The Impact of Land Use Change on Improving Surface Runoff, Peak Flood Discharge, and Sedimentation in the Maros Watershed

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ABSTRACT

The present study aims to analyze how land use changes affect surface runoff, flood peak discharge, and sedimentation. Moreover, it aims to assess the specific impact of these changes on the flood peak discharge and to propose effective strategies for reducing flood risks. Visual interpretation of the land use changes was utilized based on Landsat imagery from 2010, 2017, and 2021, along with SPOT 4 satellite data. Soil samples were collected to measure the erosion rates, water discharge, and sediment loads (both suspended and bedload). The findings showed a significant reduction in the secondary dryland forest, which shrank by 52.71 km² (a 7.99% decrease), while shrub and agricultural areas expanded by 51.03 km² (a 7.73% increase). This shift contributed to a greater surface runoff and an increased erosion, especially in dryland-shrubland areas, where erosion reached 4,248.33 tons/ha/year. The flood peak discharges rose sharply in areas converted to agriculture and settlements, halving the flood return period from 50 years to just 25 years. During the wet season, the sediment loads peaked at 782.17 tons/day (equivalent to 377,293.48 m³ per year), while the dry season sedimentation—mostly driven by quarrying—reached 10.45 tons/day. To address these issues, the current study proposes adopting adaptive spatial planning, restoring the watershed, and applying nature-based solutions, such as Biopore Absorption Holes (BAH), Rainwater Infiltration Wells (RIW), and similar technologies.

Keywords-Maros watershed conservation; surface runoff changes; peak flood discharge; sedimentation land use; flood risk mitigation

I. INTRODUCTION

The impact of land use on sedimentation in the Maros Watershed is significant. Changes in land use directly influence sedimentation rates [1]. Several factors have contributed to the degradation of the Maros watershed [2], and the conversion of forest land into dry agricultural areas. These activities have accelerated both land and water degradation. The region's tropical climate—characterized by high annual rainfall ranging from 1,501 mm to 3,000 mm—further intensifies these effects.

The area contains various soil types, including young alluvial, regosol, lithosol, and mediterran soils. Forests and paddy fields are the dominant land cover types within the watershed. The sediment discharge in the watershed is influenced by multiple factors, including the speed and volume of the water flow, as well as the concentration of sediment in the river channel [3].

Land degradation in the Maros watershed has resulted in severe natural disasters, including major floods. These recurring flood events highlight the urgent need to restore land and agricultural areas within the watershed using engineered solutions. Proposed restoration methods include building conservation ponds, implementing artificial groundwater recharge systems, applying riverside polder techniques, and designating groundwater protection zones [4–7]. Effective mitigation requires a combination of structural and non-structural strategies [6]. Land degradation caused by changes in land use has a significant impact on surface runoff and peak flood discharge. Increasing the rate of water infiltration into the soil can greatly reduce the surface runoff [8]. However, land use changes often lead to the opposite effect, namely more surface runoff and less rainwater infiltration [9]. This, in turn, reduces the availability and quality of groundwater reserves [10]. Groundwater in watershed areas (DAS) plays a crucial role in sustaining the river flow, especially during dry seasons. When surface runoff is minimized, more rainwater can infiltrate the soil, helping to reduce the peak flood discharges in rivers [11–13]. In addition to increasing the flood risk, land use changes also alter the watershed's overall hydrological behavior [14, 15] and contribute to higher flood peaks [16, 17]. These effects are further compounded by the influence of climate change [18–20]. Therefore, an effective land management within watershed areas is essential for protecting the entire river ecosystem. Poor land management practices not only influence the river water levels and flood intensity, but also accelerate the climate change impacts. One consequence is a reduction in flood return intervals from what was once a 50-year event to a 25-year event, making severe floods more frequent.

The objectives of this research are threefold. Firstly, to analyze the surface runoff and sedimentation patterns; secondly, to assess the impact of land use changes within the Maros watershed on increased runoff, flooding, and sedimentation; thirdly, to identify effective mitigation strategies. By understanding the interplay between land use and hydrological responses, the study aims to develop informed strategies to reduce flood risks and promote sustainable watershed management.

II. METHODOLOGY

A. Location

The research was carried out in the watershed area of the Maros River, South Sulawesi Province. The upstream and middle regions (Subdistricts of Tombobulu, Simbang, and Tanralili) of Maros River were chosen as the sample location.

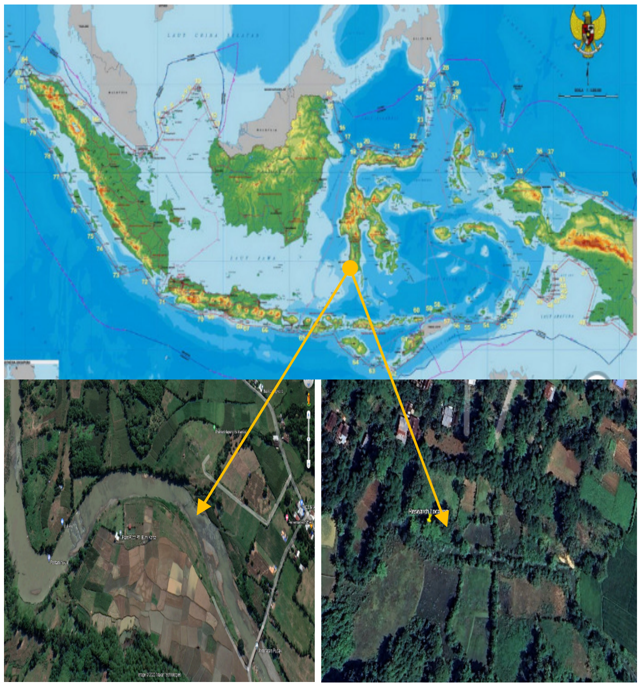

Fig. 1. Sand sampling location in Maros River, South Sulawesi, Indonesia.

B. Required Data

The data required for the present research include:

- Daily rainfall data from three rainfall stations (Bessi, Tanralili, and Tompobulu) spanning from 1997 to 2018. Specifically, the data from Bessi and Tanralili stations cover the years 1997-2018, while the data from Tompobulu station cover the years 1997-2017.
- Soil type maps of the Maros watershed.
- Suspended load sample data.
- Land use maps of the Maros watershed for the years 2010, 2017, and 2021.

C. Research Type

This research employs a quantitative approach, involving data collection through field observations. The data collection includes measuring flow velocity, collecting sediment samples, and soil sampling to assess the erosion rates.

III. RESULTS AND DISCUSSION

A. Analysis of Land Use Change

Ωisual interpretation approach was employed. The classification is based on Ground Check Positions (GCP), combined with a digital analysis of Landsat Imagery from 2010, 2017, and 2021, using SPOT 4 satellite imagery, as presented in Table I.

TABLE I. CHANGES IN LAND USE IN THE MAROS WATERSHED IN 2010, 2017, AND 2021

No	Type of land use	Years 2010th		Years 2017th		Years 2021st		Changes	
		km²	%	km²	%	km²	%	km²	%
1	Secondary dry land forest	239.48	36.3	223.47	33.87	186.78	28.31	-52.71	-7.99
2	Mixed gardens	36.84	5.58	28.95	4.39	24.68	3.74	-12.16	-1.84
3	Shrubs	116.46	17.65	102.76	15.58	95.11	14.42	-21.35	-3.24
4	Dryland-shrub farming	46.84	7.1	49.79	7.55	97.87	14.83	51.03	7.73
5	Savanna - grassland	4.52	0.69	3.62	0.55	3.07	0.47	-1.45	-0.22
6	Open field	1.27	0.19	1.35	0.21	1.92	0.29	0.66	0.10
7	Settlement	15.66	2.37	29.81	4.52	25.35	3.84	9.70	1.47
8	Ricefield	176.92	26.81	191.37	29	189.66	28.75	12.74	1.93
9	Pond	21.78	3.3	28.66	4.33	35.33	5.36	13.55	2.05
	Total	659.78	100	659.78	100	659.78	100		

B. Impact of River Basin Land Conversion on Surface Runoff

The factors affecting the surface runoff include the land cover types, cover density, rainfall, slope, and soil types in the Maros watershed. The results of the surface runoff analysis, using data from 2010, 2017, and 2021, are depicted in Figures 1 and 2.

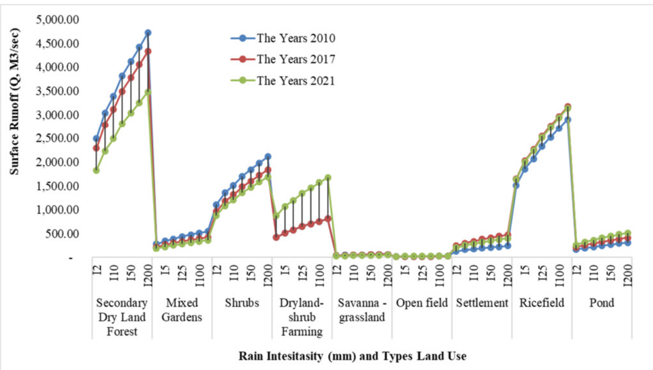

Fig. 2. The influence of rainfall intensity period and land use type on surface runoff.

Figure 2 illustrates the impact of forest land conversion on the surface runoff. When forest land is converted into agricultural or plantation areas, the surface runoff increases significantly. Secondary dry forest land tends to produce more surface runoff than open land or paddy fields. This type of land conversion not only increases the runoff, but also reduces the amount of rainwater that infiltrates into the ground, thereby diminishing the groundwater recharge [21]. As a result, the peak flood discharge rises, and the interval between major flood events (flood recurrence interval) becomes shorter. These findings highlight the need to consider the land use changes during the planning of the sustainable management of natural resources [22].

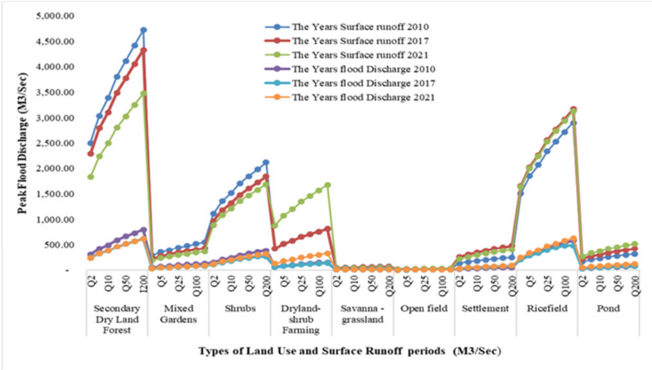

Fig. 3. Effect land use type and surface runoff on peak flood discharge.

Figure 3 shows that the conversion of forest land to dryland agriculture in the Maros River Basin has significantly increased the surface runoff and peak flood discharge [23]. Among the different land use types, dryland-shrub areas generated the highest flood peaks, while forested and pond areas had the lowest—highlighting the crucial role of vegetation in controlling runoff. From 2010 to 2021, both runoff and peak discharge have steadily increased, indicating an ongoing and cumulative watershed degradation [24]. This study builds on earlier research [26, 27] by providing higher spatial and temporal resolution. Unlike studies that assess the land use impacts at a single point in time, this research uses integrated modeling to track the hydrological changes across multiple land use types and time periods. An important finding is the shortening of the flood return periods, for example, from a 50-year flood (Q50) to a 25-year flood (Q25), as a direct result of land use change [25]. This fills a critical knowledge gap by showing how specific land conversions impact the flood behavior over time. The study also provides broader evidence that unchecked land development intensifies extreme hydrological events [28].

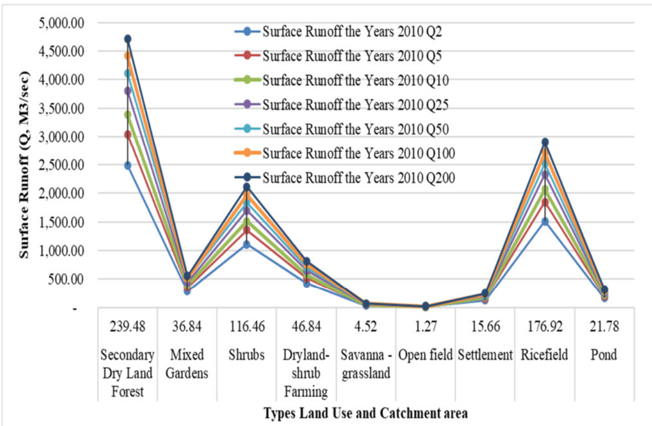

Fig. 4. Effect of land use type and catchment area on surface runoff for 2010.

Figure 4 indicates that the secondary dry forest and paddy fields exhibit significant runoff values. The conversion from forest to paddy fields leads to increased surface runoff. This demonstrates that converting forest land to agricultural land enhances the surface runoff due to reduced vegetation and expanded open areas [29, 30]. Another impact is the reduction in watershed infiltration [16, 29], an increase in the peak flood discharge, and a shorter peak flood discharge period [30, 12]. Five thematic maps that affect flood events, including slope, elevation, land use, peak discharge, and flow accumulation, are classified to produce a flood hazard map [31]. Flood hazard mapping serves as a reference for stakeholders in decision-making as a step to mitigate flood risks quickly and accurately.

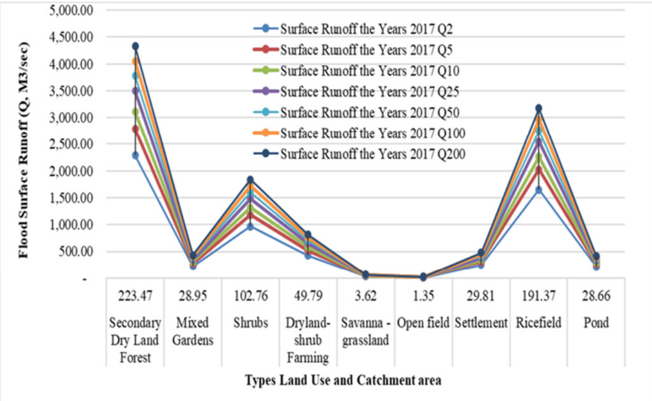

Fig. 5. Effect of land use type and catchment area on surface runoff for 2017.

Figure 5 illustrates a consistent trend from 2010 to 2017, indicating that the conversion of forests to agricultural or residential land results in increased surface runoff. The impact of converting forests to residential and agricultural areas leads to increased surface runoff and changes in water flow patterns [12, 32]. High surface runoff reduces infiltration in the watershed area [15, 16], increases peak flood discharge, and shortens the peak flood discharge period [12, 32].

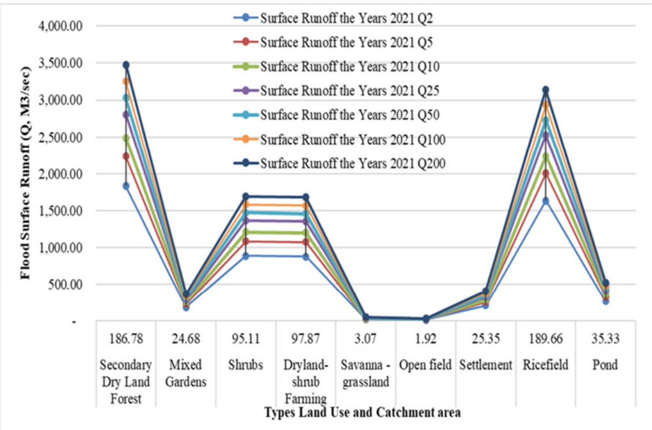

Fig. 6. Effect of land use type and catchment area on surface runoff for 2021.

Figure 6 illustrates a noticeable increase in the surface runoff across various land uses, particularly in areas where the secondary dry forest has been converted into agricultural or residential land. This transformation leads to a reduced water absorption and significantly higher runoff levels [33, 34]. As a result, flooding becomes more unpredictable, with rainfall and flood events occurring earlier and more intensely than expected [29]. Such conditions are common, marked by short but intense rainfall events that closely resemble the runoff patterns observed when the watershed was still largely forested, prior to the widespread land conversion in the 2000s and earlier. Figures 2-6 show that changes in land use from forest to agriculture or settlements have increased the surface runoff throughout the Maros Watershed between 2010 and 2021. Vegetation plays a key role in slowing the surface runoff and enhancing surface detention, namely the ability to temporarily hold water above ground, which helps reduce both the speed and volume of the runoff [35]. This is reflected in a lower surface runoff coefficient, which represents the proportion of rainfall that becomes runoff [36, 37]. Surface runoff is influenced by two main groups of factors. Hydrological factors, such as the type of precipitation, rainfall intensity, duration, and how rain is distributed across the watershed and physical characteristics of the land – including land use, soil type, and topography of the drainage area [38, 39]. Understanding the interaction of these factors is essential for managing runoff and minimizing flood risks in areas undergoing a rapid land use change.

C. Impact of River Basin Land Conversion on Peak Flood Discharge

The utilization of watershed land leads to environmental changes within the watershed. The impact of land conversion includes increased surface runoff, higher peak flood discharge, hydrological alterations, and changes to the primary function of the watershed as a buffer for groundwater availability to support the river flow. Figures 7-10 illustrate how land changes affect the peak flood discharge.

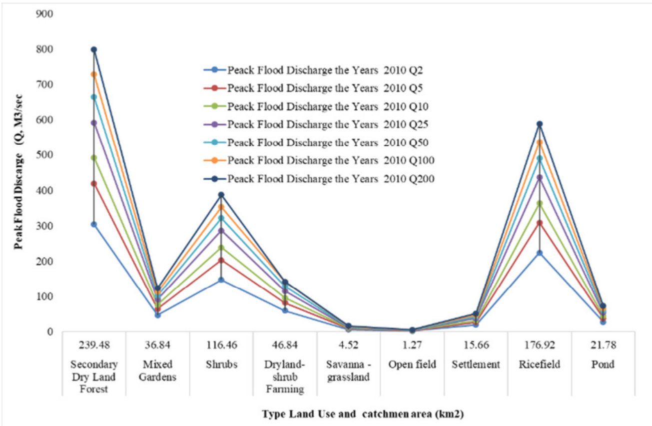

Fig. 7. Influence of land use type and water catchment area on the peak flood discharge for 2010.

Figure 7 shows that the conversion of secondary dry forest to mixed gardens, shrubland, and dry agricultural land increases the peak flood discharge. The secondary dry forest exhibits the highest peak discharge. This indicates that deforestation and the conversion of forest land to agricultural land increase the risk of flooding and peak water discharge

[40]. The more extensive the land conversion is, the higher is the trend of the peak flood discharge [25]. Consequently, this condition leads to a shorter peak flood discharge period [41, 30]. Another impact is that the return period of the peak flood discharge can be shorter, causing previously unpredictable flash floods. Thus, flash flood mitigation is needed by classifying it in the form of a flood hazard map [31] to solve this issue more quickly.

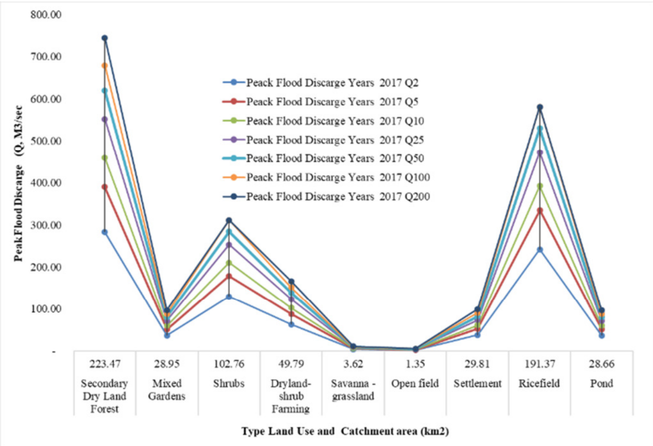

Fig. 8. Influence of land use type and water catchment area on the peak flood discharge for 2017.

Figure 8 shows that larger catchment areas, such as secondary dry land forest and rice fields, exhibit the highest peak flood discharges across all return periods. Land uses with higher infiltration capacities, such as ponds and mixed gardens, tend to have lower peak discharges despite the varying return periods. The trend across the return periods (Q2-Q200) consistently shows increasing peak discharges, highlighting the impact of flood probability on the discharge magnitude.

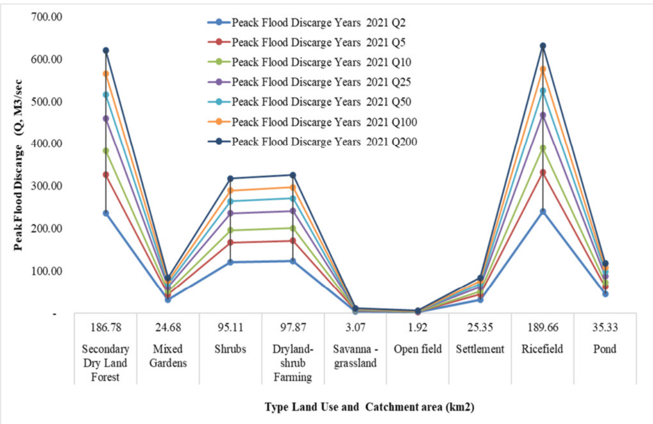

Fig. 9. Influence of land use type and water catchment area on the peak flood discharge for the 2021 period.

Figure 9 displays a significant increase in the peak flood discharge in areas that have undergone substantial land conversion. The secondary dry forest still exhibits the highest peak discharge, but there is a notable increase in agricultural and residential land. Figures 8 and 9 indicate that changes in land use and land conversion increase the risk of flooding and peak water discharge, especially in areas that were previously forested [42-46]. Another impact is that the return period of the peak flood discharge can become shorter, leading to previously unpredictable flash floods.

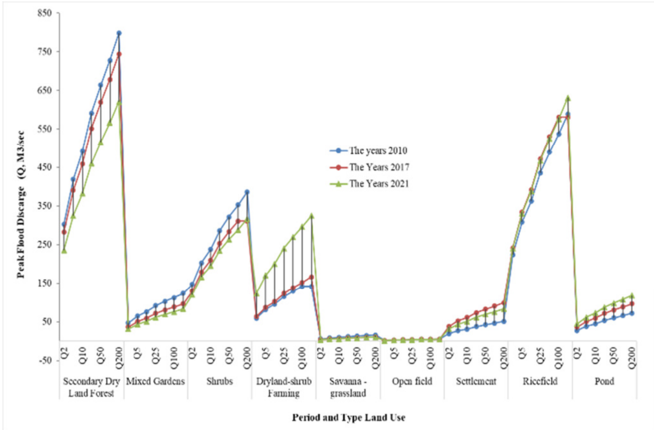

Fig. 10. Effect of land use type and catchment area on peak flood discharge.

Figure 10 illustrates that the conversion of land into agricultural fields, residential zones, and open areas has led to a steady increase in the peak flood discharge from 2010 to 2021. This trend shows that replacing forested land with agriculture and housing reduces the soil's ability to absorb water, significantly raising the risk of flooding [44, 45]. The reduced infiltration not only contributes to higher flood peaks, but also affects the availability of the groundwater base flow in the Maros River. As a result, flash floods which used to be rare and unpredictable have become more common. These conditions make the region highly vulnerable to severe flooding and landslides during the rainy season, as well as water shortages and drought during the dry season [30, 44]. The current study confirms that land use changes over the 2010–2021 period have led to increased flood risks. The data underscore the important role of forests in mitigating floods and maintaining a balanced hydrological system. These findings highlight the need for sustainable land use practices and spatial planning that account for the impacts of land conversion especially in urban and agricultural areas on flood risk and watershed stability.

D. Impact of River Basin Land Conversion on Surface Runoff and Peak Flood Discharge

The impact of watershed land conversion leads to an increased surface runoff and peak flood discharge, as depicted in Figures 11-14. Figure 11 indicates that the conversion of the secondary dry land forests to various other land types, such as mixed gardens and dryland-shrub farming, increased the peak flood discharge [11]. The secondary dry land forests experienced the highest peak discharge, followed by rice fields and shrublands. This demonstrates that land use changes increase the flood risk and peak discharge in the Maros watershed [20, 46].

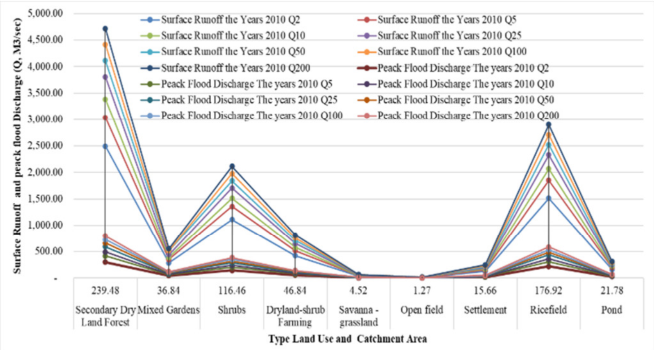

Fig. 11. Effect of land use type and catchment area on surface runoff and peak flood discharge for 2010.

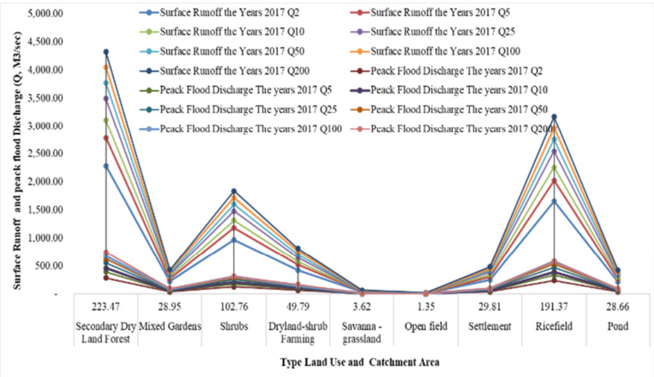

Fig. 12. Effect of land use type and catchment area on surface runoff and peak flood discharge for 2017.

Figure 12 exhibits that the trend of increasing the peak flood discharge was evident in areas undergoing land conversion from forest to agricultural and residential uses. The highest peak discharge remained in secondary dry land forests; however, there was a significant increase in the peak discharge in agricultural and residential areas. This demonstrates that the conversion of forest land to agricultural land and urbanization increases the peak flood discharge and the frequency of flood events [47, 48].

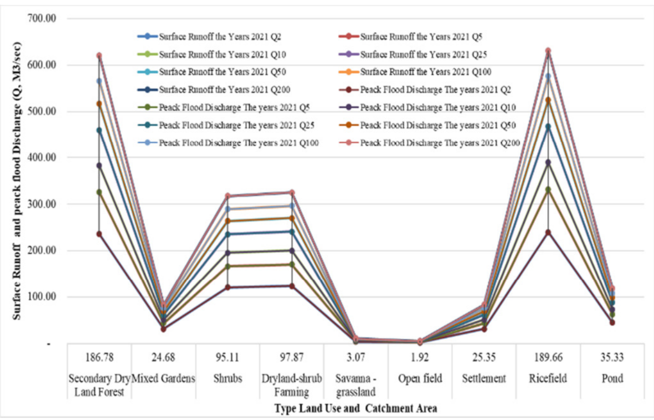

Fig. 13. Effect of land use type and catchment area on surface runoff and peak flood discharge for 2021.

Figure 13 shows a significant increase in the peak flood discharge in areas undergoing land conversion. The secondary dry land forests still exhibited the highest peak discharge, but the agricultural and residential areas displayed the most substantial increases. This indicates that land use changes and urbanization significantly increase the flood risk and peak water discharge, particularly in areas that were previously forested [49, 50].

Figure 14 demonstrates an important variation in the surface runoff and peak discharge based on the land use types, with the secondary dry land forests and rice fields playing a major role. This variation stresses the importance of land use management in flood mitigation. The present study provides essential data that can be utilized to formulate more effective land management strategies [51, 52]. Figure 14 shows that the changes in the land use significantly influence the increase in the surface runoff and peak flood discharge in the Maros River. Factors, such as open land and rainfall intensity in the Maros watershed area, contribute to an increased runoff and peak flood discharge. The presence of vegetation land cover in the watershed can inhibit surface runoff, increase the surface runoff coefficient, and accelerate the rate of infiltration, thereby reducing the likelihood and duration of flooding [53]. According to [54], infiltration is a key process in runoff management; if infiltration is high, the surface runoff will be lower, reducing the probability of major floods. Factors affecting infiltration include soil conditions, deforestation, and vegetation. The reduced rate and volume of runoff are related to the change (decrease) in the value of the surface flow coefficient [55, 56]. Logging, agricultural activities, and settlement development contribute to land use changes [36, 57]. In the watershed, these changes initiate alterations in the hydrological cycle and affect the forest's role as a buffer for the river flow [58, 6]. Forests are substantial for human life as they are the primary source of clean water. The quality of clean water is strongly influenced by the natural systems within forests. To prevent prolonged water crises and unpredictable flooding, it is essential to maintain and restore the natural functions of forests.

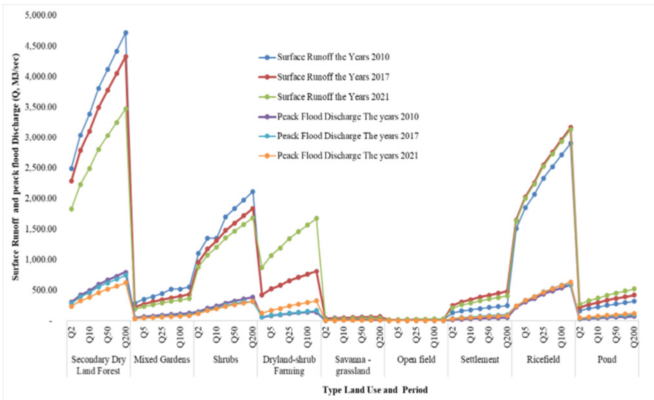

Fig. 14. Effect of land use type and period on surface runoff and peak flood discharge.

E. Sedimentation in the Maros Watershed

1) Erosion Distribution Analysis

The changes in land use within the Maros watershed have increased annually, leading to a significant reduction in the function of protected forest areas as buffers for river water. The distribution of erosion across land units in the Maros watershed for the year 2021 is detailed in Table II.

TABLE II. EROSION DISTRIBUTION FOR LAND USE IN THE MAROS WATERSHED IN 2021

No	Land use	Land area (Ha)	Potential erosion (ton/ha/year)
1	Secondary dry land forest	18677.66	1470.43
2	Mixed gardens	2468.16	336.7
3	Shrubs	9511.26	4073.73
4	Dryland-shrub farming	9787.25	4248.33
5	Savanna - grassland	307.05	39.83
6	Open field	192.52	106.25
7	Settlement	2,535.3	75.78
8	Ricefield	18965.65	1383.52
9	Pond	3533.27	531.166
Total number		65978,02	Ave. 1362.75

According to the variation in erosion values observed in forested areas, it is attributed to the degree of soil vegetation cover [59, 60]. Denser and healthier vegetation cover effectively reduces erosion, resulting in lower erosion values. Conversely, a sparse vegetation cover leads to higher erosion values. Authors in [55, 56] indicate that maintaining the vegetation cover is the most effective and economical method for preventing surface erosion and its extent [61, 62].

2) Sedimentation During the Dry Season and Type-C Mining Excavation in the Maros River

The results of sediment sampling during the dry season, along with the impact of Type-C mining excavations in the Maros River, indicate a sedimentation rate of approximately 10.45 tons/day, or 1553.48 m³ over 4 months, and 4536.15 m³ per year. The minimum flow recorded in the Maros River is 47.31 m³/sec. The sedimentation during the dry season is significantly influenced by mining activities, such as sand and gravel extraction, within the river area, which adversely affects the river ecosystem [63]. These mining activities have severely altered the river contour due to their massive and continuous nature, leading to a decline in the riverbed, changes in river morphology, increased flooding, and the extinction of flora and fauna habitats around the river [63]. Another consequence is that the reduction in the riverbed leads the river slope to become more gradual, slowing the river flow and exacerbating seawater intrusion further upstream [64, 65], given that the elevation difference between the Maros River estuary and the river center is approximately +2 to 3 m.

3) Rainy Season Sedimentation and the Impact of Land-Use Change

The sediment sample results from the rainy season, influenced by the surface runoff, indicated a sedimentation of approximately 782.172 tons/day, or 257,251.79 m³ over eight months, and 377,293.48 m³ per year. This is due to several factors, as noted in [22, 66, 67], where it was stated that the land cover has a significant impact on sedimentation. Additionally, authors in [54] explained that the construction of buildings in water catchment areas and sand mining within the watershed causes the degradation of the Maros watershed. The conversion of forests into dry agricultural land has further exacerbated land and water degradation [35]. This research employs an integrated approach to analyze the combined effects of land use changes on the hydrological parameters in the Maros watershed. By utilizing advanced modeling techniques and empirical data collection, the study quantifies the impacts of various land use scenarios on surface runoff, peak discharge, and sediment transport. Thus the transformation of land use and its impacts on hydrological processes are analyzed, providing essential data for developing sustainable land management strategies and effective flood mitigation measures.

IV. CONCLUSIONS

Based on the results of the present study, the following conclusions are drawn:

- This study confirms that the conversion of 52.71 km² of secondary dry forest land to 51.03 km² of scrubland agriculture in the Maros watershed has significantly increased the surface runoff and soil erosion (4248.33 tons/ha/year), exceeding levels reported in previous studies. This indicates an intensified land degradation and highlights the gaps in the enforcement of sustainable land use.
- Land use conversion has reduced the flood return period from 50 to 25 years, providing stronger spatial and quantitative evidence than previous studies. By integrating recent multitemporal satellite data and flood modeling, this study advances the understanding of the direct hydrological response to land use conversion, addressing an important knowledge gap.
- Sedimentation during the rainy season (782.17 tons/day) and dry season (10.45 tons/day) exceeds the values in comparable watersheds, indicating more severe sediment dynamics, influenced by land use and mining activities. This study offers seasonally separated sediment insights that are rare in the existing literature.
- Based on the above analysis, an integrated mitigation strategy combining Biopore Absorption Holes (BAH), Rainwater Infiltration Wells (RIW), upstream polders, and flood hazard mapping based on slope, elevation, and discharge is proposed. This holistic approach departs from previous single-solution frameworks, offering a new adaptive planning model for watershed resilience and flood risk reduction.

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