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ORIGINAL RESEARCH ARTICLE

Geomorphology of the Guacimal River catchment, Costa Rica

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ABSTRACT

The Guacimal River catchment has an area of 181 km^2 and is located in the NW of Costa Rica, between the coordinates 84.745° W-10.016° N and 84.909° W-10.325° N. In this territory, as in most of the country, detailed geomorphological studies are scarce; therefore, the objective of this paper is to present the geomorphological mapping at a scale of 1:25,000 of the Guacimal River, which allows us to explain the dynamics of the agents involved in the modeling of the catchment. The work methodology consisted of three stages: pre-mapping, field activity and post-mapping, which resulted in a map in which ten relief forms are represented, ordered according to their morphogenesis in endogenous modeled and exogenous (fluvial, gravitational and littoral). This document will be the base line for land use planning, both continental and coastal, and for local risk management.

Keywords: Geomorphology; Dynamics; Morphogenesis; Landforms; Mapping

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1. Introduction

Geomorphological mapping comprises a group of techniques that allow the evaluation of the terrain, considering aspects such as landforms (morphology), processes and forming agents, as well as the materials that constitute the relief of the Earth's surface. In general, geomorphological maps can be identified in three types: the first consists of the elaboration of regional base surveys for land use planning and environmental impact management at scales of 1:25,000 or higher. The second are general geohazard or natural resource management maps at scales between 1:10,000 and 1:50,000. The third type is associated with geomorphological mapping with a specific objective to delineate and categorize particular landforms[1]. Geomorphological maps should contain all the basic elements of representation (morphography, morphometry, genesis and age of the relief) and can be classified thematically as morphostructural, morphometric, morphographic, morphogenetic, morphochronological, and morphodynamic[2,3].

Advances in geomorphological mapping prior to the 2000s were not really very new, because detailed mapping was time consuming and costly, and the focus was on specific themes or applications rather than holistic and scientific maps[4]. On the other hand, in recent years there has been a growing body of research involving spatio-temporal databases, GIS technology and modeling of various aspects of geomorphological systems to solve conceptual and practical problems such as natural hazard modeling, landscape evolution, shape relationships, geomorphic processes and patterns, and digital geomorphological mapping[5,6].

In many countries of the world and Latin America there are geomorphological maps from national scales (small scales at 1:1,000,000), regional scales (medium scales such as 1:200,000) and even detailed or large scales (1:25,000 or higher), according to the base cartography of each country[3]. In the case of Costa Rica, there are maps for the whole country at small scales of 1:1,000,000[7], medium scales of 1:350,000 and 1:100,000[8–10], and few at large scales of 1:50,000 [11,12]. However, there is no geomorphological mapping at 1:50,000 scale for the whole country (base mapping), in addition to very few maps at scales 1:25,000 or larger[13–21]. This absence of detailed geomorphological cartography for Costa Rica creates the need to generate new maps that integrate the variables of genesis, formation processes, morphology, evolution and age of the relief, at scales that can be useful as instruments for land-use planning and risk management.

Costa Rica is a country influenced by both endogenous and exogenous agents; while the former are governed by tectonics and volcanism, the latter by solar radiation, gravity, hydrometeorological events and human beings[22]. Given these tectonic, geological, geomorphological, climatological and even ecological conditions, the country is considered a political-administrative unit with intense geodynamics both internally and externally, which constantly shapes its relief through natural processes that could become dangerous for the population. Currently, in the absence of effective land use planning in the country, factors such as the growth of the percentage of urban vs. rural population, as well as the urban pressure that this generates, the change in land use and overuse, the demand for services and public and private infrastructure, water vulnerability with the contamination of surface and groundwater, as well as the development of rings of poverty and slums must be added[23,24]. Practically 90% of the incidences and records of disasters in the last four decades for Costa Rica are associated with floods and landslides[24,25].

Therefore, the need to develop detailed geomorphological studies for baseline studies for the environmental viability required to grant endorsements for cantonal (municipal) regulatory plans, as a necessary input in the process of land use planning at the local level in the country[24]. On the other hand, it is imperative to use detailed geomorphology to determine the areas susceptible to floods and landslides, since it favors risk management based on susceptibility models and probability of occurrence of hazardous processes. The objective of this work was to carry out geomorphological mapping at a scale of 1:25,000 of the Guacimal River catchment, which is accompanied by an analysis of the physical-geographical characteristics that explain its morphological dynamics, and of each of the mapped landforms based on their tectonic, gravitational and fluvial morphogenesis.

2. Physical-geographical characterization

The Guacimal River catchment is a complex territorial unit in a reduced geographic space, with an extension of 181 km^2, located in the NW of Costa Rica, between the coordinates 84.745° W 10.016° N and 84.909° W 10.325° N. This territory presents diverse types of lithology, in addition to tectonic, geomorphologic, hydrographic, edaphic, and land use changes in an intense dynamic that model this relief in multiple ways, given the tropical characteristics of climatic and ecological transition between the Central Pacific and Northern Costa Rica. This catchment is located on the Pacific slope, specifically in the Puntarenas canton, and its three main tributaries are the San Luis, Veracruz and Acapulco rivers, forming the Guacimal River that flows into the Gulf of Nicoya (**Figure 1**).

The endogenous and exogenous dynamics of the Guacimal watershed are explained based on a physical-geographical analysis of the variables that compose it, and make it a region with a constant modeling of its morphologies, processes that could be dangerous for the population intervene. The characteristics studied were geology, precipitation, soils, vegetation and land use. In this sense, the geology of the study area is composed of several formations, lithodems and geological groups, which have been studied by the Directorate of Geology and Mines (DGM) in conjunction with the Czech Geological Survey[26,27]. The formations that make up the catchment are Monteverde, Aguacate Group, Punta

Carballo, Descartes, San Buenaventura, Bagaces and Quaternary fluvial deposits[28].

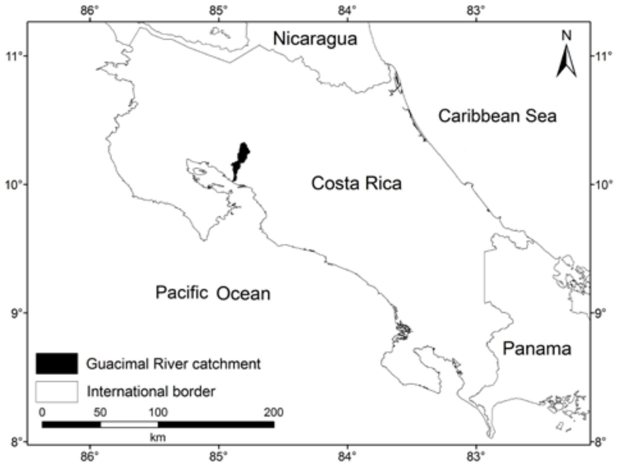

Figure 1. Location in the regional context of the Guacimal River catchment.

The Monteverde formation of Lower Pleistocene age, is mainly located at altitudes above 1,000 masl; it corresponds to the upper parts of the Tilarán mountain range and is composed of fresh andesitic to andesite-basaltic undisturbed lavas; in smaller quantities there are pyroclastic rocks (breccias and tuffs) and lahars deposits[28]. The Miocene-Pliocene Guacimal Granite-Gabbro formation is located at northwest of the study area and outcrops as an intrusive body of granites, quartz monzodiorites and gabbros[29]. The Aguacate Group, of Miocene Pliocene age, is part of the ancient volcanic arc composed mainly of basaltic to basaltic-andesitic lavas, pyroclastic rocks, breccias and subordinate volcanoclastic sediments; its origin is eminently volcanic, both extrusive and intrusive, related to fault zones or intrusions that give rise to hydrothermal alteration of regional character[28,30]. The Holocene fluvial sediment deposits correspond to the marine-coastal transition part, with depositional formations during recent periods; they are mainly composed of fluvial deposits, sands, gravels and blocks, in which a sedimentation regime fed by material coming from the fluvial system predominates[30].

According to the climatic classification of Costa Rica by Solano and Villalobos[31], the Guacimal River catchment belongs to the Tropical Pacific Region; part of the area of this catchment corresponds to the Central Subregion of the North Pacific (SCPN), and another part coincides with the Western Subregion of the Nicoya Peninsula (SOPN). The first portion has a total annual rainfall of up to 1,800 mm, while the second reaches 2,385 mm, which contributes to lush vegetation, especially in the SOPN.

The distribution of the soils is explained by the parental material that gave rise to them, basically a Miocene volcanism that has developed deep weathering crusts containing ultisols, practically throughout the catchment. In the higher altitude areas, there are small sectors where ultisols predominate, while the entisols are linked to fluvial activity and the rejuvenation of the parent material. Inceptisols are found in the lower catchment and in the town of San Marcos; here the weathering processes have a moderate intensity[32].

Vegetation is determined by Holdridge's classification of life zones, based on variables such as altitude, temperature and humidity. In the upper and middle part of the catchment, there are low montane rainforests, very humid low montane, very humid premontane, humid premontane and humid tropical forests. In the lower part of the catchment, there are tropical humid transition to dry and premontane humid forests with basal transition[33]. In the lower catchment, near the mouth of the Guacimal River, there is mangrove forest in the transition between the continental part and the Gulf of Nicoya. This forest is composed of five mangrove species: red mangrove (*Rhizophora mangle*), salt mangrove (*Rhizophora racemosa* and *Avicenia germinans*), piñuela mangrove (*Pelliciera rhizophorae*), and the mangrove mariquita or *Laguncularia racemosa*[34,35].

Land uses in the catchment are varied and are developed according to its altitude, geomorphology, soil types and climatic conditions[36]. The predominant uses of the watershed are secondary forests and pastures. On the other hand, other uses such as primary forest, rice cultivation, coffee, sugarcane, forest plantations, charral and tacotal, wetlands and urban areas are dispersed and in small extensions. Livestock and shrimp farming are also developed.

3. Methodology

The development of the geomorphological mapping of the Guacimal River catchment was based on three phases: pre-mapping, field work and post-mapping[36]. The pre-mapping phase identified the region of interest and the purpose of the map. Remote sensing information was obtained (for this work we used the Quick Bird 2013 satellite image, scale 1:5,000), as well as geological[27,28,37–39]; and edaphological information[32].

As a first step, all the rivers and tributaries of the catchment were digitized in order to have a better knowledge of the erosive/accumulative characteristics of the study area. An initial legend was prepared based on a morphogenetic classification[2,40,41], which separates the landforms according to their origin into endogenous, endogenous modeled and exogenous; the preliminary geomorphological map was made from this legend. Subsequently, the relief forms were digitized based on an interpretation of aerial images (i.e. aerial photographs or satellite images), in this case the QuickBird satellite image (2013). Subsequent analysis resulted in the initial geomorphological map, which was corroborated in the field.

In the next stage, a geospatial database was designed with all the variables organized in a geographic information systems program (digitized rivers, geology, landforms, towns, roads, and others), and a preliminary fieldwork map was constructed at an appropriate scale (1:25,000). A fieldwork sheet was then created with relevant information for each geoform: slope, cover, dominant processes, soil type and anthropogenic activities that could modify the local dynamics. All the necessary permits were also requested, as well as access to the places of geomorphological interest, and the geomorphological survey was carried out.

During the fieldwork phase, the routes to be used were delimited at times and distances consistent with the work plan. A satellite navigation device was used to mark the routes and points of interest. The cards prepared in the previous phase were completed, in which the consecutive numbers of the photographs taken for each point of interest were also noted. Field work was optimized to include a large number of landforms, especially those that generated doubts in the preliminary cartography.

The post-mapping phase involved downloading the information from the satellite navigator and processing it in the pre-existing database. The field data were compared with the preliminary results of the analysis of the remote sensing information (aerial photographs and satellite images). On the other hand, the photographs containing the forms, processes and dynamics corroborated in the field were integrated, and in parallel, a description of each of the relief forms was begun, based on the morphogenetic classification made in the first preliminary legend, as an aid to the analysis of the study area. Finally, the final geomorphological map was edited and published, accompanied by a legend containing colors according to their genesis, dynamics, morphology, evolution and age[4]. The output scale, given the extension of the catchment and for reasons of space in this paper, for the final product was 1:200,000.

4. Results and discussion

Geomorphology is explained on the basis of the morphogenetic classification of landforms, whose origin can be “endogenous”, “endogenous modeled” and “exogenous”[2]. Those of endogenous origin develop from the internal dynamics of the Earth and its representation on the surface of tectonic and volcanic processes that keep their original morphologies. The modeled endogenous character is linked to geoforms that have been modified by exogenous agents and that still keep some characteristics of the original endogenous relief. On the other hand, relief forms of exogenous origin are those that have been modeled entirely by exogenous agents: water, ice, sea forces, wind, dissolution of carbonate rocks and gravity.

The morphogenetics of the Guacimal River catchment includes reliefs of endogenous origin, modeled by volcanism configured by fluvial and Miocene mass removal processes, as well as tectonic geoforms modified by gravitational and fluvial dynamics. On the other hand, with an even wider development in its extension, the morphologies of exogenous origin have been generated by fluvial dynamics, product of a tropical rainfall pattern that hovers around or even exceeds 2,000 mm per year, in addition to changing temperature conditions throughout the day that favor physical and chemical weathering processes, forming extensive weathering crusts (weathering profiles). In addition to the regional climatological conditions of the catchment, there are particular characteristics of slopes, weathered substrates and the presence of disjunctive structures (including faults, fractures and diaclases), which favor the development of mass removal processes that shape the slopes of the upper and middle catchment. The inventory of landforms carried out explains each of the morphologies based on their endogenous modeled and exogenous origin, which facilitated the analysis of the particular characteristics of genesis, morphology, dynamics, evolution and age of the landforms that make up the catchment (**Figure 2**).

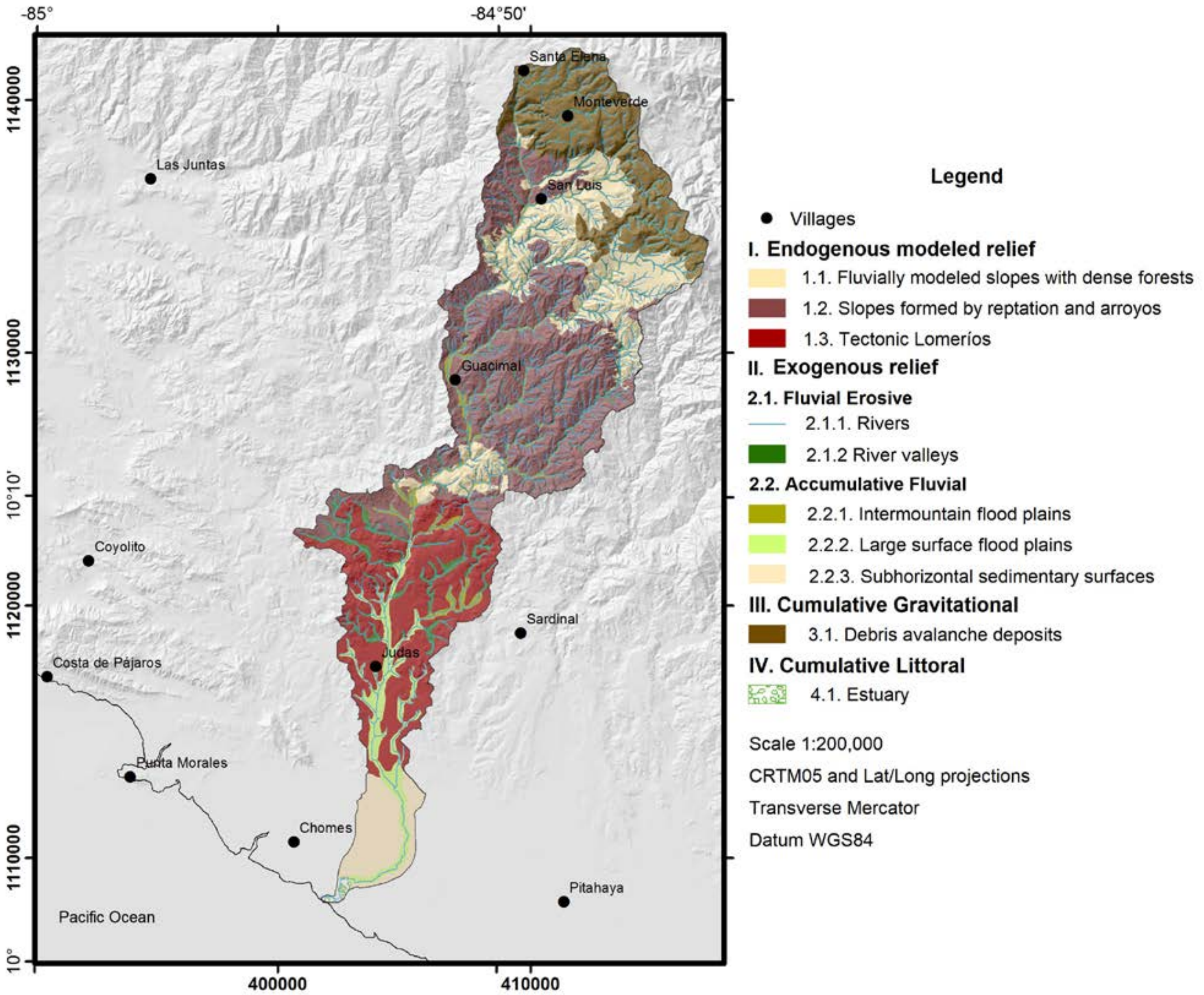

Figure 2. Geomorphology of the Guacimal River catchment.

4.1 Endogenous modeled relief

These are morphologies inherited by volcanic dynamics or generated by regional tectonics[42] that have been modeled by exogenous agents and are composed of three geoforms: mountain slopes of volcanic origin modeled by fluvial action with forests, mountain slopes of volcanic origin configured by hillside processes with pastures, and tectonic hillsides modeled by fluvial and gravitational action.

The slopes modeled by fluvial action with forests are located in the mountain zone; they have a volcanic origin dating back to the Miocene and form the regions with the highest slopes and altitudes in the study area (**Figure 3a**). These slopes are concave and straight with a high density of forests that confer certain apparent stability on soils that are highly weathered from this igneous material (**Figure 3b**). Precipitation in the regions associated with these morphologies easily exceeds 2,500 mm per year, which explains their morphologies of well-developed canyons and V-shaped valleys, a product of erosion and its alternation with sporadic slope processes such as landslides and slides that occur during periods of extraordinary rainfall or due to the effect of local and regional seismicity. The density, as well as the depth of the dissection, is high, as a result of the presence of disjunctive structures such as faults and fractures, slope and continuous geomorphological evolution, from ancient volcanic cones reduced to their relict stage, even volcanic necks can be observed in the middle catchment.

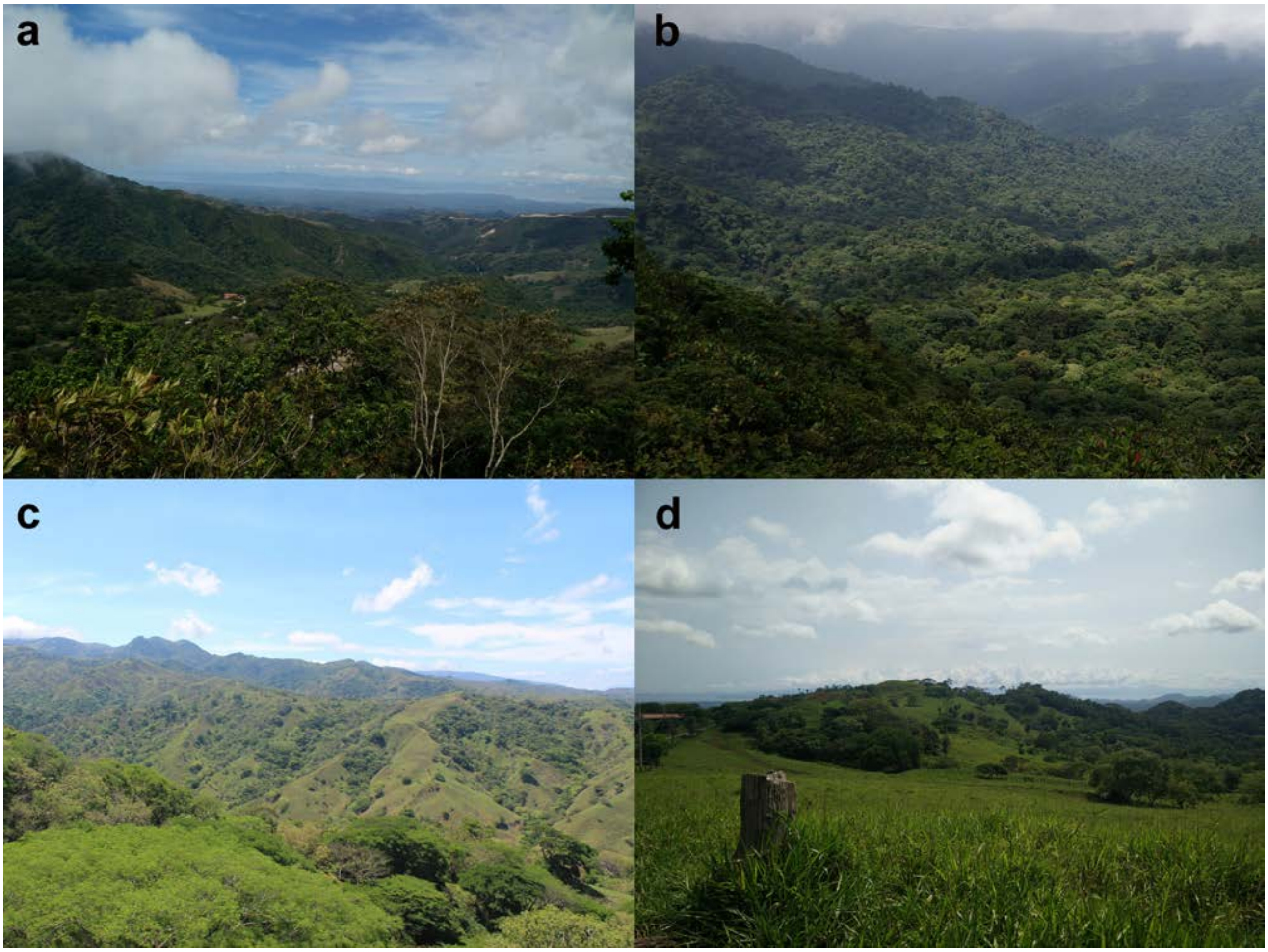

Figure 3. Endogenous modeled reliefs: (**a**) panoramic view from the upper part of the watershed; (**b**) slopes modeled by fluvial action with forests in the Monteverde Biological Reserve; (**c**) slopes configured by reptation and creeping; (**d**) tectonic hillsides.

These morphologies are characterized by wide V-shaped valleys, slopes of more than 45°, and highly altered edaphic material, as a result of the weathering of the materials contributed by constant slope movements, especially reptation and stream, due to intense surface and subsurface runoff (**Figure 3c**). These vulnerable conditions of the slopes are explained by changes in land use from forest to pasture and agriculture, especially during the last 100 years. The usual process of degradation of these landforms begins with the generation of arroyos that erode the surface layers of the soil which, in their most advanced stage, cause creeping; subsequently, furrows are created, which, if they continue to grow, could develop gullies or even badlands. It is important to emphasize that these areas are the ones that present the greatest number of hillside processes such as landslides and landslides that can constantly affect the road network, aqueducts, electrical and telephone networks of the catchment.

The tectonic hills are a group of hills not exceeding 300 m of relative relief, located in the middle catchment of the Guacimal River, which are modeled by fluvial and gravitational action (**Figure 3d**). Their location and origin are due to sedimentary materials from the Miocene and Plio-Pleistocene that have been deformed by the action of a transcurrent dextral fault[27], which generates a series of shutter ridges or compression domes, product of the tension/pressure generated by one block with respect to the other in its relative movement. These morphologies mark the transition between the upper and lower catchment, since there are no alluvial fans or a developed piedmont, what describes the middle catchment are these tectonic ridges, which have smoothed slopes, with concave slopes which, in some cases, have semi-flat surfaces on their summits. At present, vast extensions of these landforms are used for extensive cattle ranching (pastures) and, to a lesser extent, for forest protection, which causes these geoforms to suffer from creeping processes and, in some cases, other types of mass movements such as landslides.

4.2 Exogenous relief

The exogenous reliefs present are fluvial, gravitational and littoral. The first ones concentrate fluvial valleys, flood plains and subhorizontal sedimentary surfaces; on the other hand, the gravitational reliefs concentrate a large sector of a debris avalanche and other types of particular mass movements such as landslides, landslides and flows, and the littoral reliefs only consist of the land-sea transition defined by an estuary.

Fluvial reliefs are composed of morphologies that are mostly due to erosional processes and those in which sedimentation dominates their dynamics[43]. Erosive fluvial reliefs are composed of rivers and fluvial valleys (in V); the former is located throughout the Guacimal River catchment and tend to have very different drainage patterns or architectures, depending on tectonic, lithological and slope conditions. In the mountain zone, dendritic and subdendritic drainage patterns dominate, especially near the towns of Monteverde, Santa Elena, San Luis and Guacimal. In the transition to the middle and lower zones there are rectangular drains associated with the tectonic hills associated with the diaclases and faults that exert structural control. In the flood plains and subhorizontal sedimentary surfaces, accumulation forms dominate with parallel, braided and meandering patterns, the latter in the vicinity of the mouth with estuary morphology in the Gulf of Nicoya. On the other hand, the fluvial valleys are located in the mountain zone and in the fluvial headwaters of the tectonic hills, both in the high mountain zone and in the middle part, respecting the drainage patterns drawn by the rivers from their tectonic, structural and exogenous modeling control.

The cumulative fluvial reliefs are represented by flood plains (intermontane and broad-surface) and subhorizontal sedimentary surfaces. The intermontane floodplains mark an important change in slope between the fluvial valleys and mountain slopes, which indicates a deposition process predominantly on slopes of less than 15°, starting from the Guacimal settlement in the middle-upper catchment; their development is associated with the slopes modeled by reptation and stream, which is linked to an enormous contribution of sediments from the erosion of these adjacent morphologies. On the other hand, flood plains with wide surfaces (**Figure 4a**) define slopes of less than 2°, in which seasonal and extraordinary flooding processes occur, which could even affect human activities on the banks of the bodies of water; it is important to take into account that these morphologies begin when the change in slope of the terrain descends considerably and the width of the alluvial plains increases; their location includes communities such as Judas de Chomes and extends to the estuary and Coco beach. Subhorizontal sedimentary surfaces (**Figure 4b**) are morphologies with slopes less than 2° that define large alluvial plains and mark the most depressed part of the Guacimal River catchment; in these areas it is common to develop sugar cane, pineapple and pasture crops, taking advantage of the fertility of these nutrient-rich alluvial soils.

The gravitational relief consists basically of a segment of the deposits of an ancient debris avalanche, associated with andesites and lahars of the Monteverde formation, which in turn draws its margins near the communities of Santa Elena, Monteverde and around the Monteverde Biological Reserve. They are reliefs softened by the emplacement of poorly classified material, which originally were sediments that varied from sands to angular megablocks, which have been highly weathered by heavy rainfall and temperature changes in the region, which has favored the development of deep weathering crusts (weathering profiles), and soils that harbor a high ecological diversity and have a slight apparent stability of their slopes.

The coastal relief only highlights the development of an estuary (**Figure 4c**), a morphology that outlines the land-sea transition, in which fluvial, tidal and wave dynamics alternate. This geoform has particular edaphic characteristics, with constantly flooded soils in anoxic conditions, covered by highly biodiverse mangrove vegetation, which also provides important ecosystem and functional services such as carbon sinks and barriers against storms that may affect the coasts[44].

Figure 4. Exogenous reliefs: (**a**) broad floodplains; (**b**) subhorizontal sedimentary surfaces; (**c**) estuary: mouth of the Guacimal River in the Gulf of Nicoya, providing fresh water to the Chomes Mangrove.

5. Conclusions

A geomorphological map was developed with ten landforms classified as endogenous modeled and exogenous (fluvial, gravitational and coastal). This map at a scale of 1:25,000 is an instrument that facilitates the understanding of the geoforms that make up a catchment that marks an intense transition between mountainous zones, in which fluvial-gravitational modeling dominates towards a middle catchment with a predominance of the tectonic effects of a system of transcurrent faults that model the lomerios that function as the transition between the upper and lower parts of the catchment; on the other hand, the lower zone is drawn from the development of broad flood plains, subhorizontal sedimentary surfaces and the estuary that mark the boundary with the Gulf of Nicoya as well as the Pacific Ocean. The understanding of the geomorphology of the Guacimal River catchment requires not only a description of the relief forms that characterize it, but also the explanation of its dynamics from its morphogenesis, the architectures as well as its resulting morphologies and how it has evolved over time, specified in its relative ages.

The absence of geomorphological maps at detailed scales such as 1:25,000 or higher in Costa Rica, make this study a novel contribution to the understanding of the relief forms of watersheds, with a rapid transition and intense dynamics between their mountainous areas and their mouths. In addition, the scarcity of detailed geomorphological cartography increases the backwardness in fundamental issues such as land use planning and risk management in a country with severe problems in the planning of its territory and constantly affected by earthquakes, volcanic eruptions, hydro-meteorological phenomena such as storms, volcanic eruptions and volcanic eruptions, hydro-meteorological phenomena such as tropical storms (tropical cyclones and low pressure systems), cold fronts, easterly waves and the Intertropical Convergence Zone, which can generate disasters that impact the population directly or indirectly, but with high intensity. On the other hand, the knowledge of the forms and processes of the relief also has an added value for the regulation of the territory, explanation of the ecosystems and the great biodiversity of one of the most important tourist destinations in the country, such as the area of Monteverde and Santa Elena.

Conflict of interest

The author declared no conflict of interest.

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