling approach, allocating 30 points to each of the present classes. This matrix effectively computes the statistical dependability of the categorized map, to ensure classification uncertainties are minimized before proceeding with the RSQI analysis.

Riparian Strip Quality Index Analysis

The RSQI is a tool used to assess the ecological quality and condition of riparian zones. It was originally developed by Saint-Jacques and was recently applied by Saha [10]. The RSQI can be used to conduct a temporal analysis of riparian zone conditions, compare riparian conditions across different sites or regions, and identify priority areas for restoration and conservation efforts [37]. The RSQI score was calculated by applying weights to several land cover classes, as proposed by Saint-Jacques and Richard (1998) in Saha et al. [10] (Equation 1). Where %LU represents the percentage of land cover within the riparian strip, and Wi is the weight assigned to each land cover type. The weighting of each land cover type follows the criteria established by Saint-Jacques and Richard (1998) in Saha et al. [10], namely, tree cover (10), open land (1.7), agricultural land (1.9), built-up land (1.9), and shrubland (5.8). Because the index applies fixed arithmetic weights with a wide range (1.7–10), the RSQI model is highly sensitive to the proportion of land cover captured within the spatial boundary. Consequently, the differing lateral extents produced by the various delineation methods act as the primary driver of index sensitivity. Calculating the RSQI across the three different boundaries in this study allows us to quantify how delineation uncertainty dictates the final ecological score.

$$RSQI = \frac{\sum(\%LU_i \times W_i)}{10} \quad (1)$$

The RSQI values ranged from 17 to 100, indicating the quality of the riparian conditions. Higher scores indicate better riparian strip quality, whereas lower scores indicate poor riparian quality. The RSQI scores were divided into four categories: Riparian strips with RSQI scores below 40 were categorized as Very Low, while the 40-60 and 60-80 ranges were classified as Low and Moderate, respectively. Riparian strips with scores exceeding 80 were classified as high quality with optimal ecological conditions. The RSQI analysis was conducted by dividing the study area into multiple segments and calculating the RSQI for each segment. The study conducted by Machado et al. [37] divided a 4.86-kilometer river into 500-meter sections. In this study, the analyzed section of the Ayung River spanned 11.49 km. This area was separated into ten sections covering both sides of the riverbanks, with an approximate length of 1 km each (**Error! Reference source not found.**). This aimed to create proportional segment sizes that covered the study area.

Statistical Analysis

Statistical analyses were performed to compare the RSQI scores generated by the three delineation methods. A Repeated Measures ANOVA (RM-ANOVA) was employed because the RSQI scores were derived from identical river segments, meaning that the observations across the three methods were dependent (related samples). Prior to the RM-ANOVA, data normality was verified using the Shapiro-Wilk test, and sphericity was assessed using Mauchly's test. When the sphericity assumption was violated, the degrees of freedom were adjusted using the Greenhouse-Geisser correction to produce a more conservative and valid p-value. Post hoc paired t-tests with a Bonferroni correction were applied to significant result to identify which delineation methods that differed significantly. The nonparametric Friedman test was used as an alternative when the normality assumption was violated.

Results and Discussion

Results

Riparian Zone Delineation Result

Significant difference are shown in the delineation zone of several delineation methods. The fixed-width buffer approach, which applied a 50-meter buffer on both sides of the riverbank, produced the largest riparian area of approximately 105.24 ha, creating a symmetrical boundary pattern along the river corridor. The slope-based delineation method produced the smallest area of 73.44 ha. It representing a 30.2% reduction in total area compared to the fixed-width approach and an 18.4% with the Upland Terrace (Figure 5). The corridor shape of the fixed-width approach contrasts with both topographic methods. The exhibit variable widths that adapt to the river's dynamic features, producing intersecting boundaries that closely follow the active flow, particularly at sharp meanders.

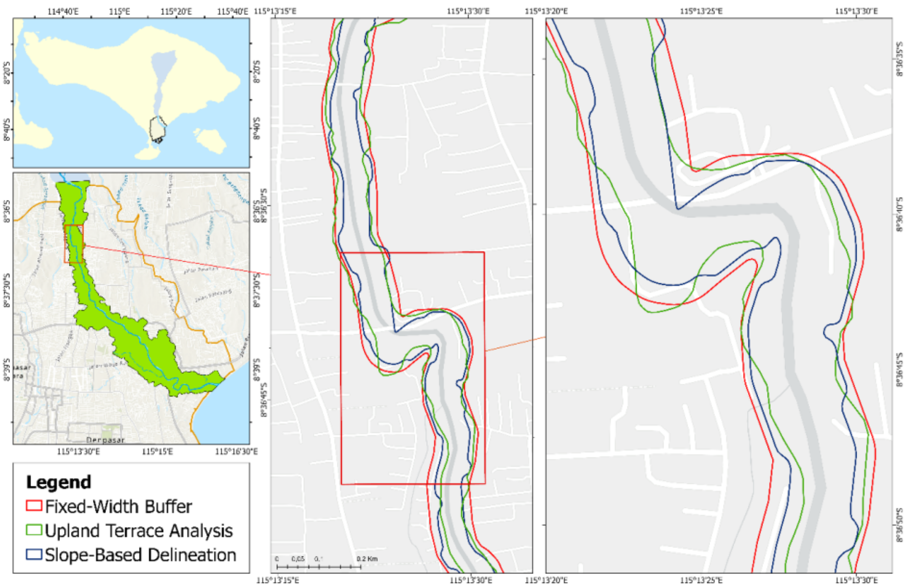

Figure 5. Spatial comparison of three riparian zone delineation methods applied to the downstream Ayung River in Bali. The map shows the boundary differences among the fixed-width buffer (red line), upland terrace analysis (green line), and slope-based delineation (blue line). The overlays show that the geomorphological approaches closely align with the river's topography, whereas the fixed-width buffer overgeneralizes the functional corridor extent.

Land Cover Analysis Result

Land cover within the riparian zones is dominated by forestland (Table 1 and Figure 6). The Upland Terrace and Slope-based methods showhigh proportions of forest cover, at 74.5% (66.72 ha) and 75.70% (55.60 ha) of their total areas. However, the Fixed-width buffer method captured the largest absolute forest area (69.51 ha), and the topographical methods yielded higher relative proportions. A distinct disparity was observed in the built-up class coverage. The Fixed-width buffer method captured the highest proportion of anthropogenic land, totaling 28.66 ha (27.23%). Conversely, the Upland Terrace and Slope-based methods captured significantly lower proportions of built-up areas, at 18.92% and 20.20%, respectively. Furthermore, variations were evident in the grass and shrub classes. Notably, the Slope-based method isolated a minimal extent of cropland (0.96 ha) compared to the Upland Terrace (3.62 ha) and fixed-width (3.42 ha) methods. Across all delineations, Grass and Shrubs consistently represented the smallest land cover fraction, ranging between 2.05 and 3.65 ha.

Table 1. Distribution of land cover area across four categories (forest, shrubs/grassland, bare land, and built-up) delineated using three riparian boundary methods along the downstream Ayung River, Bali. The data demonstrate that the fixed-width buffer has the largest riparian area and captures more built-up land compared to the topography-based methods.

Cover	Upland Terrace (ha)	Slope-based (ha)	Fixed-width buffer (ha)
Cropland	3.62	0.96	3.42
Built-up	17.02	14.84	28.66
Forestland	66.72	55.60	69.51
Grass and Shrubs	2.62	2.05	3.65
Total	89.99	73.44	105.24

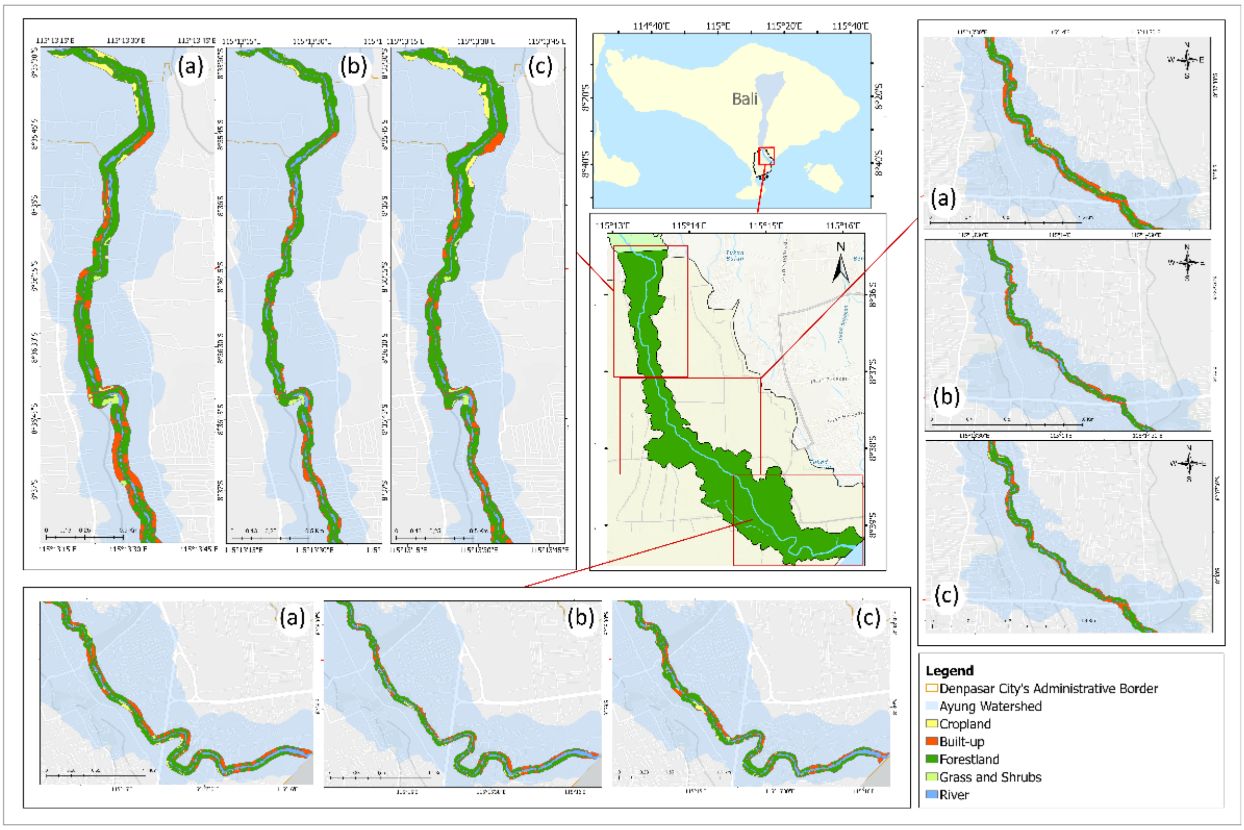

Figure 6. Land cover classification maps comparing (a) a 50-meter fixed-width buffer, (b) slope-based delineation, and (c) upland terrace delineation. These maps visually demonstrate that different methods produce different land-cover proportions. The fixed-width buffer produces significantly more built-up land in the riparian zone than the geomorphologically based delineation.

RSQI Analysis Result

The RSQI assessment showed various level of ecological quality downstream of the Ayung River (Figure 7). The spatial analysis shows possible ecological degradation in several areas that were consistenly identified in Segment 1 (right bank) and, specifically, in the fixed-width method in Segment 5 (right bank). In these specific segments, the Upland Terrace method recorded its lowest score of 59.77, whereas the Fixed-width method showed a much lower score of 50.09. Conversely, riparian zones show the best ecological conditions in Segments 2 (right bank) and 9 (right bank), which had the highest assessment scores exceeding 94 across the topography-driven methods.

Descriptive statistics revealed that the choice of delineation boundary affected the RSQI score. The Upland method classified the vast majority of the corridor (15 of 20 segments) as high quality, with a mean of 83.22 (SD = 8.70). In contrast, the fixed-width buffer method produced the widest range and the lowest overall mean (75.48, SD = 11.68), predominantly placing segments into the Moderate class (10 of 20). The Slope-based method produced scores ranging from 55.45 to 96.13 (mean 2.54, SD = 10.29), showing a central tendency similar to the Upland Terrace method, with most segments (13 of 20) classified as high. No segment across any method was classified as Very Low (< 40). This contrast shows that the fixed-width method more frequently downgrades and underestimates riparian quality than the other methods.

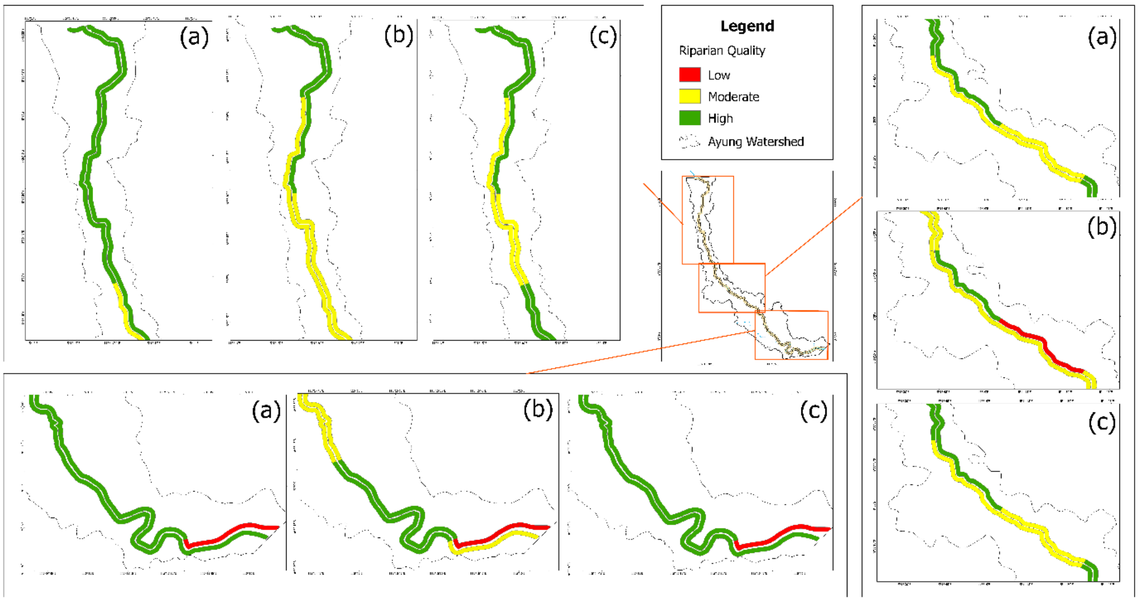

Figure 7. Spatial distribution maps of riparian ecological quality (low, moderate, high) along the downstream Ayung Watershed, comparing the (a) Upland Terrace, (b) fixed-width buffer, and (c) slope-based delineation methods. This comparison shows that the fixed-width buffer tends to underestimate riparian quality.

Statistical Analysis Result

Prior to the repeated measures ANOVA (RM-ANOVA), the Shapiro-Wilk test confirmed that the RSQI scores for all three methods, as well as their pairwise differences, did not significantly deviate from normality (p > 0.05). However, Mauchly's test indicated that the assumption of sphericity was violated (χ^2 (2) = 12.78, p = 0.002). Consequently, the Greenhouse-Geisser correction (ε = 0.663) was applied to adjust the degree of freedom. The RM-ANOVA revealed a statistically significant main effect of the delineation method on the RSQI scores, F (1.33, 25.19) = 18.31, p < 0.001. The partial eta squared (η^2) = 0.49 indicated a large effect size, demonstrating that the choice of delineation boundary substantially dictated the final ecological assessment.

To identify specific differences, post hoc paired comparisons with Bonferroni correction were performed alongside the nonparametric Wilcoxon signed-rank test (Table 2). The RSQI scores derived from the fixed-width (50 m) method were significantly lower than those produced by the Upland Terrace method (mean difference = 7.74, Bonferroni p = 0.001; Wilcoxon Z = -3.25, p = 0.001) and the slope-based method (mean difference = −7.06, Bonferroni p = 0.001; Wilcoxon Z = -3.92, p < 0.001). Conversely, no significant difference was observed between the Upland Terrace and Slope-based methods (mean difference = 0.67, Bonferroni p = 1.000; Wilcoxon Z = -0.75, p < 0.455).

Table 2. Statistical pairwise comparisons of RSQI scores across the fixed-width, Upland Terrace, and slope-based delineation methods using the Wilcoxon Signed-Rank test. The results show no significant difference between the two topography-based methods, but demonstrate that both differ significantly from the fixed-width buffer.

Comparison	Wilcoxon Z	Wilcoxon p	Difference
Upland Terrace vs Fixed-Width	−3.25	0.001	Significant
Upland Terrace vs Slope-based	−0.75	0.455	Not Significant
Fixed-Width vs Slope-based	−3.92	< 0.001	Significant

Accuracy Assessment and Field Survey

The accuracy of the land cover maps was assessed by conducting field surveys for each land cover class. The field survey results were used to compile a confusion matrix for the kappa accuracy analysis. The calculated Kappa coefficient was 0.82, which was classified as "Almost Perfect. The Built-up and Forest cover classes achieved accuracies exceeding 88% for both user and producer accuracies. The crop classes achieved 70% accuracy, whereas the shrub class achieved approximately 50%. The overall accuracy was 88.71%, which proves the high classification accuracy. Field verification confirmed a correlation between the RSQI values and biophysical conditions (Figure 8). A river segment with a high RSQI value was dominated by dense vegetation. This area has a natural river ecosystem with no concrete riverbanks.

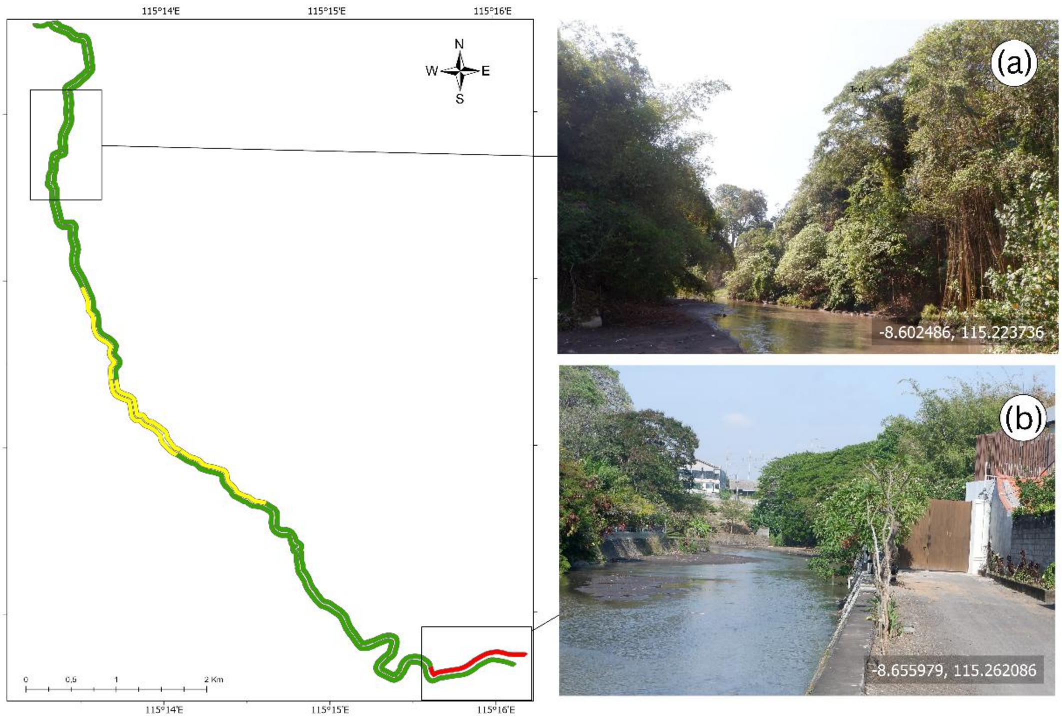

Figure 8. Field validation of the RSQI maps along the Ayung River, comparing the upstream segment (a) with a heavily degraded downstream segment (b). These ground-truth observations verify the map's accuracy, showing that the lowest RSQI scores are influenced by urban encroachment.

Discussion

Methodological Implications and Remote Sensing Performance of Riparian Delineation

The significant areal and spatial discrepancies among the three delineation methods highlight the critical importance of method selection in river landscape analysis. The standard 50-meter fixed-width buffer, while computationally simple, produced a generalized and monotonous boundary that failed to account for the river's natural sinuosity. The inclusion of a higher percentage of built-up areas (27.23%) in this method suggests that the rigid geometry artificially encompasses adjacent urbanized lands that are not functionally part of the riparian ecosystem. While adapted to gradient, the Slope-based method exhibited inconsistencies. It particularly in creates disjointed buffers, especially around sharp river bends. The Upland Terrace delineation method is the most ecologically representative approach. By utilizing geomorphological breaks [17], the varied topographic features of the river corridor can be accurately captured. It avoids the overgeneralization of the fixed-width approach and the disjointedness of the slope-based method. Consequently, the Upland Terrace offers a more precise baseline for RSQI assessment by excluding non-contributing anthropogenic areas. This is supported by our statistical findings (η^2 = 0,49), which demonstrate that the delineation boundary substantially affects the ecological assessment results. Overall, the data provide evidence that fixed-width buffer delineation underestimates riparian quality relative to a dynamic, topography-based approach.

However, despite its good ecological accuracy, the upland terrace delineation method has several limitations. This delineation process takes longer than the buffer- and slope-based delineation methods. In addition, this method involves subjectivity in determining upland terrace points. Another limitation of this method is the spatial resolution of the DEM data. The DEMNAS has a resolution of 0.27 arc-seconds (approximately 8 m), making it less effective, especially for narrow river channels, and prone to delineation bias. Although resampling techniques can artificially reduce the pixel size to enhance visual detail, they also inherently cause topographical generalization. The Upland Terrace method would have significantly higher precision if applied to high-resolution topographic data such as LiDAR. However, the resulting riparian zone is more ecologically representative of the natural conditions.

Land cover analysis using on-screen digitization achieved a high overall accuracy (88.71%), which proves the high classification accuracy of this methodology. According to Islami et al. [36], the Kappa coefficient of 0.82 indicates the classified maps have high accuracy. It shows the digitized land cover is similar in pattern to actual field conditions. However, the lower accuracy for the Shrub and Crop classes shows the challenges of spectral confusion in heterogeneous riparian environments. The low producer accuracy for shrubs may be due to field data collection or to the use of higher-resolution data (e.g., LiDAR or UAV) to better differentiate subtle vegetation types that play a vital role in bank stabilization. Despite these limitations, the consistency between the index-based assessment and field observations by Cunha et al. [38] confirms the usefulness of this approach for monitoring riparian vegetation health.

The lower producer accuracy for the shrub class (50%) is due to the inherent classification bias caused by the high similarity between natural shrubs and certain agricultural lands (croplands). In standard single-date imagery, unmanaged or specific crop types frequently mimic the object signatures and texture of shrubs. To reduce this unavoidable bias in future studies, we strongly recommend integrating higher-resolution multispectral imagery (e.g., UAV-based sensors) with multi-temporal vegetation metrics. This will significantly improve the spectral separability between croplands and natural shrubs.

Ecological Quality and Anthropogenic Pressures

The Ayung River's corridor is dominated by good riparian conditions, especially in the topography-based delineation. However, degradation still remains in specific areas, such as Segment 1 (right bank) and Segment 5 (right bank). In these segments, RSQI scores dropped markedly to 59.77 under the Upland Terrace method and 50.09 under the Fixed-width method It is indicating that the riparian zone is still functional is in a stressed condition due to land cover conversion from vegetation to built-up areas. Urbanization is one of the drivers that accelerates land conversion in riparian zones [39]. Anthropogenic pressure leads to disturbance of vegetation structure, which affect the pollution-filtering mechanisms, bank stabilization, and other ecosystem services [40]. The high-quality scores in Segment 9 indicate the potential for riparian recovery, where natural vegetation is still dominant.

A previous study by Wijana et al. [41] conducted water quality monitoring across the Ayung River. This study indicate that the middle section of the river (8°34'56.13"S, 115°13'26.02"E), which is located near Segments 9 and 10, has recorded a good water quality status. This pattern is simmiliar to the historical Water Quality Index (WQI) trends reported by Arivany et al. [42], whichappear to match the spatial patterns recorded in our RSQI score. Other sampling station from previous study in Segment 9 recorded good water quality (WQI score of 48.78), which aligns with the high RSQI score and dense vegetation cover identified in our spatial analysis. However, historical records for the sampling station in Segment 5 showed poor water quality (WQI score of 54.51), and very poor water quality at the Padang Galak estuary (WQI score of 75.06). These areas are densely populated and have already been converted into built-up areas. Such land conversions reduce the natural filtering capacity of riparian vegetation, possibly allowing surface runoff to flow more directly into the river channel.

Although this study did not conduct primary hydrochemical sampling to directly prove this filtering capacity, our spatial RSQI findings correlated well with those historical water quality trends. This correlation indicates that good riparian conditions with dense vegetation cover are associated with ecosystem stability by securing habitat corridors and sustaining ecological integrity [43]. The sharp contrast between the RSQI values of the healthy and degraded areas shows that the RSQI has good sensitivity for assessing riparian conditions in accordance with actual field conditions.

Forest cover in riparian zones strongly affectsthe RSQI. Forest areas serve as a reference standard for the highest ecological function [44]. It is related to forested vegetation that provides a vertical canopy structure, increases vegetation cover, and serves as an effective buffer ecosystem [45], as represented by the conditions mapped in Segment 9. In contrast, built-up areas and infrastructure expansion along riverbanks, as in Segments 1 and 5, drastically reduce the function of these buffer ecosystems. Land cover shift to built-up areas reducewater infiltration and retention capacity, increasing surface runoff volume and velocity [46]. These compositions, reduce stability, and degrade ecosystem health [47].

The structure and distribution of vegetation in riparian zones are strongly influenced by the morphology of the river [48]. River morphology factors, such as bank elevation, soil moisture gradient, and flooding frequency, influence plant zonation. Along the Ayung River corridor, the more stable terrace zones are dominated by woody species. However, areas near channels that are often inundated are generally dominated by hydrophilic plants [49]. Morphological conditions and vegetation cover significantly influence the sediment transport dynamics. Riparian vegetation roots actively prevent slope erosion, whereas tree trunks and canopies slow flow velocity, retain, and deposit sediment before it enters the river [48]. Forest vegetation plays a crucial role in filtering fine sediments that cause turbidity and prevent river channel siltation [50]. The vegetation structure of riparian zones plays a crucial role in maintaining biodiversity and aquatic habitats. Riparian forests can serve as habitats or stopover corridors for terrestrial invertebrates. The shade of the forest canopy also influences microclimate conditions and helps maintain water temperature stability, which affects dissolved oxygen levels, a critical factor for the survival of fish and aquatic organisms [51]. In addition, trees in riparian areas provide large woody debris that serves as shelter for aquatic animals while also supplying organic matter in the form of leaf litter, which is important in food webs [52].

One of the main limitations of this study was that the water quality buffering capacity was derived from a theoretical model based on RSQI land cover metrics. No empirical hydrochemical sampling was conducted to test for actual water quality variations across the delineated segments. The 8m spatial resolution of DEMNAS limits this topography-based delineation in narrow river systems, which would require high-resolution data, such as LiDAR or UAV imagery, for accurate application. Future research should combine RSQI spatial assessments with ground-truth water quality monitoring. Conducting an empirical inventory of Ayung River riparian vegetation can be an important step toward further riparian studies. These findings have further implications for managing tropical rivers across Southeast Asia and other tropical regions, particularly those characterized by steep V-shaped morphologies and intense monsoonal rainfall. In these vulnerable catchments, urban expansion combined with generalized fixed-width buffers accelerates environmental degradation and exacerbates flood risk [53]. The Upland Terrace method offers a highly transferable and practical model that can be generalized to other rapidly urbanizing tropical regions worldwide. Beyond ecological protection, accurate riparian delineation brings an opportunity to achieve urban green space goals. Under Indonesia's Spatial Planning Law, which mandates 30% urban green space, riparian zones are vital assets. Previous research by Wirayuda et al. [54] shows that riparian areas form a substantial portion of Denpasar's green spaces. Preserving the integrity of riparian zones through accurate delineation methods such as the Upland Terrace approach is an ecological need and a critical strategy for sustainable urban development.

Policy Implication and Recommendations

The determination of river boundaries in Indonesia is regulated by the Minister of Public Works and Public Housing (PUPR) Regulation Number 28/PRT/M/2015 [55] has been evaluated by [56]. This regulation uses a fixed-width approach to delineate river boundaries, setting standard riparian widths based on administrative zoning, river depth, and location, such as 10m, 15m, or 30m in urban areas, and 50m or 100m outside urban areas [57]. While designed to facilitate administrative control and disaster mitigation (e.g., flood management), this one-size-fits-all policy fails to accommodate local ecological conditions [58]. These standardized regulations do not address important aspects of river geomorphology, such as slope gradients and upland terraces [24,25,27,28]. This rigidity leads to inconsistent protection, especially in V-shaped river morphologies or steep cliffs, as seen in several segments of the Ayung River [18].

The fixed-width buffer approach inevitably leads to delineation bias by generalizing riparian areas, even when these zones do not function ecologically as riparian corridors. The shift to a morphological approach, such as the Upland Terrace method, is essential because it considers actual geomorphological features, effectively excluding areas that do not affect the river conditions. Therefore, river management must shift from a fixed-width approach to a geomorphologically based framework to ensure the protection of river ecosystems. The implementation of this transition may cause significant institutional challenges. Sufficient governance capacity is required to map and monitor riparian boundaries in dynamic topography. Applying morphological analysis at a regional scale requires high-resolution spatial data, such as LiDAR or UAV photogrammetry [44], which incurs substantial financial costs, or even land ownership conflicts [57]. Expanding riparian boundaries inevitably causes the mandated no-build zone to overlap with legally owned private properties and existing infrastructure [58]. Field observations in degraded areas (e.g., Segment 1) confirmed this, showing severe violations of current river boundary regulations and the construction of physical structures in the riparian zone.

A previous study by Rohmah and Basyaiban [59] has similar findings, which several commercial accommodations, such as hotels and villas along the Ayung River, systematically violate established river boundary frameworks. In tourism hotspots, such as the Ayung River, expanding the riparian zone would intersect with the operations of tourism accommodations that hold prior legal permits and could trigger severe social conflicts among the government, landowners, and local communities who depend economically on the riparian corridor [58]. Considering these substantial challenges, governance interventions must be adapted. A phased approach is the most realistic and equitable strategy [57]. Regulations and sterilizing riparian zones cannot be achieved through blind enforcement. Mitigation can be adapted to the specific RSQI conditions of each river segment. In pristine areas that maintain excellent ecological integrity, such as Segment 9 right bank (Upland terrace RSQI score 94.41), the government must enforce strict spatial and legal protection. formally designating these high-quality segments as Urban Green Spaces is essential for sustainably maintaining ecosystem services. Conversely, in heavily degraded and densely built-up segments, such as Segment 1 (RSQI 59.77 on Upland Terrace) and Segment 5 right bank (fixed-width score = 50.09), a restoration process is needed, especially for buildings that have been found to violate current land-use regulations. In areas where structural restoration is not needed, spatial mitigation and adaptation strategies should be prioritized. This includes integrating bioengineering infrastructure, implementing strict wastewater management, and actively involving local communities in the governance of riparian areas.

Conclusions

This study found that the RSQI score downstream of the Ayung River showed localized degradation in areas subjected to heavy land conversion (Segments 1 and 5), while upstream areas (Segment 9) retained pristine conditions. Methodologically, ecological assessment outcomes are heavily dependent on the delineation method used. The fixed-width buffer generalized the riparian zone and underestimated its quality, whereas the Upland Terrace method proved more ecologically representative for steep, V-shaped tropical rivers and performed similarly to the slope-based method. Consequently, policymakers may shift from current fixed-width regulations to a geomorphological approach. Implementation of these ecology-based boundaries into the Regional Spatial Plan can prevent further land conversion and guide targeted restoration efforts. Future research should use higher-resolution topographic data to achieve more accurate delineation and conduct ground-truthed water quality surveys to validate these findings.

Author Contributions

IKAKW: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **IPGEHP**: Writing - Review & Editing, Sampling; **MDP**: Writing - Review & Editing, Sampling; **MS**: Writing - Review & Editing.

AI Writing Statement

During the writing process, the authors used Gemini and Grammarly to check the grammar and improve the readability of the sentences. After using these services, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Conflicts of Interest

There are no conflicts to declare.

Acknowledgments

The author gratefully acknowledges the support of various parties who contributed to the completion of this research. Special appreciation is extended to the anonymous reviewers, whose constructive comments and insightful suggestions greatly improved the quality and clarity of this manuscript.

References

1. Latuconsina, H. *Ekologi Perairan Tropis: Prinsip Dasar Pengelolaan Sumber Daya Hayati Perairan*; UGM Press: Yogyakarta, Indonesia, 2019; ISBN 978-602-386-296-2.
2. Rusnák, M.; Goga, T.; Michaleje, L.; Šulc Michalková, M.; Máčka, Z.; Bertalan, L.; Kidová, A. Remote Sensing of Riparian Ecosystems. *Remote Sens.* **2022**, *14*, 2645, doi:10.3390/rs14112645.
3. Salo, J.A.; Theobald, D.M. A Multi-Scale, Hierarchical Model to Map Riparian Zones. *River Res. Appl.* **2016**, *32*, 1709–1720, doi:10.1002/rra.3019.
4. Pramadaningtyas, P.S.; Chandrasari, N.; Izdihar, R.S.; Iqbal, W.M.; Cahyaningsih, A.P.; Setyawan, A.D. Analysis of Riparian Vegetation in the Siwaluh River, Karanganyar District, Central Java, Indonesia. *International Journal of Bonorowo Wetlands* **2023**, *13*, 45–56, doi:10.13057/bonorowo/w130201.
5. Priosejati, A.N.; Jauhari, A.; Kissinger. Komposisi dan Struktur Vegetasi Hutan Riparian Sempadan Sungai Kiram Kabupaten Banjar. *Jurnal Sylva Scienteae* **2023**, *6*, 1–11, doi:10.20527/jss.v6i1.8192.
6. Ainy, N.S.; Wardhana, W.; Nisyawati, N. Struktur Vegetasi Riparian Sungai Pesanggrahan Kelurahan Lebak Bulus Jakarta Selatan. *Bioma* **2018**, *14*, 60–69, doi:10.21009/Bioma14(2).2.
7. Arif, M.; Zhang, S.; Jie, Z.; Charles, W.; Mzondi, P.S.; Li, C. Evaluating the Effects of Pressure Indicators on Riparian Zone Health Conditions in the Three Gorges Dam Reservoir, China. *Forests* **2020**, *11*, 214, doi:10.3390/f11020214.
8. Siahaan, R.; Ai, N.S.; Rengkung, F.R.D. Peranan Vegetasi Riparian dalam Mencegah Erosi Tebing Suangi Ranoyapo Bagian Hulu, Kabupaten Minahasa Selatan, Provinsi Sulawesi Utara. *Jurnal Lentera: Penelitian dan Pengabdian Masyarakat* **2020**, *1*, 10–12, doi:10.57207/sqtcbq12.
9. Hu, S.; Yue, H.; Zhou, Z. Preferences for Urban Stream Landscapes: Opportunities to Promote Unmanaged Riparian Vegetation. *Urban For. Urban Green.* **2019**, *38*, 114–123, doi:10.1016/j.ufug.2018.12.001.
10. Saha, D.; Das, D.; Dasgupta, R.; Patel, P.P. Application of Ecological and Aesthetic Parameters for Riparian Quality Assessment of a Small Tropical River in Eastern India. *Ecol. Indic.* **2020**, *117*, 106627, doi:10.1016/j.ecolind.2020.106627.
11. Rivas-Fandiño, P.; Acuña-Alonso, C.; Novo, A.; Pacheco, F.A.L.; Álvarez, X. Assessment of High Spatial Resolution Satellite Imagery for Monitoring Riparian Vegetation: Riverine Management in the Smallholding. *Environ. Monit. Assess.* **2023**, *195*, 81, doi:10.1007/s10661-022-10667-8.
12. Tomsett, C.; Leyland, J. Remote Sensing of River Corridors: A Review of Current Trends and Future Directions. *River Res. Appl.* **2019**, *35*, 779–803, doi:10.1002/rra.3479.
13. Huylenbroeck, L.; Laslier, M.; Dufour, S.; Georges, B.; Lejeune, P.; Michez, A. Using Remote Sensing to Characterize Riparian Vegetation: A Review of Available Tools and Perspectives for Managers. *J. Environ. Manag.* **2020**, *267*, 110652, doi:10.1016/j.jenvman.2020.110652.
14. Cole, L.J.; Stockan, J.; Helliwell, R. Managing Riparian Buffer Strips to Optimise Ecosystem Services: A Review. *Agric. Ecosyst. Environ.* **2020**, *296*, 106891, doi:10.1016/j.agee.2020.106891.
15. Lind, L.; Hasselquist, E.M.; Laudon, H. Towards Ecologically Functional Riparian Zones: A Meta-Analysis to Develop Guidelines for Protecting Ecosystem Functions and Biodiversity in Agricultural Landscapes. *J. Environ. Manag.* **2019**, *249*, 109391, doi:10.1016/j.jenvman.2019.109391.
16. Sharma, S.; Agrawal, M.; Roy, A. Riparian Ecotones: An Important Derivative for Managing River Pollution. In *Water Pollution and Management Practices*; Singh, A.; Agrawal, M.; Agrawal, S.B., Eds.; Springer: Singapore, 2021; pp. 201–220, doi:10.1007/978-981-15-8358-2_9.

17. Salo, J.A.; Theobald, D.M.; Brown, T.C. Evaluation of Methods for Delineating Riparian Zones in a Semi-Arid Montane Watershed. *J. Am. Water Resour. Assoc.* **2016**, *52*, 632–647, doi:10.1111/1752-1688.12414.
18. Eryani, I.G.A.P.; Nurhamidah, N. Sedimentation Management Strategy in River Estuary for Control the Water Damage in Downstream of Ayung River. *Int. J. Adv. Sci. Eng. Inf. Technol.* **2020**, *10*, 743–748, doi:10.18517/ijaseit.10.2.10832.
19. Dharmayasa, I.G.N.P.; Surakit, K.; Jindal, R.; Thongdara, R. Investigation on Impact of Changes in Land Cover Patterns on Surface Runoff in Ayung Watershed, Bali, Indonesia Using Geographic Information System. *Environ. Nat. Resour. J.* **2022**, *20*, 168–178, doi:10.32526/ennrj/20/202100161.
20. Eryani, I.G.A.P.; Jayantari, M.W. Water Conservation Model in Ayung River Estuary Based on Ecotourism. *J. Phys. Conf. Ser.* **2019**, *1402*, 033021, doi:10.1088/1742-6596/1402/3/033021.
21. Praganingrum, T.I.; Wangsa, A.A.R.R.; Graha, I.M.S.; Pradnyadari, N.L.M.A.M. Identifikasi Pola Pemanfaatan Lahan Tepian Sungai Ayung, Bali. *Pranatacara Bhumandala: Jurnal Riset Planologi* **2023**, *4*, 153–164, doi:10.32795/pranatacara_bhumandala.v4i2.4815.
22. Badan Pusat Statistik Provinsi Bali. Population Projection of Bali Province 2023–2025. Available online: https://bali.bps.go.id/id/statistics-table/2/NDE0IzI=/proyeksi-penduduk-provinsi-bali-menurut-kabupaten-kota-dan-jenis-kelamin.html (accessed on 17 May 2025).
23. Majumdar, A.; Avishek, K. Riparian Zone Assessment and Management: An Integrated Review Using Geospatial Technology. *Water Air Soil Pollut.* **2023**, *234*, 319, doi:10.1007/s11270-023-06329-1.
24. Dodds, W.K.; Barmuta, L.A.; Bernal, S.; Corman, J.; Harms, T.K.; Johnson, S.L.; Li, L.; Fernandes Cunha, D.G.; Olden, J.D.; Riis, T.; et al. Defining Stream Riparian Zones across Multidimensional Environmental Gradients. *J. Environ. Qual.* **2025**, *54*, 1674–1697, doi:10.1002/jeq2.70080.
25. Verry, E.S.; Dolloff, C.A.; Manning, M.E. Riparian Ecotone: A Functional Definition and Delineation for Resource Assessment. *Water Air Soil Pollut. Focus* **2004**, *4*, 67–94, doi:10.1023/B:WAFO.0000012825.77300.08.
26. Meehan, M.A.; O'Brien, P.L. Using the Rosgen Stream Classification System to Aid in Riparian Complex Ecological Site Descriptions Development. *Rangel. Ecol. Manag.* **2019**, *72*, 729–735, doi:10.1016/j.rama.2019.05.001.
27. Flores-Díaz, A.C.; Guevara Hernández, R.; Mendoza, M.E.; Langrave, R.; Quevedo, A.; Maass, M. Hierarchical Procedure for Creating Local Typologies for Riparian Zone Research and Management Based on Biophysical Features. *Phys. Geogr.* **2018**, *39*, 118–139, doi:10.1080/02723646.2017.1387427.
28. Kasprak, A.; Hough-Snee, N.; Beechie, T.; Bouwes, N.; Brierley, G.; Camp, R.; Fryirs, K.; Imaki, H.; Jensen, M.; O'Brien, G.; et al. The Blurred Line between Form and Process: A Comparison of Stream Channel Classification Frameworks. *PLoS ONE* **2016**, *11*, e0150293, doi:10.1371/journal.pone.0150293.
29. De Sosa, L.L.; Glanville, H.; Marshall, M.; Abood, S.; Williams, A.P.; Jones, D. Delineating and Mapping Riparian Areas for Ecosystem Service Assessment. *Ecohydrology* **2018**, *11*, e1928, doi:10.1002/eco.1928.
30. Irene, S.; Persadanta, P.; Adrian, W. Airport Plan Topographic Examination: Accuracy Analysis by DEMNAS and ASTER GDEM Method in Terrestrial Surveys. *Journal of Airport Engineering Technology (JAET)* **2023**, *4*, 12–21, doi:10.52989/jaet.v4i1.116.
31. Susetyo, D.B.; Lumban-Gaol, Y.A.; Sofian, I. Prototype of National Digital Elevation Model in Indonesia. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2018**, *XLII-4*, 609–613, doi:10.5194/isprs-archives-XLII-4-609-2018.
32. Petikas, I.; Keramaris, E.; Kanakoudis, V. A Novel Method for the Automatic Extraction of Quality Non-Planar River Cross-Sections from Digital Elevation Models. *Water* **2020**, *12*, 3553, doi:10.3390/w12123553.
33. Peterjohn, W.T.; Correll, D.L. Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest. *Ecology* **1984**, *65*, 1466–1475, doi:10.2307/1939127.
34. Eishoeei, E.; Miryaghoubzadeh, M.; Shahedi, K. A Novel Knowledge Base Method in Riparian Buffer Zone (RBZ) Delineation with Remote Sensing Imagery. *Ecol. Eng.* **2022**, *184*, 106756, doi:10.1016/j.ecoleng.2022.106756.

35. Gyimah, R.A.A.; Karikari, A.Y.; Gyamfi, C.; Asantewaa-Tannor, P.; Anornu, G.K. Spatial Evaluation of Land Use Variability on Water Quality of the Densu Basin, Ghana. *Water Supply* **2020**, *20*, 3000–3013, doi:10.2166/ws.2020.187.

36. Islami, F.A.; Tarigan, S.D.; Wahjunie, E.D.; Dasanto, B.D. Accuracy Assessment of Land Use Change Analysis Using Google Earth in Sadar Watershed Mojokerto Regency. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *950*, 012091, doi:10.1088/1755-1315/950/1/012091.

37. Machado, J.T.; Kim, G. Ecological Landscape Assessment of Restored Urban Stream to Guide Adaptive Management. *Heliyon* **2024**, *10*, e33880, doi:10.1016/j.heliyon.2024.e33880.

38. Cunha, D.G.F.; Saltarelli, W.A.; Bega, J.M.M.; Finkler, N.R.; de Souza Ferreira, M.; Furley, T.H.; von Schiller, D.; Dodds, W.K. Assessing Restoration of Ecosystem Functioning in Brazilian Subtropical and Tropical Streams. *Limnol. Oceanogr. Bull.* **2022**, *31*, 6–11, doi:10.1002/lob.10480.

39. Hasbi, M.; Mardianto; Astuti, P. Kajian Penggunaan Lahan Sempadan Sungai Lunto di Kawasan Pusat Kota Sawahlunto. In Proceedings of the *Seminar Nasional Mitigasi dan Strategi Adaptasi Dampak Perubahan Iklim di Indonesia*, 2017; pp. 139–147; ISBN 978-979-3793-70-2.

40. Dala-Corte, R.B.; Melo, A.S.; Siqueira, T.; Bini, L.M.; Martins, R.T.; Cunico, A.M.; Pes, A.M.; Magalhães, A.L.B.; Godoy, B.S.; Leal, C.G.; et al. Thresholds of Freshwater Biodiversity in Response to Riparian Vegetation Loss in the Neotropical Region. *J. Appl. Ecol.* **2020**, *57*, 1391–1402, doi:10.1111/1365-2664.13657.

41. Wijana, I.M.S.; Ernawati, N.M.; As-syakur, A.R. Status Mutu Air Sungai Ayung Berdasarkan Data Pemantauan Kualitas Air Tahun 2014–2018. *Ecotrophic* **2020**, *14*, 143–153, doi:10.24843/EJES.2020.v14.i02.p05.

42. Arivany, C.; Putri, P.I.D.; Wiraatmaja, I.P.P.; Nuraga, I.K. Evaluasi Kualitas Air Sungai Ayung Metode WQI (Water Quality Index) sebagai Dasar Penanganan Pencemaran dan Rekomendasi Pengelolaan Sungai. *Journal of Innovative and Creativity* **2025**, *5*, 36518–36532, doi:10.31004/joecy.v5i3.6027.

43. Ramos, L.; Negreiros, D.; Ferreira, B.S.S.; Figueiredo, J.C.G.; Paiva, D.C.; Oki, Y.; Justino, W.D.S.; Santos, R.M.D.; Aguilar, R.; Nunes, Y.R.F.; et al. Strong Relationships between Soil and Vegetation in Reference Ecosystems of a Riparian Atlantic Rainforest in the Upper Doce River Watershed, Southeastern Brazil. *iForest—Biogeosci. For.* **2023**, *16*, 226–233, doi:10.3832/ifor4313-016.

44. Novoa, J.; Chokmani, K.; Lhissou, R. A Novel Index for Assessment of Riparian Strip Efficiency in Agricultural Landscapes Using High Spatial Resolution Satellite Imagery. *Sci. Total Environ.* **2018**, *644*, 1439–1451, doi:10.1016/j.scitotenv.2018.07.069.

45. Burdon, F.J.; Ramberg, E.; Sargac, J.; Forio, M.A.E.; de Saeyer, N.; Mutinova, P.T.; Moe, T.F.; Pavelescu, M.O.; Dinu, V.; Cazacu, C.; et al. Assessing the Benefits of Forested Riparian Zones: A Qualitative Index of Riparian Integrity Is Positively Associated with Ecological Status in European Streams. *Water* **2020**, *12*, 1178, doi:10.3390/w12041178.

46. Pal, S.; Sarda, R. Modelling Water Richness in Riparian Flood Plain Wetland Using Bivariate Statistics and Machine Learning Algorithms and Figuring out the Role of Damming. *Geocarto Int.* **2022**, *37*, 5585–5608, doi:10.1080/10106049.2021.1920637.

47. Segura-Méndez, F.J.; Pérez-Sánchez, J.; Senent-Aparicio, J. Evaluating the Riparian Forest Quality Index (QBR) in the Luchena River by Integrating Remote Sensing, Machine Learning and GIS Techniques. *Ecohydrol. Hydrobiol.* **2023**, *23*, 469–483, doi:10.1016/j.ecohyd.2023.04.002.

48. Gutiérrez, R.; Mendoza, A.; Berezowsky, M. Influence of Riparian Vegetation on River Morphodynamics: A Numerical Modeling Framework. *Water* **2026**, *18*, 883, doi:10.3390/w18070883.

49. Keeton, W.S.; Copeland, E.M.; Sullivan, S.M.P.; Watzin, M.C. Riparian Forest Structure and Stream Geomorphic Condition: Implications for Flood Resilience. *Can. J. For. Res.* **2017**, *47*, 476–487, doi:10.1139/cjfr-2016-0327.

50. Hatten, J.A.; Segura, C.; Bladon, K.D.; Hale, V.C.; Ice, G.G.; Stednick, J.D. Effects of Contemporary Forest Harvesting on Suspended Sediment in the Oregon Coast Range: Alsea Watershed Study Revisited. *For. Ecol. Manag.* **2018**, *408*, 238–248, doi:10.1016/j.foreco.2017.10.049.

51. Warren, D.R.; Keeton, W.S.; Kiffney, P.M.; Kaylor, M.J.; Bechtold, H.A.; Magee, J. Changing Forests—Changing Streams: Riparian Forest Stand Development and Ecosystem Function in Temperate Headwaters. *Ecosphere* **2016**, *7*, e01435, doi:10.1002/ecs2.1435.
52. Entrekin, S.A.; Rosi, E.J.; Tank, J.L.; Hoellein, T.J.; Lamberti, G.A. Quantitative Food Webs Indicate Modest Increases in the Transfer of Allochthonous and Autochthonous C to Macroinvertebrates Following a Large Wood Addition to a Temperate Headwater Stream. *Front. Ecol. Evol.* **2020**, *8*, 114, doi:10.3389/fevo.2020.00114.
53. Eryani, I.G.A.P.; Jayantari, M.W. Mitigation Strategy for the Impact of Changes in Land Use in the Badung Watershed Based on GIS. *International Journal of Multidisciplinary and Current Educational Research* **2023**, *5*, 96–104.
54. Wirayuda, I.K.A.K.; Widayani, P.; Sekaranom, A.B. Urban Green Space Analysis and Its Effect on the Surface Urban Heat Island Phenomenon in Denpasar City, Bali. *Forest and Society* **2023**, *7*, 150–168, doi:10.24259/fs.v7i1.24526.
55. Kementerian Pekerjaan Umum dan Perumahan Rakyat Republik Indonesia. *Peraturan Menteri Pekerjaan Umum dan Perumahan Rakyat Republik Indonesia Nomor 28/PRT/M/2015 tentang Penetapan Garis Sempadan Sungai dan Garis Sempadan Danau*; Jakarta, Indonesia, 2015.
56. Alwajdi, M.F.; Spaltani, B.G. Quo Vadis Pengaturan Garis Sempadan Sungai di Indonesia. *Jurnal Legislasi Indonesia* **2023**, *20*, 52–64, doi:10.54629/jli.v20i3.1020.
57. Maryono, A. *Pengelolaan Kawasan Sempadan Sungai*; UGM Press: Yogyakarta, Indonesia, 2020; ISBN 978-979-420-874-8.
58. Hadinata, I.Y.; Muchamad, B.N. Studi Penyusunan dan Penentuan Sempadan Sungai di Kota Banjarmasin. *Jurnal Kebijakan Pembangunan* **2018**, *13*, 1–7.
59. Rohmah, U.B.Y.; Basyaiban, M.K. Pencemaran Tukad Ayung: Dampak dan Upaya Penanganannya di Bali, 2010–2021. *Environmental Pollution Journal* **2022**, *2*, 538–552, doi:10.58954/epj.v3i3.88.