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RESEARCH ARTICLE

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Determining the Suitable Location of Constructed Wetland for the Polluted River Water Treatment Based on Analytical Hierarchy Process and Geographic Information System Analysis

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ABSTRACT

The Tukad Badung River is a vital raw water source in Denpasar City and Badung Regency. Concerning the water pollution of the river, water treatment is necessary to manage the water quality. Constructed wetlands are a water treatment technology used for water purification. In this regard, information is essential regarding the appropriate location for the placement of the constructed wetland based on criteria related to the water treatment plant. The research was conducted to determine the suitability level of water treatment locations in the watershed using the Analytic Hierarchy Process method in integration with a Geographic Information System. The Geographic Information System analysis included overlaying steps of the processed and classified data from each criterion: land use, slope, and water pollution index. The Analytic Hierarchy Process method was carried out to obtain the weight of each criterion down to the sub-criteria, which were compiled through interviews with three informants from academic, government, and community representatives. Weight calculations were performed using Expert Choice 11 software to obtain weight values with a consistency ratio of < 0.1. Geographic Information System analysis using the Analytic Hierarchy Process method produces three suitable land types according to the level of suitability for water treatment locations, with constructed wetlands located in the upstream, middle, and downstream parts of the river. Information regarding suitable land is useful for planning the technical design of water treatment plants with constructed wetlands.

Introduction

Tukad Badung is one of the rivers that flows and enters Denpasar City after it flows from the Badung Regency area [1], with headwaters located 12 km north of Denpasar City, emptying into Benoa Bay. With a watershed area of 37.7 km^2 and a channel length of 25.17 km, Tukad Badung is a vital water source for Denpasar City and the southern part of Badung Regency, namely as a source of irrigation water and drainage for Denpasar City and southern parts of Badung Regency. waste from industry, markets and domestic pollutes Tukad Badung River [2]. In addition, in the downstream area water was collected and used as a raw source for drinking water after processing at the Tirta Mangutama water treatment plant (WTP) [3]. Nevertheless, according to the pollution index classification, the Tukad Badung River is slightly polluted [4-5]. Therefore, water quality management is crucial. Constructed wetlands (CW) are natural wetland ecosystems modified by adaptive aquatic vegetation [6]. CW have been used to treat various types of liquid waste, including domestic, agricultural, industrial, polluted river water, and urban runoff [7-9]. CW are complex water treatment systems that integrate water, plants, animals, microorganisms, and the environment [10].

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Wetlands have several functions such as water purification [11]. For water purification, artificial wetlands use physical, chemical, and biological methods in an ecosystem, utilizing filtration, adsorption, sedimentation, ion exchange, and microbial decomposition [12]. According to Rachmawardani [13], using a constructed wetland is an appropriate system for the Tukad Badung River to address water pollution problems. To manage the water quality, it is necessary to develop water treatments before downstream utilization as a raw drinking water source [3]. Nevertheless, there is yet to be a study on a suitable location for a water treatment plant or structure along the Tukad Badung River. According to Government Regulation Number 38 of 2011 concerning rivers, rivers with a watershed area of less than 500 square kilometers, as a rule, have a minimum border distance of 50 m from the left and right banks along the river in the riparian zone. In this case, the riparian zone is a potential site for water treatment plants, and the riparian zone is a link between rivers and land ecosystems that accommodates the exchange of energy, inorganic and organic materials, and biota [14–16]. Several criteria are required to determine the location of the Tukad Badung River for water treatment. Therefore, a multicriteria analysis is necessary. One such method is the Analytic Hierarchy Process (AHP).

AHP is a decision-making method that involves many criteria, and can help determine the importance level of each criterion based on expert judgment [17]. In addition, it is possible to integrate AHP analysis with geographic information system (GIS) analysis concerning the correlation of location suitability decisions with geospatial information [18]. Several studies related to land suitability analysis have been conducted using GIS analysis of the AHP Method to determine the weight value of each parameter involving expert opinions [19–21]. These factors can be considered by examining the availability of existing data to determine the locations of water treatment plants in the Tukad Badung. Technological aspects are related to water quality, as indicated by the pollution index. In this regard, the technology used must meet the pollutant removal requirements. Socioeconomic factors are correlated with land use type [22]. Undeveloped land undoubtedly has a negligible impact compared with built or cultivated land. Furthermore, ecological factors must consider land conditions. In this case, the slope of the land becomes very important because the process must apply a gravity system. This study aimed to determine the suitability of water treatment plant sites using constructed wetlands in the Tukad Badung watershed by considering three water treatment criteria based on AHP and GIS analysis: land use, pollution index, and land slope.

Materials and Methods

Study Area

This study was conducted in the Tukad Badung Watershed, Denpasar City, Bali Province. Geographically, the research location is located at 115°10’23” to 115°16’27” East Longitude (E) and 08° 35’31” to 08°44’49” South Latitude (S). The research was conducted in this area because it is densely populated and located in the administrative area of Denpasar city. The dealination area of the Tukad Badung Watershed is shown in Figure 1.

Data Analysis Method

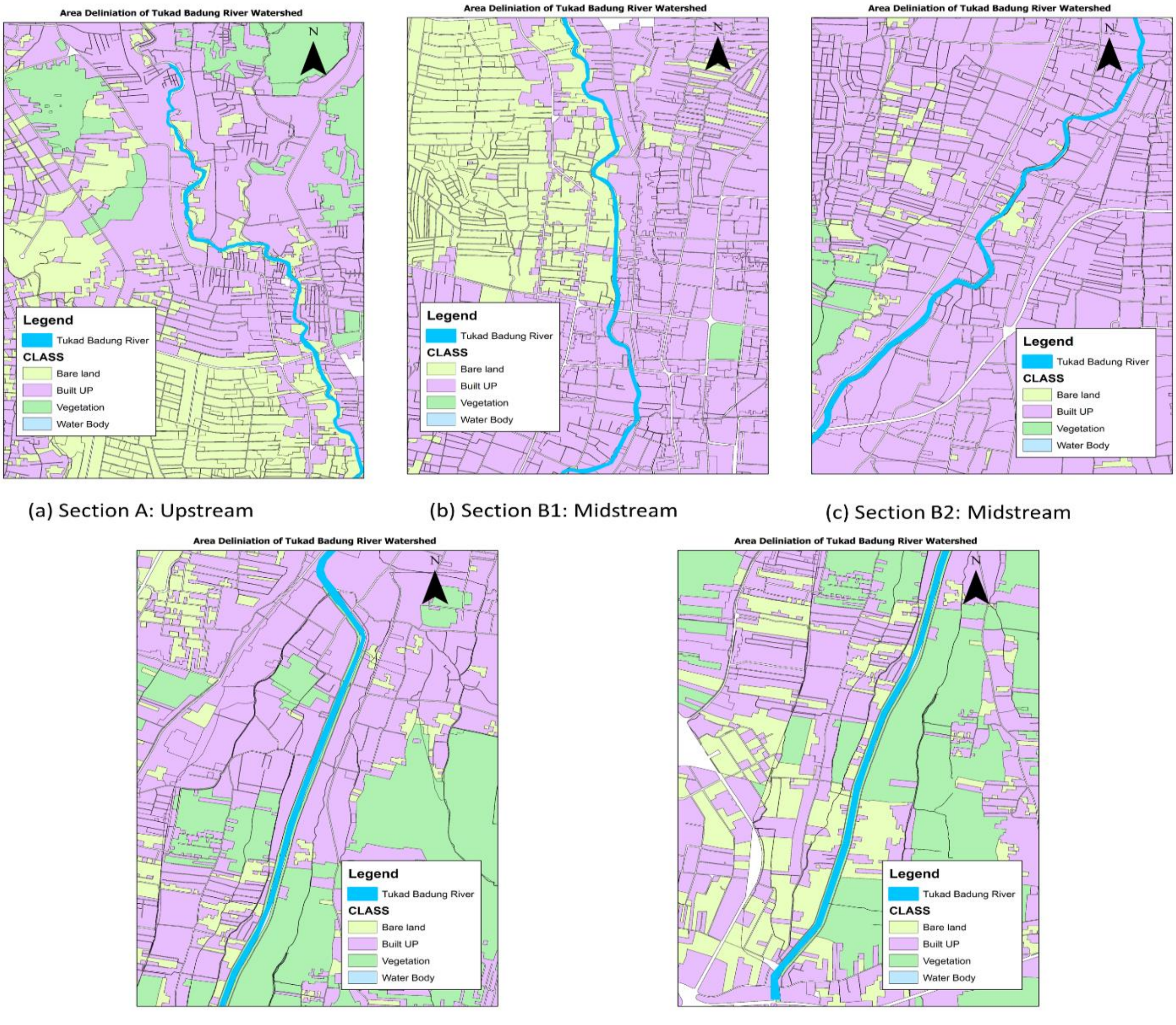
The research steps included data collection, processing, and classification, weighting data, overlaying between data, and presenting land suitability maps for water treatment sites with constructed wetlands. In the processing, classification and overlay stages, the QGIS application is used. In the data weighting stage, the Expert Choice 11 software application is used. The implementation stages are shown in the flowchart in Figure 2.

Data Collection

The data used in this research are the Denpasar City Spatial Plan Map for 2011–2031 and Badung Regency Spatial Plan Map for 2013–2033, Digital Elevation Model *Nasional* (DEMNAS) imagery data with 8.1 meters spatial resolution downloaded from http://tides.big.go.id/DEMNAS/ (accessed on 8 January 2023), Tukad Badung River water pollution index data at three points that located at upstream, middle, and downstream parts of the river that was studied in 2022 by Harmayani et al. [3], and criteria weighting questionnaire data from interviews with three experts, i.e., representatives from educational institutions, government agencies, and community group leaders.

Data Processing and Classification

This step was performed to prepare data for overlay purposes. At this stage, there were three main activities. The primary activities include processing and classification, data weighting, and vector data conversion to a raster. Digitization and classification were conducted for each data input during the overlay process. The collected data were then processed and classified into several classes. Land use data and DEM in vector data were processed using QGIS software to produce raster data. Water pollution index data from secondary data were interpolated using the Inverse Distance Weight (IDW) method in QGIS to create a distribution of pollution index values throughout the river area. The classification process in a GIS platform using the processed data includes classifying a value and range using reclassification tools, multiple ring buffer tools, and attribute table editing [23].



(a) Section A: Upstream (b) Section B1: Midstream (c) Section B2: Midstream

(d) Section C1: Downstream (e) Section C2: Downstream

Figure 1. Area deliniation of the Tukad Badung River Watershed.

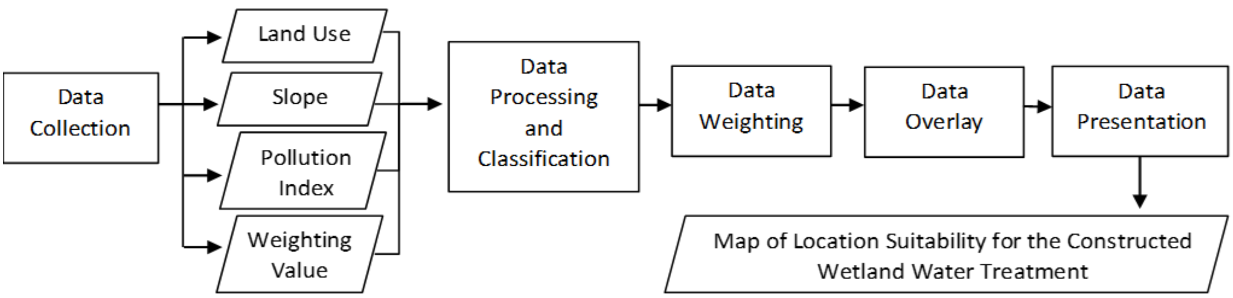


Figure 2. Research steps for determining the suitable location of the Tukad Badung River water treatment using constructed wetland based on AHP and GIS analysis.

Data Weighting

The weight value is used in the processing and data analysis (overlay) stages. There are three main activities for determining the weight value. The main activities involved compiling hierarchies, performing pairwise comparisons, and calculating weight values [24]. The arrangement of hierarchies was constructed to decompose the problem into a hierarchical form from the highest level until it was impossible to describe it. The highest level is the goal, which is a suitable location for constructing a Tukad Badung River water-treatment plant in a constructed wetland. The second level is the criterion for determining appropriate locations for water treatment. The third level is the sub-criteria, which provides a more detailed description of the requirements. The fourth level is the sub-sub-criterion, which provides a more detailed description of the sub-criteria. The last level is an alternative in the form of alternative locations for constructed wetland water treatment. Pairwise comparisons were generated to prioritize comparisons among the criteria, sub-criteria, and sub-sub-criteria, based on a previously arranged hierarchy. First, a pairwise comparison matrix is created using a printed questionnaire. The expert then assigned a priority scale score to the printed [25]. The value of priority scale ranges from one to nine [26] , as described in Table 1 according to Saaty and Vargas [24].

Table 1. Criteria and alternative assessments.

Intensity	Description
1	Both elements are equally important
3	One element is less important than the others
5	One element is more important than the others
7	One element is clearly more absolutely essential than the others
9	One element is more important than the other
2,4,6,8	Values between two adjacent considerations

Source: Saaty and Vargas [24].

After the three experts completed the assignment of priority values, weight values were calculated. This process was performed to obtain the weight values of the criteria, sub-criteria, and sub-sub-criteria. The weight values were calculated using Expert Choice 11 software. As this study involved the opinions of three experts, it was necessary to calculate the average value of the criteria, sub-criteria, and sub-sub-criteria from the assessment of the three experts. The average value was calculated by adding the priority scale values of the three experts and then dividing the sum by three (3). The average value was processed using Expert Choice 11 software to obtain the weight value. This weight value can be used if the Consistency Ratio (CR) is < 0.1. Each classified data point was assigned a respective weight value. Each dataset has a different weight value. Vector data weighting was performed by creating a new column named "weight" in the attribute table for each dataset. The weight column is then filled with the weight value of each class. Raster data weighting was performed using the Reclassify software. The pixel value of each raster class changed according to its weight value. All data were assigned a weight value, and data that were still in the form of vector data were converted to raster data. Conversion was performed using the Polygon-to-Raster conversion tool in QGIS. Each transformation is carried out by maintaining the weight value of each parameter; in other words, the selected value field is the "weight" column. The conversion process results in new raster data with the smallest pixel units containing unique information in the form of a weight value.

Data Overlay

This process was performed to determine a suitable location for the constructed wetlands. This overlay process was conducted using the Raster Calculator in QGIS software. The overlay process was performed between the data at the same hierarchical level. Overlay process was first generated at a hierarchical level, where the raster pixel value was weight to the lowest level. In this study, an overlay was first established at the subcriteria level. This is because the sub-criteria's raster pixel value is the lowest level's weight value, that is, the sub-criteria. The result of the overlay between the sub-criteria is a criterion raster, which must be overlaid with other criterion to produce a Land Suitability Map for constructed wetland. Overlay process is a mathematical process performed on raster data to obtain the total final weight value. The total final weight is the basis for determining the suitability level of a location. According to Pahlavani et al. [27], the formula used for the overlay process is given by Equation 1.

$$f(x) = \sum_{l=1}^{m} V_{li} W_l \quad (1)$$

Description:

m : number of rasters

Vli : location value of i on the raster

Wl : weight value of rater l

The greater the final weight value, the more suitable the land is for the constructed wetland water treatment location, and vice versa. The resulting total weighted final score is divided into three classes: suitable, less suitable, and unsuitable. Classification was performed using the equal interval method in QGIS or the same class interval formula according to Umar et al. [28], as shown in Equation 2.

$$I = \frac{c-b}{k} \quad (2)$$

Description:

I : class interval distance

c : total value of the highest weight

b : total value of the lowest weight

k : the desired number of classes

Data Presentation

The data presentation step included symbolization activities, layout creation, and map printing. The process of symbolizing and creating layouts was produced using the QGIS Software. The process of symbolizing and creating a layout begins with setting the color and symbol of the map, followed by setting the paper size and orientation of the map, entering information on the edges of the map, creating a grid, and adjusting the resolution of the resulting image to 500 dpi.

Results and Discussion

The weight values of the criteria were determined through interviews with the three sources. The resource persons were Lecturers of the Environmental Engineering Study Program, Faculty of Engineering, Udayana University, Staff of Bali-Penida River Basin Agency, Directorate General of Water Resources, Ministry of Public Works, and Dauh Puri Kaja Village Officials. The criterion weight values obtained from the opinions of the three informants had a CR of 0.1% (Table 2). The criteria weighting results indicate that the pollution index had the highest weight value of 0.36. The pollution index criterion was the top priority, because the constructed water treatment plant was expected to reduce pollution optimally at the point with the highest pollution load. The weighting consistency ratio for all criteria was 0.00.

Table 2. Criteria weighting.

Criteria	Land use	Slope	Pollution index	Priority vector
Land Use	1.00	0.88	0.89	0.31
Slope	1.14	1.00	0.89	0.33
Pollution Index	1.13	1.13	1.00	0.36
Total	3.27	3.00	2.78	1.00
Principal Eigen Value (lmax)				3.00
Consistency Index (CI)				0.00
Consistency Index (CR)				0.1%

Pollution index data show the river water quality based on pollutant parameter values describing the potential pollution distribution at a given point or area. The data used refers to the research data of Harmayani et al. [3], which signified the pollution index value of the Tukad Badung River in the previous year, that is, 2022. In this study, the pollution index value at three monitoring points showed a value of 2.41 at point 1, which represents the upstream area, 4.46 at point 2, which is the middle of the river, and 4.27 at point 2 in the area approaching the downstream of the river. For this reason, the pollution index sub-criteria were divided into four classes with the smallest to largest value range of 0.00 to 4.46, as indicated in Table 3. The higher the pollution index value, the more suitable the surrounding area is for water treatment.

The land use criteria were also considered essential, weighing 0.33. Land use criteria are important because they can determine whether land can be used as a water treatment plant. In addition, the slope of the land affected the possibility of implementing a gravity treatment system. Land use can be interpreted as a description of the biophysical cover used by humans; therefore, up-to-date reference data are an important input for producing reliable land-use maps [29]. The land-use data used were in the form of a map that describes the condition of the Earth's surface, which can explain the relationship between nature and society. The land-use criteria were classified into four sub-criteria as described in Table 3: bare land, vegetation, water bodies, and built-up areas. Considering the socioeconomic impact, bare land is a suitable site, areas of vegetation and water bodies are less suitable, and built-up areas are unsuitable for developing wetland water treatment plants.

Table 3. Sub-criteria classification of the criteria.

Criteria	Sub-criteria	Classification	Classification value
Pollution index	0.00–2.41	Very low suitability	0
	2.42–3.09	Low suitability	1
	3.1– 4.27	Moderate suitability	2
	4.28–4.46	High suitability	3
Land use	Built-Up Area	Very low suitability	0
	Water Body	Low suitability	1
	Vegetation	Moderate suitability	2
	Bare Land	High suitability	3
Slope	5% <	Very low suitability	0
	3–5%	Low suitability	1
	2–3%	Moderate suitability	2
	2% >	High suitability	3

Another criterion is the slope of land. Slope data were obtained from a Digital Elevation Model (DEM) of DEMNAS data processing. DEM is a digital representation of the height of the ground surface with respect to any datum reference [30]. These data provide an overview of the slope of the land in the Tukad Badung Watershed, which is the best location from a slope perspective. Under the conditions in the Tukad Badung Watershed area, a suitable location is an area with a slope of > 2% to allow the system to flow by gravity. Land with a slope of 0 to 2% was considered less suitable for unsuitable conditions. The classification of each subcriterion is presented in Table 3. The suitability level indicated values of very low, low, moderate, and high suitability in the range of 0 to 3. The map of each data criteria classification, that is, land use, slope, and pollution index, according to the sub-criteria, is shown in Figure 3.

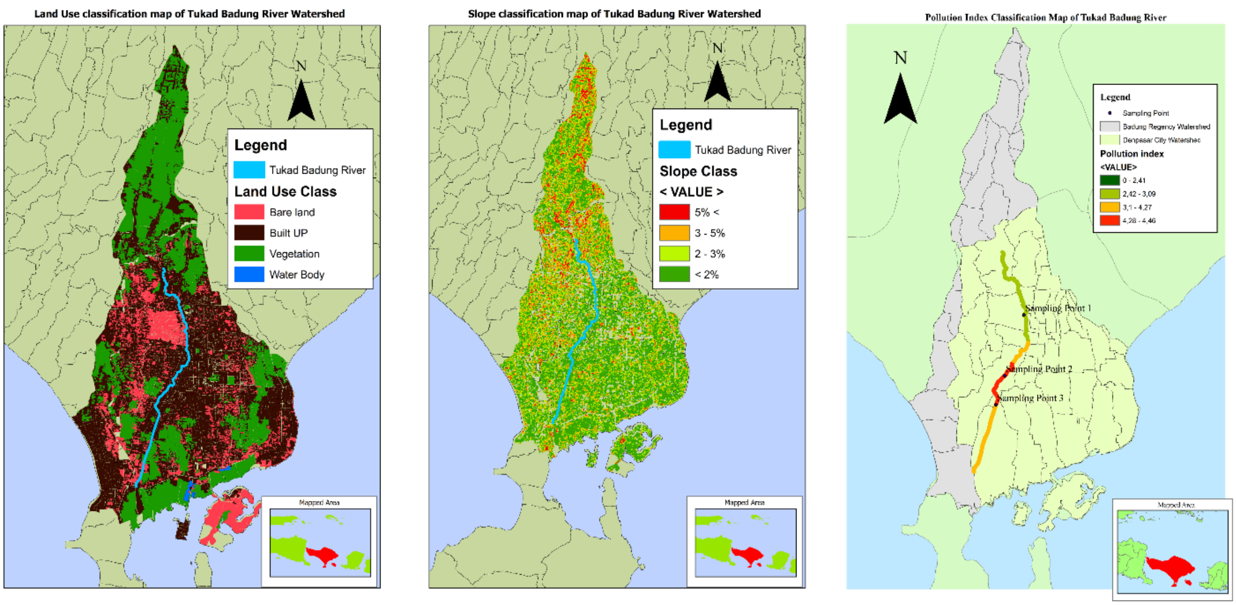
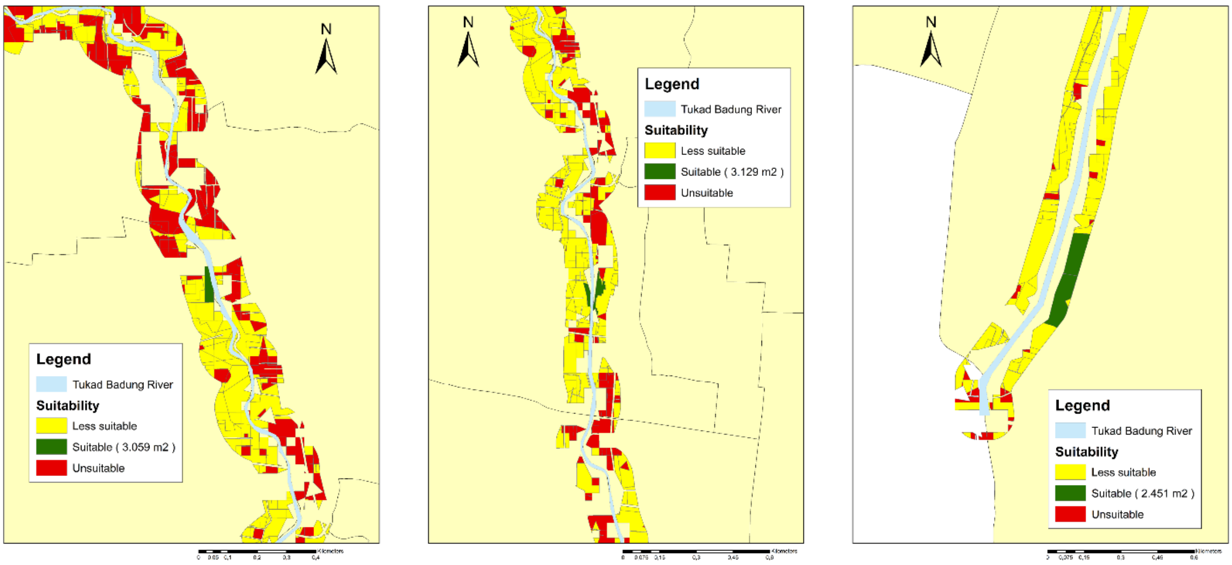


Figure 3. Classification map of land use, slope, and pollution index criteria.

The map of land use, slope, and pollution index criteria indicates the sub-criteria classification of each criterion in the different areas. The land-use criteria with four classifications were bare land (high suitability) in pink, vegetation (moderate suitability) in green, water bodies (low suitability) in blue, and built-up areas (very low suitability) in brown. The slope also has four different classifications: > 5% (very low suitability), 3–5% (low suitability), 2–3% (moderate suitability), and < 2% (high suitability) with red, orange, light green, and dark green, respectively. Moreover, the IDW interpolated water pollution index based on the secondary data in three points presented in four different classifications, i.e, Red color for value of 4.28–4.46 (high suitability), Orange color for value of 3.1–4.27 (moderate suitability), light green color for value of 2.42–3.09 (low suitability), and dark green color for the area with index value of 0.00–2.41 (very low suitability). According to Harmayani et al. [3], the Pollution Index indicates a slightly polluted category at sampling locations. The Pollution Index value increased from Point 1 (upstream) to Point 2 (middle), which showed the highest value among the three pollution points. Pollutant sources were identified based on land use around the sampling points: point 1 (rice fields and settlements), point 2 (settlements, rice fields, and empty land), and point 3 (trade and services, empty land, and settlements). From 2004 to 2014, with indications of wastewater pollution in the Tukad Badung River 2014, the government constructed a centralized Wastewater Treatment Plant (WTP) in Suwung, Denpasar. The wastewater pipe network covers the Dauh Puri Kauh Village area, South Denpasar. WTP was built and maintained around sampling point 2. However, the system does not cover locations before and after the sampling point [3].

The following analysis was performed through a data overlay process using classified land-use, slope, and pollution index data. The data were overlaid, where the values multiplied by the AHP weights were summed, and then these values were classified into three classes: appropriate, somewhat appropriate, and inappropriate. The overlay result map is shown in Figure 4, which indicates that the green, yellow, and red areas are suitable, less suitable, and unsuitable, respectively. The mapping results indicate suitable locations in the upstream, midstream, and downstream areas.

According to the Department of Environment and Science of Queensland [31], the application of wetlands for water treatment is ideally located on low-lying land with low or no agricultural productivity and runoff discharged by the area of agricultural production. Sites that were previously wetlands and had been drained or cleared were also suitable for retaining water and landscape wetlands through advanced hydrological modification. Other artificial depressions, because of their low costs, have the potential to be modified into treatment wetlands.



(a) Section A: Upstream (b) Section B: Midstream (c) Section C: Downstream

Figure 4. Constructed wetland water treatment suitability locations in the Tukad Badung watershed.

Conclusions

The suitability level of the water treatment location in the Tukad Badung watershed using constructed wetlands was determined through data collection, data processing and classification, data weighting, overlay between data, and map presentation. Based on the AHP multi-criteria analysis referring to the criteria related to water treatment plants, it was determined that the priority scale of the criteria, namely, the pollution index, was 36%, the slope was 33%, and land use was 31%, with a weighting consistency ratio of < 0.1. The criteria data were classified into several sub-criteria with a value range of 0 to 3 indicating the level of land suitability, and then mapped and overlaid to generate a land suitability map with suitable, less suitable, and unsuitable classifications. Locations classified as suitable were those with a high pollutant index, slope > 2%, and vacant land locations distributed upstream, midstream, and downstream of the river. Furthermore, the location suitability level map can be utilized to design a water treatment plant for constructed wetlands in Tukad Badung to improve the water quality.

Author Contributions

DRM: Data curation, Formal analysis, Software, Investigation, Visualization, Writing – original draft, Writing - Review & Editing; **KDH**: Writing - Review & Editing, Supervision, Validation, Resources, Project administration, Conceptualization; **NMP**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing - Review & Editing; **MN:** Resources, Supervision; **IARW**: Resources, Supervision; **IGAGWB:** Investigation, Data curation; **NDS:** Investigation and **DSF:** Investigation.

Conflicts of interest

There are no conflicts to declare.

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