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Between Anthropogenic Influence and Resource Management: Impacts of Risks and Preservation Strategies in the Ikopa Watershed, Madagascar

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Abstract:

The impacts of anthropogenic risks on water resource management underscore the necessity for a careful and adaptable approach to ensure long-term sustainability. In the Ikopa Watershed in Madagascar, numerous human activities present significant challenges. Water quality is impacted by pollution resulting from agricultural practices. Uncontrolled deforestation intensifies watershed degradation, jeopardizing the availability of water resources. Rapid urbanization and escalating human activities further contribute to the deterioration of water quality. The hypothesis posits that responsible exploitation of natural resources contributes to preserving and sustaining water resources in the Ikopa Watershed. This study concentrates on investigating potential anthropogenic risks that influence resource degradation and the perception of mitigation measures. The main objective of this section is to assess the anthropogenic risk factors contributing to water resource degradation in the watershed. The study employs change detection studies through remote sensing and GIS approaches, complemented by social analysis. This methodology aims to identify potential anthropogenic risks affecting responsible water resource management, along with an exploration of local mitigation strategies. The results underscored potential risks the local population faces in the watershed, including challenges associated with agriculture, urbanization, inadequate drainage network management, and high population density. Binary logistic regression analysis reveals significant connections between anthropogenic risks and the mitigation strategies local communities adopt in the Ikopa Watershed. The findings indicate that specific characteristics of degradation or local interventions can either positively or negatively influence the adoption of these strategies.

Keywords:
Local perception; anthropogenic risks; mitigation strategy; Ikopa's watershed

I. Introduction

In the current context, the impact of anthropogenic risks on water resource management has emerged as a crucial issue, with human activities exerting significant pressures on both water availability and quality (Gleick 2003; Postel 2000). Pollution stemming from traditional agricultural practices, uncontrolled deforestation, water wastage, unregulated exploitation of forest resources, and rapid urbanization present substantial challenges for water resource management in the Ikopa Watershed in Madagascar (FAO, 2018; WWDR, 2018). These various anthropogenic activities accentuate environmental risks, consequently compromising the stability of aquatic ecosystems and the availability of water resources (Falkenmark & Rockström, 2004; Senker, 2011). This underscores the need for adaptive and sustainable management practices (Ostrom, 2009).

Given this complexity, it becomes crucial to comprehend the interconnections among various human-induced pressures to formulate customized solutions designed to alleviate these environmental challenges (Falkenmark & Folke, 2002; Molden, 2013). The research objective is to untangle the intricate interactions in order to evaluate the anthropogenic risk factors contributing to the degradation of water resources within the watershed. What impact do agricultural practices, deforestation, urbanization, and other human activities have on water quality and availability? Furthermore, what strategic approaches can be envisioned to achieve balanced water resource management in the region? These questions emphasize the necessity for a comprehensive and tailored approach to tackle the intricate challenges associated with water resource management in the Ikopa Watershed. We investigate the hypothesis that the responsible exploitation of natural resources plays a role in preserving and sustaining water resources on the scale of the mentioned watershed.

II. Research Method

2.1 Sampling Area

We conducted our study within the Ikopa Watershed, Madagascar, utilizing a sample size of 386 households. The selection of this sample followed a classic stratified sampling method with proportional allocation, ensuring a well-balanced representation of the various zones within the watershed (Groves et *al.*, 2009; Lohr, 2019). A multi-stage probability sampling method was employed, with the first stage involving the determination of primary sampling units (PSUs) through the analysis of cartographic and population data. Subsequently, sampling grids were created, and spatial points were randomly selected in proportion across different zones of the watershed. Each sample stratum consisted of 55 households, resulting in a total of 386 households for the entire study. Field surveys of households were conducted using the mWater mobile data collection tool (Feighery et *al.*, 2015). The utilization of this platform streamlined and enhanced the efficiency of data collection, ensuring accuracy and facilitating the subsequent management and analysis of the gathered data.

2.2 Analysis of Anthropogenic Risks

The analysis of anthropogenic risks followed a rigorous methodology that integrated advanced statistical techniques. This approach aimed to identify, rank, and quantify the risks impacting water resources within the study basin (MacQueen, 1967). To identify potential risks, we adhered to a multi-step approach. Firstly, we employed the Kruskal-Wallis Test (Ahmed & Jena, 2023; Kruskal & Wallis, 1952) to compare risk exposures in various zones of the basin concerning the anthropogenic risk factors variable. Significant differences revealed by this test enabled us to highlight notable variations in risk levels. Afterwards, a Frequency Analysis was employed to identify risks whose values surpassed the mean. (Agresti, 2019), thus focusing on the most concerning risks. In the final step, a Binary Logistic Regression was employed to establish the relationship between the identified potential risks and the observed impacts (Agresti, 2019; Hosmer Jr et *al.*, 2013), providing a comprehensive understanding of factors contributing to water resource degradation.

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k$$

$\ln\left(\frac{p}{1-p}\right)$: Natural logarithm of the odds ratio (odds ratio)

β_i : Coefficient measuring the change in log-odds in the probability of success for a one-unit change in the explanatory variable X_i

X_i : Explanatory variable i

2.3 Change analysis

A change analysis was carried out to evaluate variations in land cover within the study basin spanning a five-year period, from 2017 to 2022 (Karra et al., 2021). Initially, global changes were quantified using Sentinel-2 L2A satellite images with a resolution of 10 meters (Drusch et al., 2012; Karra et al., 2021). The total surface area for each year was calculated, excluding irrelevant classes such as "Clouds". This approach enabled us to acquire an aggregated measure of changes across the entire study area.

$$Sum\ of\ area\ in\ 2017 = \sum_{i=1}^{n} Area_{2017,i}$$

$$Sum\ of\ area\ in\ 2022 = \sum_{i=1}^{n} Area_{2022,i}$$

n : Total number of study zones

$Area_{2017,i}$ $Area_{2022,i}$: Area of each zone for the years 2017 and 2022

Change rates for each land cover class were calculated (Foody, 2002), expressed as a percentage relative to the initial surface in 2017. By employing this approach, we could identify classes that underwent significant changes.

$$Change\ rate\ X = \frac{\sum_{i=1}^{n}(Area_{2022,i} - Area_{2017,i})}{\sum_{i=1}^{n} Area_{2017,i}} \times 100$$

Furthermore, a class-wise analysis was carried out to quantify the specific changes within each category, thereby offering a detailed understanding of the alterations.

$$Difference\ of\ area\ for\ class\ X = \sum_{i=1}^{n}(Area_{2022,i} - Area_{2017,i})$$

$$P(Y_{t+1} = j|T_y = i) = \frac{Change\ area\ from\ i\ to\ j}{Total\ of\ change\ area\ of\ i}$$

2.4 Analysis of mitigation strategies

The mitigation strategies were analysed to understand the practices adopted by local communities to address natural resource degradation. Binary Logistic Regression Analysis was employed to explore the relationship between observed impacts and various mitigation measures or strategies implemented by local communities (Hosmer Jr et al., 2013). By adopting this approach, we could assess the effectiveness of mitigation strategies and identify the most impactful practices. The analysis was enriched by integrating a set of variables related to anthropogenic risk mitigation measures. This integration facilitated a comprehensive evaluation of the practices adopted by local communities

III. Result and Discussion

3.1 Anthropogenic risks encountered by local communities

Identifying human-induced risks is essential for evaluating threats to the preservation of water quality and availability in the Ikopa Watershed. This section is dedicated to mapping and evaluating these potential risks.

a. Identification of Potential Anthropogenic Risks

The results of this study revealed uniformity in the distribution of potential anthropogenic risks across different locations within the watershed. Statistical tests demonstrated no significant disparities in levels of anthropogenic risk between location categories. This consistency suggests homogeneity of potential risks related to human activity, regardless of geographical position within the basin.

Upon specifically scrutinizing the averages of potential risks, certain factors emerge with levels surpassing the overall average. Agricultural activities, urbanization, poor drainage network management, and population density were identified as significant contributors to higher levels of anthropogenic risk in the basin (Table 1). However, other potential risks including deforestation, bushfires, inadequate waste management, and wastewater treatment deficits, exhibit averages below the overall average. This suggests lower risk levels in certain locations within the basin.

Table 1. Analysis of potential risks related to the anthropogenic risk factors variable

Variable\Test	Variables' names	p-value (two-tailed)	Groups	Frequency
AnthRisk – 1	Deforestation	0,6136	A	48,19
AnthRisk – 2	Bushfires/Wildfires	0,6688	A	50,00
AnthRisk – 3	Agriculture (fertilizers, etc.)	0,1670	A	**52,07**
AnthRisk – 4	Urbanization	0,8334	A	**52,85**
AnthRisk – 5	Poor waste management	0,5239	A	49,74
AnthRisk – 6	Poor drainage network managemei	0,3490	A	**52,33**
AnthRisk – 7	Wastewater treatment deficit	0,8593	A	50,52
AnthRisk – 8	Population density	0,1375	A	**52,59**
			Mean	**50,83**

The analysis of impacts associated with each identified anthropogenic risk in the Ikopa Watershed revealed significant relationships between human activities, anthropogenic risks, and environmental impacts. The results demonstrated significant decreases in agricultural input expenditures and reliable stream flows during the dry season due to agriculture. Urbanization also led to reduced water flows and increased damages to fields. Poor drainage network management was associated with a decrease in production area and unsustainable practices. Lastly, the rise in population density was associated with notable geographical variations and intricate interactions with other socio-economic and environmental factors.

b. Classification of Observations by Exposure to Risks

A K-means classification analysis was conducted to group observations based on their exposure to anthropogenic risks. Three distinct classes emerged, each presenting specific characteristics in terms of risk exposure. Class 1 was identified as the most exposed, displaying elevated levels of risks associated with agriculture, urbanization, and population density. Class 2 exhibits moderate exposure, while Class 3 is characterized by lower exposure to these risks.

Table 2. Characteristics of Observation Classes Based on Exposure to Encountered Anthropogenic Risks

		Class 1 (Most exposed)	**Class 2 (Moderate exposure)**	**Class 3 (Less exposed)**
Results per Class:	Objects	99	184	103
	Intra-class Variance	0,499	0,748	0,500
	Minimum distance to centroid	0,644	0,804	0,639
	Average distance to centroid	0,701	0,862	0,702
	Maximum distance to centroid	0,773	0,930	0,776
Initial class centroids:	AnthRisk - 3	0,538	0,519	0,507
	AnthRisk - 4	0,556	0,443	0,587
	AnthRisk - 6	0,419	0,603	0,536
	AnthRisk - 8	0,556	0,496	0,529

3.2 Dynamics of Land Use and Vulnerability of Natural Resources in the Ikopa Watershed

The findings from the land use study conducted in the Ikopa Watershed between 2017 and 2022 have unveiled noteworthy changes and significant environmental challenges confronting the region. Data analysis has shown an expansion of aquatic areas, alarming decline in forested areas, rapid expansion of cultivated lands, and significant implications for sustainable natural resource management.

a. Dynamics of Land Use in the Watershed

The evaluation of land use in the Ikopa Watershed between 2017 and 2022 has revealed several important trends. Analysis of results by class highlighted significant changes in the environmental composition of the region.

The comparison of the two land use maps disclosed a rise in aquatic areas, expanding by 11.64% compared to its surface area in 2017. This suggests an enlargement of aquatic zones within the watershed.

Forested areas decreased by 5.76% of the wooded area due to deforestation phenomena. Flooded vegetation areas experienced a surface expansion of 45.02%, signaling changes in wetland areas. Cultivated areas significantly increased by 62.69%, indicating the expansion of agricultural lands. Construction zones increased by 22.10% of the total area in 2017, reflecting increased urbanization in the watershed. Bare soil areas decreased by 78.76%, indicating increased land use and vegetation cover. Cultivated lands decreased by 60.61%, indicating abandonment and change in land use.

Table 3. Land Use Change Matrix of the Ikopa Watershed in 2017-2022

Classe	**Water**	**Trees**	**Flooded Vegetation**	**Crop**	**Construction areas**	**Bare Soil**	**Cultivated Land**
Water	15 194,33	88,57	536,41	338,64	119,69	569,31	1 097,58
Trees	191,24	62 868,91	183,77	2 098,48	143,55	4,78	27 411,02
Flooded Vegetation	456,01	35,63	4 050,97	586,18	81,30	3,05	564,51
Crop	448,75	676,27	1 717,98	85 970,09	1 962,53	13,47	27 648,26
Construction areas	81,25	63,82	69,85	361,55	32 090,10	29,93	800,39

Bare Soil	997,62	22,79	8,82	1 574,56	49,84	1 793,67	7 520,53
Cultivated Land	2 663,16	23 792,16	1 809,25	101 750,72	6 442,26	128,34	1 928 033,45

b. Vulnerability of Land Use Transition

The analysis of natural resource vulnerability in the Ikopa Watershed between 2017 and 2022 (Figure 01) revealed significant change dynamics in different land use classes:

Class stability: The results highlight strong stability within each land use class, with high probabilities of remaining in the same category. Water areas (0.847), flooded vegetation (0.701), cultivated land (0.726), construction zones (0.958), cultivated terrain (0.934), and tree areas (0.677) showed high probabilities of stability, reflecting resilience or predominance of existing land use.

Notable transitions: Some transitions between land use classes were particularly remarkable, indicating significant changes in these areas. Notable transitions include shifts from water to bare soil (0.032) and cultivated land (0.061), tree areas to cultivated lands (0.295), and flooded vegetation areas to cultivated zones (0.101), suggesting potential transformations related to human activities or environmental conditions.

Minimal changes: Some changes were characterized by very low probabilities, suggesting minimal or infrequent modifications. Transitions from tree areas to bare soil (0.001) showed very low probabilities, as did shifts from construction zones to other classes (0.001), and transitions from cultivated land to flooded vegetation (0.001), emphasizing the predominance of existing landscape features.

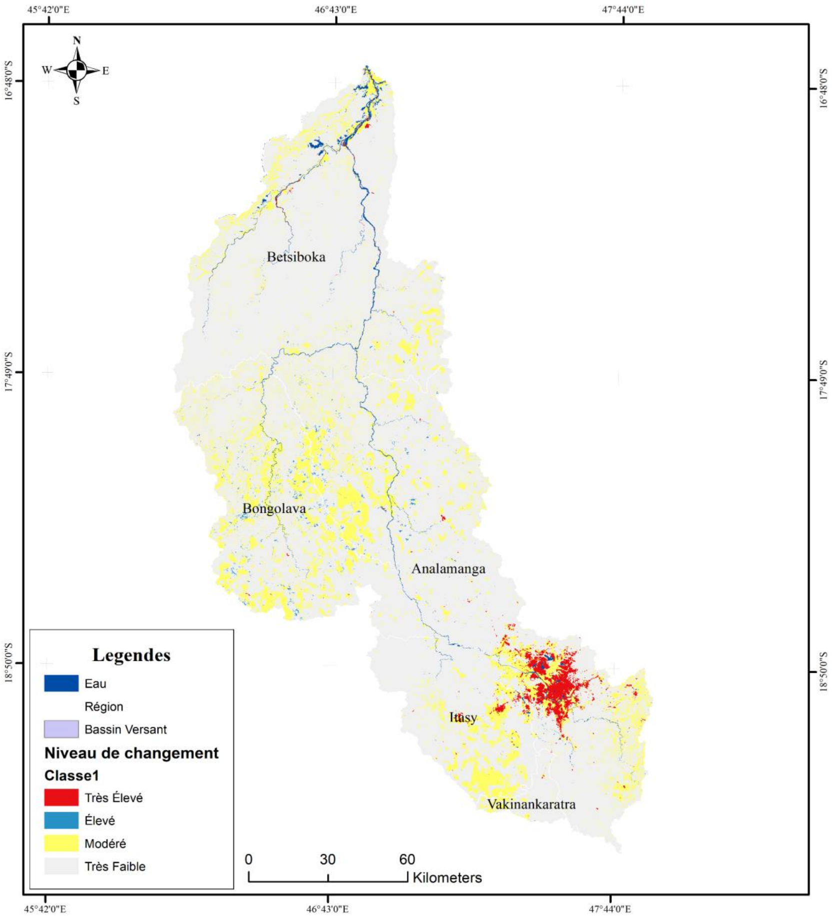

Figure 1. *Vulnerability to Land Use Change from 2017 to 2022*

3.3 Mitigation Strategies by Local Communities in Response to Natural Resource Degradation

Regression models revealed varied relationships between levels of anthropogenic risk and the adoption of mitigation strategies by local communities. The results highlighted diverse associations between levels of anthropogenic risk and the adoption of mitigation strategies by local communities. Some levels of risk, particularly related to urbanization (p: 0.052, Cox and Snell R-squared: 0.049, Nagelkerke R-squared: 0.066) and population density (p: 0.013, Cox and Snell R-squared = 0.060, Nagelkerke R-squared = 0.080), showed a significant relationship with mitigation strategies. However, for other levels of risk related to agriculture (p: 0.073, Cox and Snell R-squared = 0.047, Nagelkerke R-squared = 0.062) and poor drainage network management (p: 0.387, Cox and Snell R-squared = 0.030, Nagelkerke R-squared = 0.040), this relationship was not statistically significant.

The results revealed several variables that influenced the mitigation strategies adopted by local communities. Concerning the impact of agriculture, altering the cropping calendar exhibited a notable association with the adoption of mitigation strategies. Simultaneously, stringent enforcement of forestry regulations was linked to a decrease in these probabilities. Regarding the impact of urbanization, diversifying income sources and the active involvement of local communities in planning emerged as positive factors for the adoption of mitigation strategies. Conversely, the availability of appropriate funding was associated with a decrease in these probabilities. In the context of the impact related to poor drainage network management, emphasizing the social importance of resources was linked to an increase in the likelihood of adopting mitigation strategies.

Lastly, regarding the impact of population density, implementing local surveillance and investing in locally appropriate solutions emerged as positive factors for adopting mitigation strategies. Conversely, enhancing local skills was associated with a decrease in these probabilities.

Table 4. Equation variables

Risks	**Strategies**	**B**	**E.S**	**Wald**	**ddl**	**Sig.**	**Exp(B)**	**95% confidence interval for EXP(B)**	
								Inferior	**Superior**
AnthRisk - 3	MesDeg_1(1)	0,459	0,210	4,783	1	0,029	1,583	1,049	2,388
AnthRisk - 3	StratDeg_AppReg	-0,478	0,212	5,098	1	0,024	0,620	0,409	0,939
AnthRisk - 4	MesDeg_3(1)	0,425	0,212	4,010	1	0,045	1,529	1,009	2,316
AnthRisk - 4	StratDeg_FinActImp(1)	-0,425	0,214	3,926	1	0,048	0,654	0,429	0,995
AnthRisk - 4	StratDeg_ImpLocPlan(1)	0,471	0,215	4,784	1	0,029	1,601	1,050	2,442
AnthRisk - 6	StratDeg_MisValLoc(1)	0,416	0,210	3,900	1	0,048	1,515	1,003	2,289
AnthRisk - 8	MesDeg_4(1)	0,602	0,213	8,024	1	0,005	1,827	1,204	2,771
AnthRisk - 8	StratDeg_RDCLoc(1)	-0,448	0,213	4,444	1	0,035	0,639	0,421	0,969
AnthRisk - 8	StratDeg_InvSol(1)	0,463	0,213	4,726	1	0,030	1,589	1,047	2,413

MesDeg_1 : Modification of cropping calendar
MesDeg_3 : Diversification of income sources
MesDeg_4 : Establishment of local surveillance
StratDeg_AppReg : Strict application of all regulations governing forest space
StratDeg_FinActImp : Adequate funding to carry out all significant management activities
StratDeg_RDCLoc : Strengthening of local skills
StratDeg_MisValLoc : Highlighting social importance: Providing a level of importance to the livelihood of local communities
StratDeg_InvSol : Investing in locally appropriate integrated water resource management

solutions
StratDeg_ImpLocPlan : Actively involving local communities in the planning process (especially including women and marginalized groups)

3.4 Discussion

a. Environmental Vulnerability Factors

The results underscore the importance of understanding these interactions to develop effective mitigation strategies. The different strata of anthropogenic risks present varied relationships with the mitigation strategies adopted by local communities, highlighting the need to tailor environmental management strategies according to specific risk levels (Brooks et *al.*, 2005; Patt & Schroter, 2008; Wilbanks & Kates, 1999). The results highlight the importance of focusing efforts on sustainable agricultural practices, thoughtful urban planning, effective drainage network management, and population density control (Satterthwaite, 2009; Scoones et *al.*, 2020; Turner et *al.*, 2007).

Statistical models identified specific risk levels that show a significant relationship with risk impacts, providing a solid foundation for the development of specific mitigation measures (Adger et *al.*, 2005; Agrawal, 2008; Agrawal, 2010). The results confirm the importance of targeting specific actions for each risk source and highlight the need for differentiated measures based on the specific degradation characteristics associated with each anthropogenic activity (Burgess et *al.*, 2014; Liverman & Cuesta, 2010).

The analysis of environmental changes in the watershed reveals significant ecological and anthropogenic dynamics, highlighting human activities' direct and indirect effects on the environment (Adger et *al.*, 2005; Folke et *al.*, 2002). The results call for adaptive management and continuous monitoring to ensure the sustainability of natural resources and ecosystem resilience in the face of growing environmental pressures (Brooks et *al.*, 2005; Scoones et *al.*, 2020).

b. Adaptation Perspectives to Climate Variability Risk Factors

A comprehensive study of the relationships between human activity and mitigation strategies in the Ikopa watershed highlights the importance of adaptive responses to water resource pressures (Adger, 2000; Berkes, Colding, & Folke, 2008; Pelling, 2010). Key factors of local resilience, such as income diversification and active community engagement in planning, are identified as positive contributors to the sustainable management of these fragile resources (Smit & Wandel, 2006; Walker et *al.*, 2004). However, complex dynamics are observed where some mitigation strategies may increase vulnerability, thus emphasizing the need for a holistic approach that integrates socio-ecological resilience and local resource management practices (Folke, 2006; Lebel et *al.*, 2006).

The integration of these findings into conservation and resource management policies can strengthen beneficial practices at the local level, promoting a collaborative approach that integrates community knowledge and resilience into decision-making (Ostrom, 2009; Ribot, 2002). However, despite these advances, limitations remain, including the need to further explore cultural and social variables influencing mitigation strategies (Adger et *al.*, 2005). One proposal to enhance research would be to broaden surveys to include these specific factors, thereby allowing for a deeper understanding of challenges and opportunities in water resource management in the Ikopa watershed.

IV. Conclusion

In conclusion, the comprehensive study of the Ikopa watershed has validated the hypothesis that "responsible exploitation of natural resources contributes to the preservation and sustainability of water resources at the watershed scale." The analysis of anthropogenic risks has identified specific factors such as agriculture and urbanization, providing solid grounds for targeted policy interventions. Furthermore, the assessment of vulnerability has underscored the importance of adopting differentiated approaches for water resource management in densely populated areas.

The assessment of the effectiveness of mitigation strategies has pinpointed beneficial practices, including income diversification and active involvement of local communities. These findings offer valuable guidance for policy interventions and management practices centered around sustainable agriculture, considerate urban planning, and adequate drainage network management.

Finally, while this study makes substantial contributions, it is crucial to acknowledge limitations such as the restricted geographical scope and temporal constraints of the available data. For future research, expanding the study to encompass other watersheds and incorporating more extensive temporal data could enhance our understanding of hydro-environmental dynamics. In summary, this study emphasizes the vital importance of comprehending the interactions between human activities and water resources. It advocates for sustained engagement in monitoring, research, and the implementation of adaptive strategies to ensure a sustainable future for the Ikopa watershed.

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