Geomatics-Based Approach for Detecting Erosion Prone Areas in the High Atlas Mountains, Morocco: A Case Study of the Imini Basin

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Abstract. Water erosion and mud floods create major obstacles to sustainable development in North Africa, particularly within drainage basins rich in natural resources. This study investigates the dynamics of water erosion in the Imini basin, located in the Middle High Atlas region of Morocco. Utilizing a geomatics approach that integrates Geographic Information Systems (GIS) and remote sensing (RS) techniques, we generated detailed maps of slope gradients, lithological types, land use, and vegetation cover. These maps were instrumental in applying the PAP/CAR model, a robust qualitative assessment tool for water erosion analysis. Our results indicate that 47% of the basin is subject to strong erosion, 22% to medium erosion, and 31% to weak erosion. These findings highlight the Imini basin's considerable vulnerability to erosion, emphasizing the urgent need for strategies to enhance land resilience and soil stability. The cost-effectiveness of the employed methods also facilitates their application across larger areas, enabling them to assist decision-makers in sustainable development planning.

1 Introduction

Erosion processes result in the annual loss of approximately 50,000 square kilometers of agricultural land, threatening 40% of arable land and exacerbating the ongoing crisis. The impacts of erosion extend beyond environmental issues; they also affect national economies [1]. Erosion is considered a significant threat to wild and populated areas, influencing global economic and environmental sustainability [2]. To tackle these challenges and promote sustainable development, it is crucial for individuals to safeguard land resources, including water, soil, and vegetation [2, 3]. These natural resources support communities by enabling stable land use and maximizing potential [1, 3]. Interactions with hydrological processes and local ecosystems establish the watershed as a fundamental socioeconomic unit [4, 5]. This

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viewpoint posits that a watershed includes both natural and social systems. Additionally, the capabilities of the watershed compose the primary means to ensure food security. As a result, the watershed is recognized as an independent natural unit that influences societal development based on its inherent potential. Moreover, effective land use within a watershed can enhance food productivity while minimizing environmental impacts [4, 6].

In fact, managing and enhancing watersheds is often facing challenges [3, 4]. The complexity and high costs associated with the management process pose significant obstacles to implementing environmental protection measures. Effective management strategies necessitate collaboration with academic research and technical services providing knowledge and support. Therefore, to adopt suitable techniques, it is essential to comprehend the existing challenges and opportunities within the watershed [7]. Subsequently, basin parameters must be evaluated to characterize and determine the watersheds' sensitivity. In this context, watershed analysis involves prioritizing watersheds based on their immediate need for intervention [6]. The watershed study encompasses the collection and analysis of information regarding the basin's components to identify vulnerable areas and explore management opportunities.

Geomatic aspects are highly effective and adaptable for analyzing basin physical characteristics. These tools facilitate comprehensive spatial data analysis, enabling precise mapping of land features and their susceptibility to degradation. Remote sensing provides helpful information by using high-resolution imagery, which detects changes in land cover and topography over time [7]. Geographic Information Systems (GIS) integrate diverse data sources, including land cover, soil properties, land use patterns, and hydrological models, to produce detailed assessments of environmental degradation. Their capability to manage and extract extensive databases effectively addresses challenges in numerical analysis [3, 4, 5]. As computer technology continues to improve, GIS has become more automated, making it easier to work with large datasets and solve difficult problems. The ability to visualize and spatially analyze these parameters deepens the understanding of land dynamics [5]. Watershed analysis is optimized when basin characteristics are derived from a detailed Digital Terrain Model (DTM), which generates accurate representations of features that reflect real-world conditions [4]. Moreover, the application of geomatic techniques identifies critical areas requiring intervention, informing effective watershed management strategies. This integration not only enhances the accuracy of land degradation assessments but also supports sustainable land-use planning by promoting informed decision-making in resource management [5].

In recent decades, researchers have explored various methods to identify sensitive areas of the watershed. For example, some studies ranked the vulnerability of sub-watersheds based on annual sediment yield, while others employed hydrological modeling for prioritization. Numerous investigations worldwide have focused on detecting vulnerable sub-watersheds through their morphometric parameters. Certain studies have combined morphometric parameters with land use characteristics to obtain more detailed insights [4, 5]. As a result of this extensive research, several models have been developed to assess soil erosion, including FAHP, RUSEL, CPA, EPM, and PAP/CAR [7]. Each model features distinct methodologies and data requirements. According to existing literature, the PAP/CAR model was specifically developed to predict soil loss [8]. It has been effectively applied in various North African countries, demonstrating its ability to predict soil erodibility. This model is especially useful in areas where there is limited data [9,10, 11]. It assesses land features that affect water erosion processes [12].

The PAP/CAR model has been selected for identifying vulnerable lands due to its effectiveness. This model was employed to create soil erodibility maps for the Imini basin, in the High Atlas Mountains. The basin was chosen because of its heightened sensitivity to erosion processes. This model integrates various physical parameters, including lithological resistance, slope gradients, land use, and vegetation cover, to predict areas prone to erosion. The initial step involves generating potential erosion maps. Subsequently, direct observations are necessary to refine these preliminary outputs and improve result accuracy. Our research will evaluate the effectiveness of the PAP/CAR method in pinpointing erosion susceptibility. We will assess the precision of the potential erosion map and its correlation with actual erosion risks. By comparing predicted susceptibility zones with comprehensive fieldwork, we will determine the reliability of the method for detecting vulnerable areas. Additionally, we will analyze the relationship between susceptibility zones and observed erosion features, highlighting the method's strengths and identifying areas for enhancement.

2 . Materials and methods

2.1 Study area

The Imini basin is a sub-catchment of the Ouarzazate watershed, spanning approximately 479 square kilometers across the southeastern slope of the Middle Atlas Mountains. It is bordered by the Iriri basin to the south and west, the El Malh basin to the east, and the Tanssift basin to the north (Figure 1). Administratively, the Imini basin is part of the Drâa-Tafilalet region, specifically within the Ouarzazate province, and includes sections from four territorial communities: Ighrem N'Oukdal, Ait Zinab, Amerskan, and Tidili. The basin showcases a range of elevations, from 3,543 meters at its highest point in Adrar N'Tircht to 1,225 meters at the lowest point where the mainstream exits. Approximately 31% of the basin features steep slopes, primarily oriented towards the south and southeast, which facilitate linear erosion.

Geologically, the study area encompasses lithologies from different geological ages, beginning with the Precambrian, which is predominantly characterized by schist and quartz. Major sedimentation events occurred during the Jurassic and Triassic periods, resulting in the deposition of limestone and dolomite, topped by an impermeable clay layer (Verset, 1988) [13]. During the Miocene epoch, the sediments primarily comprised alluvial materials deposited within the valleys. The region experiences a semi-arid climate that varies monthly and annually, with precipitation often occurring intensely as brief showers. This can lead to rapid water accumulation downstream of the rivers. Additionally, the prevailing hydrological regime is torrential, characterized by sudden and severe floods during the autumn and winter months, alongside weak flows that may persist for several months.

2.2 Methodology

In this study, we employed the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER_DEM) with a 30-meter resolution to generate drainage networks and delineate watershed boundaries using ArcGIS 10.8.2 software. We also collected spatial data from 2023 satellite imagery sourced from Landsat 8. GIS tools and remote sensing technologies were then utilized to create essential maps, including those for slope, elevation, land use, and vegetation cover, which facilitated the analysis of basin sensitivity. Additionally, we utilized topographic sheets at a 1:50,000 scale and a geological map at a 1:200,000 scale, provided by Chouaib Doukkali University, to identify and locate spatial features such as roads, rivers, and lithological types. A field survey was conducted using a Geographical Positioning System (GPS) to supplement and validate selected digital data. The methodology followed the PAP/CAR model, which comprises three interconnected stages [8] (Figure 2).

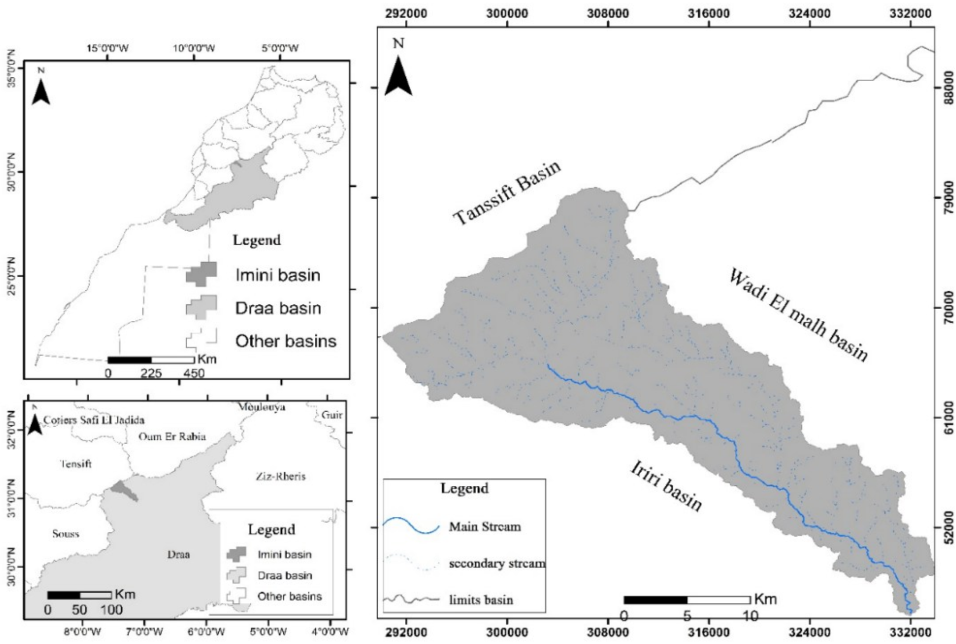

Fig. 1. Study area

The first stage is predictive and involves creating a potential water erosion map by combining an erosion sensitivity layer with a land resilience layer. To develop the erosion sensitivity map, we integrated slope data with lithological information. Conversely, the land resilience map was generated by overlaying land use and vegetation density maps [8]. The vegetation cover map was produced using the NDVI index, leveraging satellite imagery and computational capabilities.

The second stage is descriptive and focuses on identifying the predominant erosion forms in the area [8, 9]. This stage required extensive fieldwork to characterize these erosion forms (Figure 2). We conducted multiple field visits, strategically scheduled to coincide with rainfall events and subsequent post-rainfall conditions.

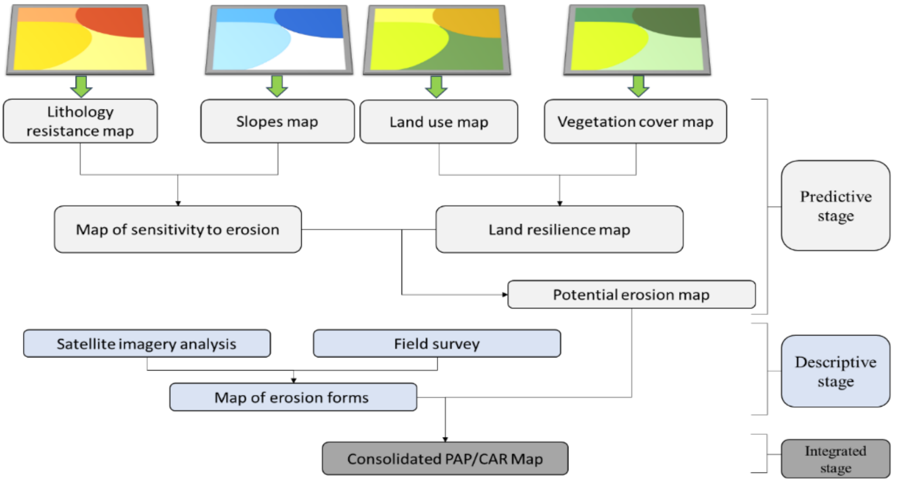

Fig. 2. Methodology stages

The third stage is integrative, involving the overlay of potential information with actual data [8, 9]. In this phase, we connected theoretical predictions with practical fieldwork, giving us valuable information about regions at risk of erosion. As the final step, this stage synthesized findings from the potential erosion map with the actual erosion.

3 Results

3.1 Predictive stage

3.1.1 Sensitivity to erosion

As mentioned earlier, this stage involves identifying areas susceptible to water erosion based on soil sensitivity and land resilience. Our map of sensitivity to erosion was created by overlaying lithology and slope maps, allowing for a comprehensive analysis of the factors contributing to erosion risk. Indeed, the geological formation map reveals various rock resistances to erosion (Figure 3a). In the northwestern and eastern parts of the basin, areas of high resistance are primarily composed of hard volcanic rocks, such as basalt and rhyolite. These regions cover approximately 187 square kilometers, which represents about 39% of the basin's area (Figure 3a). In contrast, moderately resistant rocks account for about 9% of the basin, covering around 42 square kilometers (Figure 3a). Low- and very-low-resistant rocks represent approximately 5% of the basin area and primarily consist of Quaternary deposits along the Imini River and its tributaries (Figure 3a). On the other hand, the slopes map indicates that 57% of the watershed area is characterized by steeper terrain, encompassing about 272 km². Medium slopes make up 18%, while low and very low slopes constitute around 25% of the watershed area (Figure 3, a and b). On these two maps, steep slopes predominantly characterize the upper watershed and the basin's boundary areas, where solid rocks are present. These rigid lithologies effectively limit water erosion, resulting in the formation of steep relief features. In contrast, weak slopes are concentrated in the lower areas, particularly along the talweg lines, which are occupied by softer Quaternary lithologies (Figure 3, a and b).

Furthermore, we conclude that 51% of the Imini watershed area consists of zones with low susceptibility to erosion, while approximately 29% represent regions with very high erosion susceptibility (Figure 3, c). Geographically, these areas with high susceptibility are unevenly distributed across the entire watershed. They are mostly in Ait Nasser, Tourjdale, Angle Ankal, Agrem Noukdale, and the lower watershed. This inequitable distribution can be attributed to the prevalence of steep slopes exceeding 12%, which frequently correspond with low and very low resistant formations (Figures 3a, b, and c).

3.1.2 Land resilience

Overall, the land use map indicates that the Imini watershed is characterized by bare land and weak vegetation cover, accounting for 93% of the catchment area. Approximately 166 km² are classified as highly degraded areas, representing 35% of the entire basin. In contrast, the remaining area comprises only 7%, primarily consisting of seasonal crops and sparse plantations at 6%, while forested areas constitute a mere 1% of the watershed's area (Figure 4a). These values suggest that the watershed is largely unprotected against climatic factors, which may increase water erosion dynamics. Furthermore, the vegetation map reveals significant variability across the basin area. Areas with a high degree of vegetation cover occupy only 3%, while those with a medium degree represent over 60% of the watershed.

This chart demonstrates that the basin vegetation density is very low, leaving the entire basin exposed to erosion processes (Figure 4b).

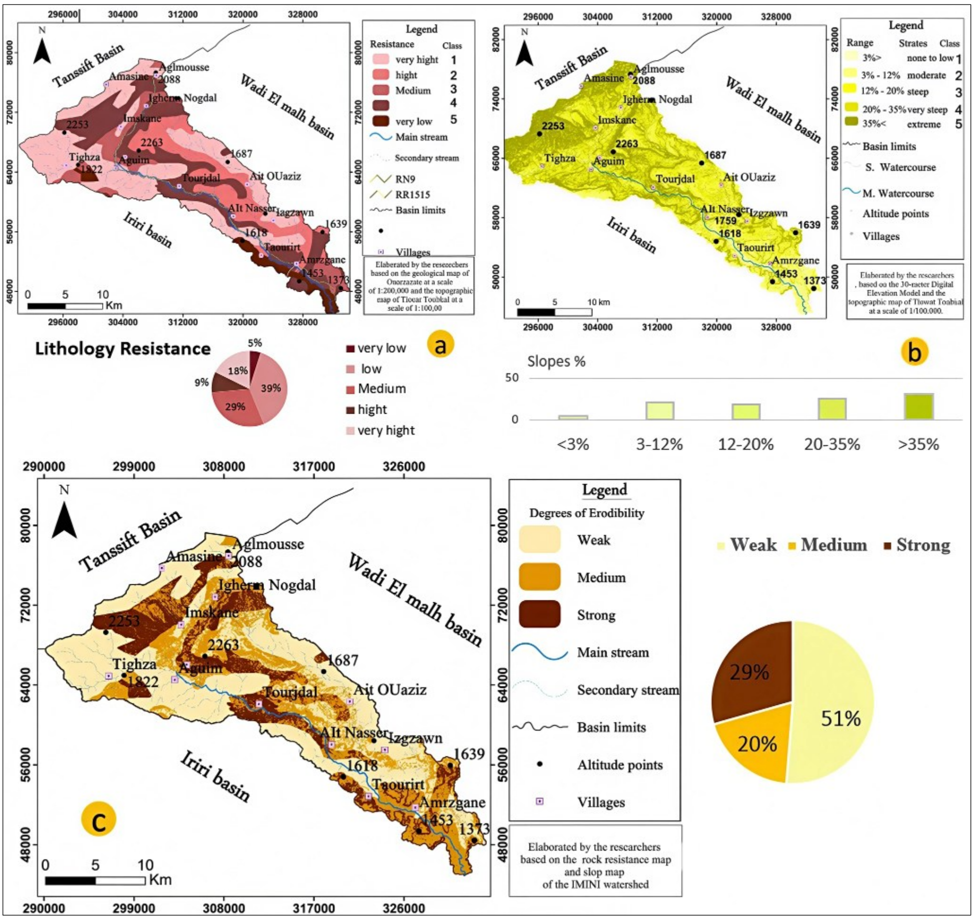

Fig. 3. (a), lithology resistance map of the Imini watershed, (b), slopes map of the Imini watershed, (C), Map of sensitivity to erosion

Moreover, the land resilience map illustrates variation in protection against erosion (Figure 4c). It distinguishes areas with weak protection from those with moderate and high protection. Overall, the map indicates that regions with weak protection dominate, comprising approximately 95% of the basin's area, which amounts to around 455 km² (Figure 4c). In contrast, protected areas account for only 5%, covering an area of 24 km². In terms of spatial distribution, areas with high protection are aligned with agricultural lands and forested regions (Figures 3a and c).

3.1.3 Potential erosion map

The potential erosion map classifies 31% of the basin's area as experiencing very low to low erosion processes (Figure 6a). These regions correspond to areas with gentle slopes and dense vegetation. The other erosion zone constitutes about 22% of the basin and includes areas with less plant cover and steep to moderate slopes (Figures 3b, 4a, and 6a). The strong and forceful erosion zones are the most prevalent, comprising 47% of the total area, which translates to about 224 km². Such areas are characterized by steep and moderate slopes, soft rock formations, and low vegetation cover (Figures 3a, 4a, and 6a).

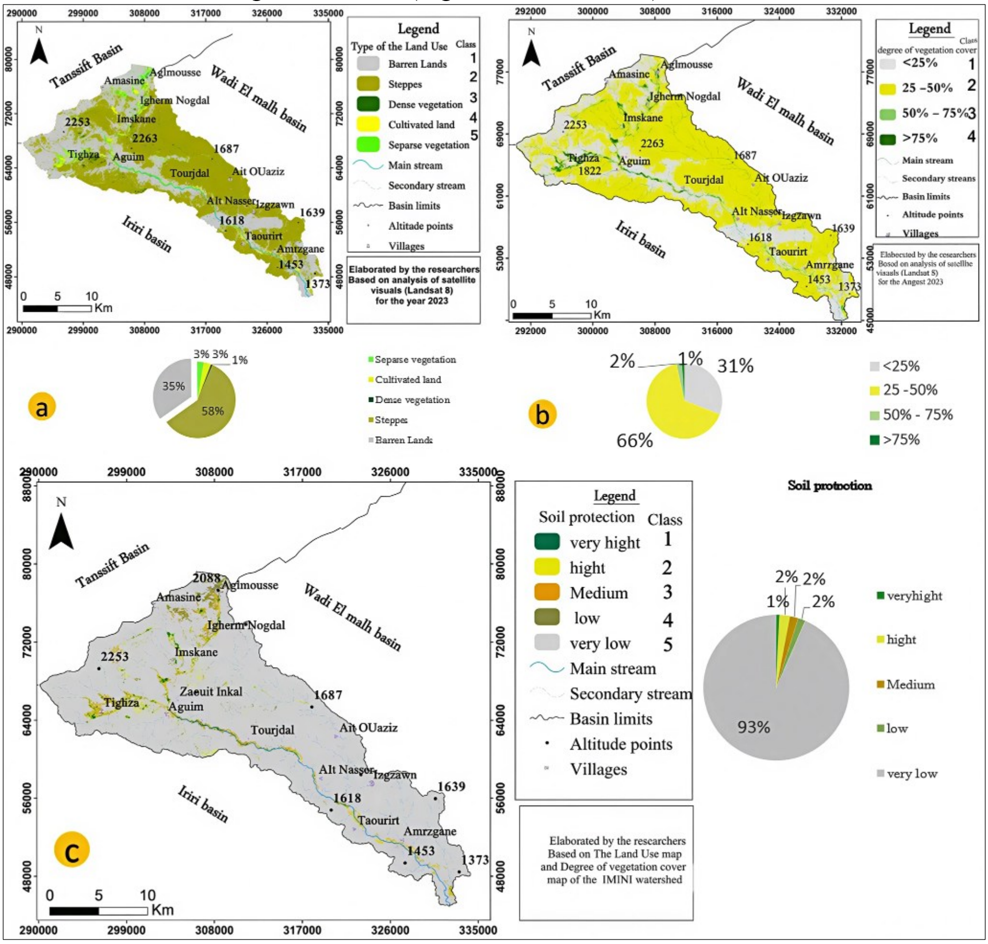

Fig. 4. (a), land use map, (b), degree of vegetation cover, (c), land resilience map

3.2 Descriptive stage

The images below showcase the main forms of erosion observed, while Figure 6b illustrates their spatial distribution. Our field investigation in the Imini basin identified various erosion types, differing in size, shape, and depth. Furthermore, the field survey confirmed and validated the erosion forms initially detected through satellite imagery analysis. These forms result from a combination of multiple factors, such as aggressive rainfall, unprotected land, and lack of anti-erosion practices. Previous research throughout Morocco has highlighted the importance of these erosion dynamics factors. Within the Imini basin, the most common erosion form is gullies, which include both active ones and those in relatively stable states (Figure 5b and c). The second major form is sheet erosion, marking an early stage of linear dynamics (Figure 5a). Extensive studies suggest that if these small forms are not addressed, they can evolve and result in the degradation of soil texture and structure. On the other hand, developed ravines, the rarest form, have the potential to significantly degrade land and create badlands that are typically unsuitable for agricultural use (Figure 5d).

3.3 integrated stage

Our integrated erosion map illustrates a clear relationship between areas highly susceptible to erosion and those frequently undergoing erosion processes (Figure 6a, b, and c). These regions exhibit pronounced topographical changes and major soil loss, underscoring their vulnerability to continued land degradation. Conversely, areas defined by surface dynamics; indicative of relative stability and resilience, align with regions at low risk of erosion (Figure 6a, b, and c). Field investigations indicate that the size and shape of linear erosion features are primarily influenced by vegetation cover, which serves as a protective barrier against erosive forces. Steeper slopes intensify gravitational forces, thereby stimulating soil movement. Furthermore, lithology characterized by low resistance exacerbates erosive processes, contributing to the overall degradation of these areas.

Fig. 5. Erosion forms found during field work, (a), surface erosion, (b), gullies relatively in stable state, (c), active gully, (d), badlands

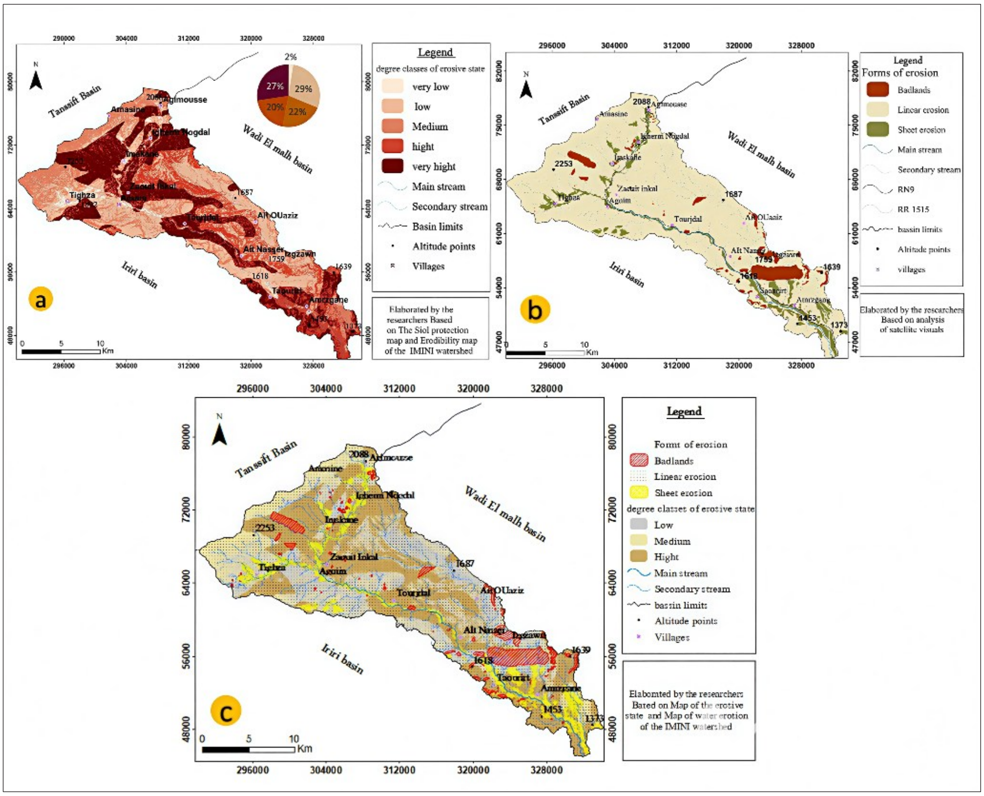

Fig. 6. Erosion maps elaborated in the Imini watershed, (a), potential erosion map using Gis tools and remote sensing, (b), erosion map based on satellite imagery analysis and field investigations, (c), integrated map of erosion by combining potential data, satellite imagery information, and field survey

4 Discussion

The results deduced by the PAP/CAR method within the Imini watershed emphasize the principal factors influencing erosion dynamics. The findings indicate significant vulnerability, with over 90% of the basin area exhibiting erosive factors. This high vulnerability can be attributed to the combination of steep slopes and soft rock formations, as 75% of the basin's characteristics align with these conditions. The identification of approximately 30% of the watershed as highly susceptible to erosion highlights critical zones that require targeted conservation efforts. The analysis of land resilience reveals a concerning lack of vegetation cover and the presence of highly degraded areas, which diminish the watershed's capacity to withstand erosive forces. The potential erosion map, indicating that nearly half of the basin is subject to strong erosion processes, emphasizes the urgent need for effective land management strategies. The prevalence of gullies and sheet erosion, as confirmed by field investigations, further underscores the necessity for immediate interventions.

These findings can serve as a framework for stakeholders to implement effective erosion control measures, including reforestation and sustainable land use practices. Such erosion mitigation strategies are instrumental in reducing water runoff and stabilizing soil, thereby enhancing land resilience [3, 9, 10]. Active participation from local communities, governmental organizations, environmental NGOs, and researchers is essential to achieving sustainable development within a basin area. Local communities can engage in forest restoration and adopt land management techniques, while government agencies can formulate policies and allocate resources for erosion control initiatives. NGOs can play a vital role in facilitating education and awareness programs, promoting a collaborative approach to conservation. Furthermore, researchers can continue to monitor and assess erosion dynamics, contributing to the refinement of strategies and ensuring their long-term effectiveness. Collectively, these efforts are key to creating a sustainable and resilient watershed environment in the Imini basin.

5 Conclusion

The geomatic aspects effectively identify areas prone to erosion. Remote sensing and Geographic Information Systems (GIS) facilitate the extraction of essential parameters for processing the PAP/CAR model. These technologies integrate derived data with field surveys to accurately assess land sensitivity to erosion. This study demonstrates the importance of advanced methodologies in improving watershed management practices. The precision in detecting vulnerable regions and evaluating erosion susceptibility highlights the method's value in environmental research. Findings reveal diverse classes of erosion within the watershed, with some areas classified as "Very High Degree" due to significant degradation risk. Conversely, other regions are categorized as "Very Low Degree," indicating resilient land with stable soil. This classification provides a framework for resource allocation and strategic planning, emphasizing targeted interventions in high-risk zones. To enhance the erosion mapping process, future research should incorporate high-resolution satellite imagery and LiDAR data. Additionally, the method may be supplemented with ground-truthing techniques, such as soil sampling and water quality analysis, to validate findings and improve result reliability.

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