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Application of Hydro-Based Morphological Models for Environmental Assessment of Watersheds

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Abstract: Hydro-based morphological models are representations of the terrain related to the flow or storage of water in the landscape. However, their application in the context of an integrated environmental assessment has been scarcely explored in the literature, despite the well-known importance of water for ecosystems and land use planning. Here, we derive the HAND and TWI models, which present solid conceptual bases based on water–landscape relationships from digital terrain models. We aim to present these models as useful representations in the environmental assessment of watersheds as they are relatively easy to generate and interpret. To this end, we applied these models in a Brazilian watershed and evaluated their spatial and reciprocal occurrence in the hydrological landscape through geographic entities and their spatial relationships with other landscape elements such as land use. We argue that HAND and TWI are simple hydrological-based models with robust premises that can reveal intrinsic relationships between relief parameters and water, providing new perspectives for the environmental assessment of small watersheds. Their outcomes have tremendous implications for land management initiatives. Our results show that geometric signatures of the TWI appeared through all the structural units of the hydrological landscape. The plateau areas were most prone to water accumulation/soil saturation, followed by floodplains, hillslopes, and ecotones. Thus, there is a tendency for the greatest geometric signatures of water accumulation/soil saturation entities to be located near the higher-order channels as well as the greatest geometric signatures of the floodplains. Agriculture and planted forests increased with distance, while the areas occupied by forest remnants tended to decrease within a range of up to 50 m from channels. However, they were also found within 50 m around the springs, whereas open fields, urban areas, and water bodies remained stable. We argue that HAND and TWI are simple hydrological-based models with robust premises that can reveal intrinsic relationships between the relief parameters and water, providing new perspectives for the environmental assessment of small watersheds whose outcomes have tremendous implications for land management initiatives.

Keywords: HAND; topographic wetness index; land use; hydrological landscape; topographic footprint; geometric signature

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1. Introduction

The relief records information about the topographic evolution dynamics, and its geomorphometric study can be applied for different purposes such as hydrological, geomorphological, and landscape analysis [1,2]. Interestingly, geomorphometric records are also helpful for ecosystem management applications, land use planning as well as the assessment and perception of risks [3], besides landforms and soil mapping, modeling the occurrence of landslides, and hazard mapping in steep terrains, erosion, and deposition, mass balance modeling on glaciers and hydrological applications involving channels and floodplains [4].

This study's motivation comes from natural hazard mitigation in several watersheds in Southern Brazil caused by the incorrect use of landscape such as removing vegetation in permanent preservation areas and constructing residences in areas prone to flooding events. We argue that the link between relief and water can be explored through spatial representations that provide parameters on water action in the environment simply and rapidly without using complex cascade models. This aspect is fundamental in any environmental analyses since anthropogenic interferences are highly conditioned by the water in the landscape, possibly resulting in problems such as supply, natural disasters, pollution, and diseases. Thus, the hydrological landscape [5] plays an important role in the environmental assessment of watersheds as it relates the physical space's structural units with the water's dynamics in that environment.

This paper aims to explore the so called topographic wetness index (TWI) [6] and the height above the nearest drainage (HAND) [7–9] models as another layer of information about the geomorphological agents that condition the anthropogenic activities in the structuring units on the landscape. Such knowledge may support environmental analysis in land management initiatives and improve the structuring of the problems and the consequent search for solutions. This work contributes by bringing these hydro-based morphological models from their single dimensions [7,10–21] to the context of the environmental analysis of watersheds. Thus, a hypothesis was formulated that the combined use of HAND and TWI models allows for even better characterization of the landscape and benefits land management initiatives. Such models can help identify the different geomorphological strata that form the landscape such as water accumulation zones, hillslopes, and plateaus, with reflections in land use planning to preserve sensitive ecological zones and prevent the occurrence of disasters caused by floods, extreme runoffs, debris flows, and mass movements.

In this paper, we briefly describe the conceptual approach in Section 2. Section 3 is divided into two subsections, where the first refers to the study area description. Then, the steps related to land use map generation are provided. Next, the DEM datasets and their processing steps are described. The three forthcoming subsections detail the determination of both the HAND and TWI models and the adopted data strategy analysis. Finally, we present and discuss the results of both the HAND and TWI models by thoroughly considering the landscape characterization.

2. The Conceptual Approach

The environmental assessment of watersheds seeks to identify, formulate, and structure the problems through data, information, and knowledge concerning the problem domain. It comprises the intelligence stage of a decision-making process [22] regarding planning anthropogenic activities in the watershed. The more elaborated this stage is, the better the chances of generating choices of viable solutions and of choosing the best possible alternative.

Chorley and Kennedy [23] mentioned the systems approach concept's applicability in analyzing complex geographic systems in which watersheds are the most viable research unit. In this approach concept, the watershed comprises two subsystems: the cascade and morphological systems. The cascade system represents the dynamic portion of the watershed, in which the state of the entities that compose it changes frequently. It is part of the system where the flow of matter or energy occurs such as the hydrological cycle and the movement of people and animals in its most diverse manifestations [23].

On the other hand, the morphological system represents the static part of the system, represented by entities in which the attributes of position and conformation do not frequently change such as the drainage network, the sub-basins (or small watersheds), and the relief itself. These entities are sometimes called features [23]. Both cascade and morphological systems are modeled by their strategies. In the case of cascade systems, mathematical models are used, called scientific models [24]. In the case of morphological systems, their modeling occurs through database modeling techniques, the most frequent of which is object orientation [25]. Spatial decision support systems (SDSS) [24,26,27] would be the technologies that deal with this conceptual universe; geographic information systems (GIS) [25], for example, a type of SDSS that works on the morphological portion of the geographic system.

The socio-economic and environmental consequences of population growth are a tacit finding for many watersheds subject to anthropogenic occupations, especially in developing countries where police and monitoring initiatives are inefficient and ineffective. In addition, houses and buildings near watercourses and springs can worsen water pollution and soil erosion, as they often lack permission from the local authorities. These structures are also associated with an increased risk of natural disasters.

These events are commonly caused by an evident lack of planning and non-continuity of occupational policies by public managers in developing countries [28,29]. All these issues may bring complexities to the system involved, together with the particular idiosyncrasies of each site, making a complete understanding of the problems and the search for their solutions challenging [30–33].

A watershed represents an environmental (geographical, hydrological, and ecological) system where topological relationships emerge, subject to being mapped through a collection of continuous geometries [34], sometimes perceived with distinct patterns, abstracted through discrete parameters, at an appropriate degree of completeness for interpreting and describing the processes and functions of these systems [35]. Watersheds are arrangements of spatial entities [36] or terrain objects [37] such as depressions, peaks, ridge lines, course lines, and break lines, with intrinsic topologies such as contiguities, adjacencies, proximities, and contingencies, among others.

The definition of these entities depends on the most appropriate conceptual data model for solving a problem and how they are represented on maps and in geographical databases. For example, geometric signatures of spatial entities [34] are usually coded in GIS through vector data structures for features such as point, line, and polygon, or even matrix/raster data structures for continuous geographical phenomena such as digital terrain models (DTM) [25]. Here, the difference between DTM and DEM merely lies in the meaning of the z attribute. In the former, the z attribute refers to the continuous variable terrain height in relation to a local or geodesic topographic reference, and the latter to the other variables of continuous spatial phenomena such as temperature, soil moisture, and parametric indices, among others.

Features identified on the terrain, revealed through DEM or based on a land use classification using remote sensing data, are relatively common in environmental assessments that are geographical in scope. However, the metrics usually applied have little or no relationship with the natural occurrence of water in the landscape.

The gravitational potential of water is a key element in the evolution of the landscape as it is the main element responsible for water flow in the soil and subsoil and can be applied in many models [38]. The relief, the soil, and its properties act as intervening agents in water and energy distribution, redistribution, and accumulation [1,5,37]. This behavior differs between the floodplain, hillslope, and plateau structural units of the hydrological landscape [5,39], and hydrological connectivity between them may eventually exist [39]. The gravity gradients between points on the terrain are the main physical agents that cause the flow or stationarity of water in the landscape, so the relief is considered the main conditioner of that behavior. These gradients can be absolute or relative, depending on the altimetric reference taken as a measure [37,40]. Thus, the landscape's evolution in watersheds results from complex interactions of multiscale (topographic, climatic, tectonic, and anthropogenic) systems that determine the surface and subsurface properties [37].

The multi-parametric nature of a DTM can be explored in multiple layers [1]. Hydro-based morphological models add relatively new layers of metrics based on the relation between relief and water. The TWI model, for example, explores the tendency for soil saturation in the terrain's low-sloping or concave surfaces through the topographic index (Equation (1)).

$$\lambda = ln\ (a/tan\beta) \quad (1)$$

where the λ parameter is the topographic index of a point or cell on landscape. The a parameter is the contributing area per unit contour length, that is $a = A/L$ [41], where A is the upslope contributing area, and L is the perimeter of a. The a parameter reflects the amount of water that may be captured during surface or subsurface runoff or groundwater flow events. The bigger a is, the more volume of water may flow to the point or cell on the landscape. Bigger a values are expected close to watercourses, whereas smaller values are expected near the watershed perimeter. The β parameter is the terrain gradient or local slope and captures the potential gravitational gradient of a water particle to move in/on a landscape. The higher β, the larger the vertical differences between two points in relation to its horizontal distance. Therefore, local sites with a higher β attribute tend to produce higher waterflow surface velocities.

Therefore, parameter a defines the amount of water input to a point or cell and β defines its potential water output. The parameter λ indicates the presence of potential water accumulation on the surface, soil saturation, or wetland areas within the watershed's environmental assessment scope. High λ values indicate places with large areas of upslope drainage
areas with low slopes and high upslope contributing areas, which should occur in the low regions of the watershed close to the higher-order channels. On the other hand, low TWI values are expected close to the headwaters of the watershed or in the top regions of the hydrological landscapes that compose its relief structure. The water flow at these locations tends to be exclusively vertical, since water particles present little or no lateral gradient. In saturated soil zones, the vertical flow depends on the subsoil's physical properties, and there may or may not be percolation. The contour lines of these zones characterize their geometric signatures and can vary according to the volume of water present and the level of water in the ground reservoir [42]. For this reason, these zones are also known as variable flow areas (VFAs), where the anaerobic conditions of the wetlands offer conditions for the production of biogenic methane, an important element for both the local and global carbon cycle [43].

This concept was initially presented within the hydrological model TOPMODEL (topography model) [6] to estimate a hydrograph of the runoff produced by a watershed in a river control section based on a rainfall and evapotranspiration dataset. The distributed parameter of the TOPMODEL is the topographic index (TI), calculated based on the natural logarithm of the ratio between the specific contributing area (runoff watershed area/length of the edge of the entry cell—obtained in the DTM pre-processing by the routine flow accumulation and by the resolution of the cell, respectively) and the local slope of the cell [41].

The HAND model uses the drainage network to reference the heights of points on the ground. Figure 1 illustrates the methodological concept first presented by Rodda [44] for mapping the flood extent and later explored by Rennó et al. [7]. Any point on the surface has a vertical distance to a watercourse. The choice of what watercourse and what cell in the watercourse should be used for distance measurement is made based on a horizontal distance. The horizontal distance depends on the algorithm for defining the flow direction such as D-8 [41] and D-Infinity [44].

Figure 1. Schematic representation of the HAND model concept over a hypothetical elevation profile.

The idea has been evaluated in determining the geometric signatures of floods [19,45–47] and classifying the hydrological landscape [7,8,18]. It is based on the local gravitational potential of a water particle, corresponding to HAND. The HAND DEM, therefore, is a discrete 2D representation of the problem's domain, usually a watershed or stretches of floodplains.

3. Materials and Methods

3.1. Study Area Description

The case study was conducted in the Canoinhas River watershed with a size of 1440 km^2, axial length of 83.22 km, average width of 17.30 km, and drainage density of 1.13 km/km^2. The compacity index 2.71 indicates that the Canoinhas River watershed is elongated and has low susceptibility to maximum rainfall along all of its lengths, which limits the occurrence of floods on its plains to frontal rain events.

The Canoinhas River is a fifth-order channel with a length (the area and perimeter attributes were obtained from the attribute table in GIS. These values are automatically calculated when the layer is generated) of 189.08 km and a sinuosity of 2.27 km/km. It flows into the Rio Negro River, a tributary of the Iguaçu River (26°30′ S; 50°20′ W). The watershed is part of the continental hillslope in Hydrographic Region 5 (RH5), called "Planalto de Canoinhas", and belongs to the macro-region of the northern plateau of the Santa Catarina State, Brazil. The above sea level altitude ranged from 757 to 1344 m.

The vegetation comprises fields, tropical, and subtropical perennial and floodplain forests, with the North Plateau region being the most expressive forest center in Latin America [48]. The relief comprises strongly to gently undulating, mountainous, and flat strata. Soil depths vary from less than 60 cm to 150 cm, with textures ranging from clayey to very clayey. According to EMBRAPA [49], the most common soil types are described in Table 1 and further illustrated in Figure 2.

Table 1. Soil types and their attributes in the Canoinhas watershed.

Soil Type	Area (km^2)	Area (%)	Texture	Relief	Depth (cm)	Drainage
Cambisols	370	25.7%	Clayey to very clayey	Strongly undulating to gently undulating	60–150	Moderately Drained
Humic and slightly humic gley soil	187	13.0%	Clayey to medium	Flat	<60	Poorly to Very Poorly Drained
Bruno/Red latosols	498	34.6%	Very clayey	Gently undulating	>150	Well drained
Litholic soils	319	22.2%	Very clayey to clayey	Hilly to gently undulating	<60	Moderately Drainage
Nitosols	64	4.4%	Very clayey	Gently undulating	>150	Well drained

The soils of the study area show a texture varying from clayey to very clayey (Table 1; Figure 2). Latosols and nitosols are the most profound soil types, occupying ~39% of the watershed and presenting the best drainage conditions. Allied with its gentle topography, these attributes favor agricultural activities in small rural properties, typically smaller than 30 hectares in the study area.

Humic and slightly humic gley soil occupies ~13% and is located in flat areas near the Canoinhas River. The flat relief, the shallow depth, and the clayey texture assure little drainage capacity. Litholic soils are characterized by little depth, sometimes presenting a stony ground surface and moderate drainage capacity, despite being clayey or very clayey. These soils occur in hilly or gently undulating regions (Figure 2).

Cambisols occupy different landscape strata (strongly undulating to gently undulating relief) and have moderate drainage capacity at medium depths (60 to 150 cm). This class and latosols and nitosols occupy about 65% of the study area. In summary, various soil types located on different layers of the landscape, with a varied drainage capacity and a relief amplitude of 847 m, assure exploitation in different ways.

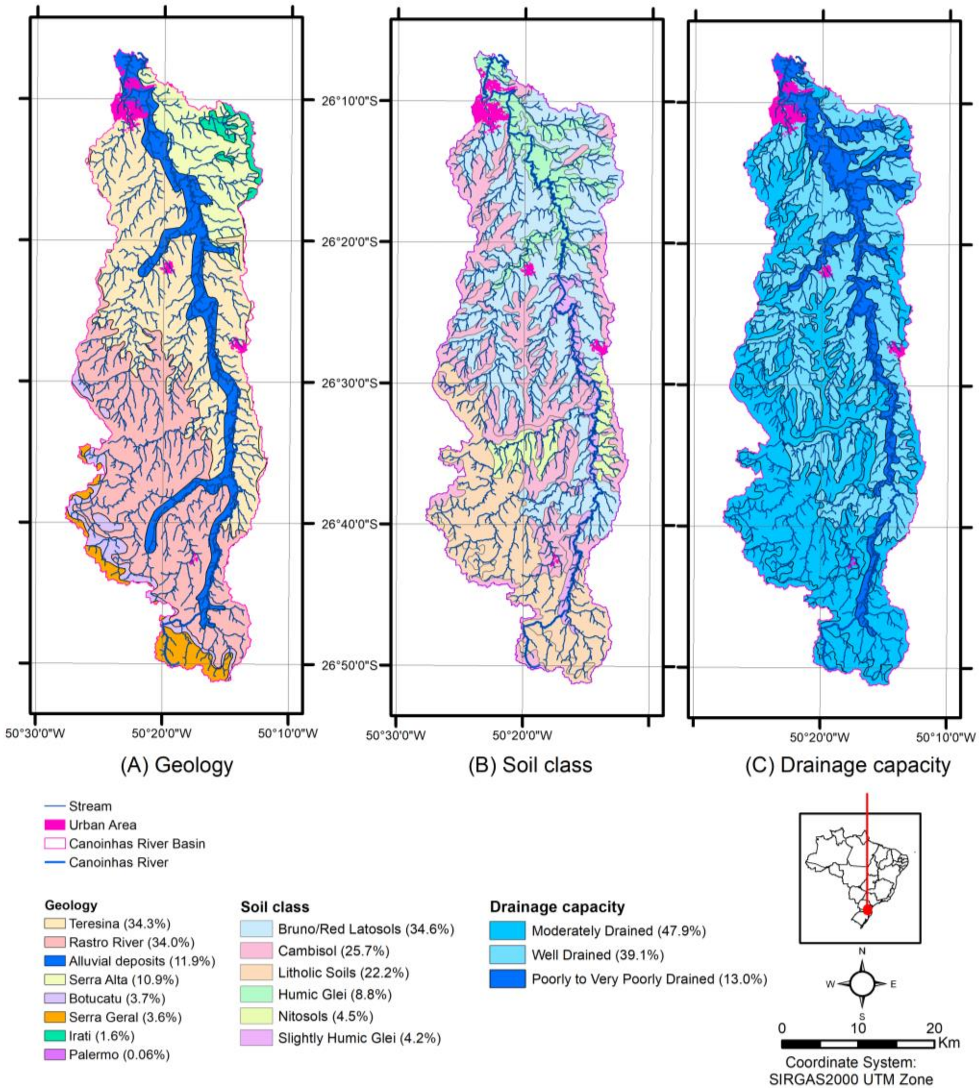


Figure 2. Geology (**A**), soil class (**B**), and drainage capacity (**C**) of the Canoinhas River watershed.

The Canoinhas River watershed is considered to be medium-sized [48] and partially covers five municipalities such as Monte Castelo (source), Canoinhas (mouth), Major Vieira, Papanduva, and Três Barras (Table 2). The urban centers of all the municipalities are found within the watershed. According to AMPLANORTE [50], these municipalities also show high municipal human development index (MHDI) scores, with the highest percentage of residents established in the urban area. The percentage of residents in the rural area is also relatively expressive, keeping a mix of rural and urban landscapes (Table 2). The essential economic activity is related to the pulp and paper industry, wood, and energy production. The region is also facing a gradual increase in the establishment of new industries and, consequently, urban growth is generating conflicts and environmental issues, which is why it was selected as a case study.

3.2. Land Use Maps

A Sentinel-2 scene with an acquisition date of 23 February 2021 was used to generate the land use map (Figure 3). The scene was chosen from the Earth Explorer, linked to the Copernicus program of the European Space Agency (ESA). First, all spectral bands were resampled at a spatial resolution of 10 m, roughly relative to the horizontal 1:50,000 map scale, which is compatible with regional studies [51].

Table 2. Information about the municipalities that compose the Canoinhas River watershed.

Parameters	Municipality				
	Monte Castelo	**Major Vieira**	**Papanduva**	**Três Barras**	**Canoinhas**
Population (inhab)	8346	7479	17928	18129	52765
Urban population (%)	58%	40%	51%	85%	74%
Rural population (%)	42%	60%	49%	15%	26%
Land area (km^2)	561	521	765	437	1148
Area covered by the watershed (%)	93%	93%	12%	40%	14%
Population density (inhab.km^{-2})	14.6	14.2	24.0	41.4	46.3
MHDI * (2010)	0.675	0.690	0.704	0.706	0.757

* MHDI: municipal human development index.

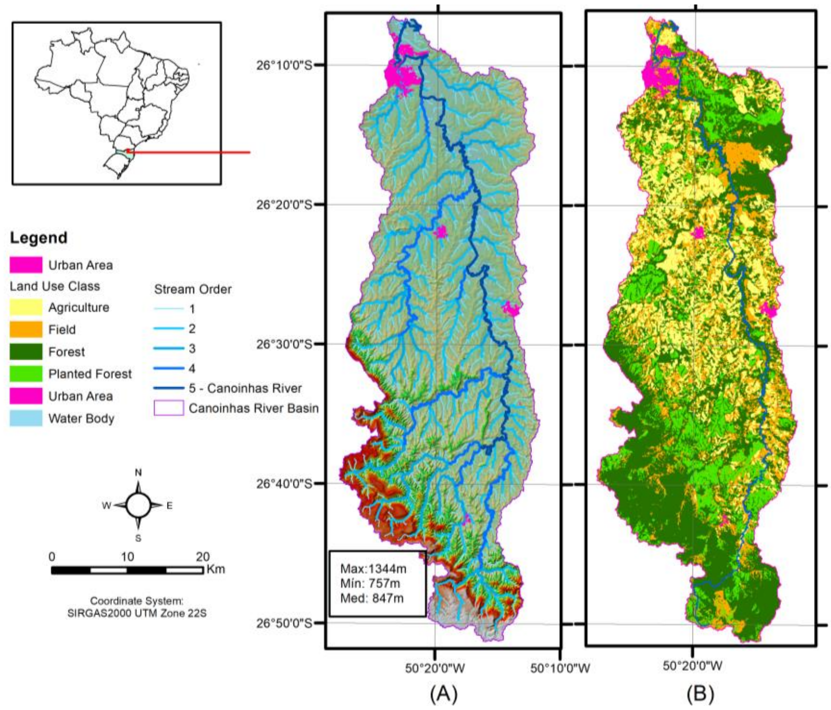


Figure 3. Representation of the study area by the digital model of the shaded terrain with the ordering of channels by the Strahler method (**A**) and land use classes (**B**). The study area is in the Northern Plateau of Santa Catarina State (Southern Brazil).

Afterward, samples were collected through the study area, and the supervised maximum likelihood was applied. Finally, a majority filter was applied to remove the isolated pixels, smoothing the classes' irregular boundaries. Further corrections were performed by comparing the classified map with the MapBiomas collection [52] of Brazilian land cover and land use, referring to 2020, in which the classification is originally from Landsat mosaics using the dynamic and procedural methodology in Google Earth Engine.

Six land use classes were defined based on the identifiable entities in the scenes and of interest to the environmental assessment of the watershed (Table 3). These classes also have a very important spatial distribution in the area. The samples of the land use class were selected through photo interpretation of the form, size, tone, color, texture, and pattern (Table 3) [53]. We used fieldwork measurements and high spatial images from different data sources such as ArcGIS and Google Earth Pro. Similar procedures were previously adopted in another regional research [54,55].

Table 3. Subsets of the six mainland cover classes in the selected study area with RGB composition, bands 4, 3, 2.

Land Cover Classes	Subset (1200 m × 800 m)
Agriculture: associated with annual agricultural activities containing maize and other crops such as beans, yerba mate, and tobacco.	
Forest: natural forest remnants belonged to the mixed ombrophilous forest under different successional forests, in addition to natural fields.	
Urban Area: urban occupation in the watershed encompassing the urban centers of Canoinhas, Três Barras, Major Vieira, Monte Negro, and Papanduva.	
Field: represents pastures formed of native or planted annual or perennial grasses, besides small-sized vegetation.	
Planted Forest: forest plantations occupied by either *Pinus* spp. and *Eucalyptus* spp. stands.	
Water: liquid surfaces such as lakes, ponds, streams, and rivers.	

3.3. Digital Terrain Model (DTM)

A total of 94 digital terrain models (DTMs) with a spatial resolution of one meter were mosaiced [56]. Afterward, the DTM was used to generate the relief information needed to build the HAND and TWI morphological models. The DTM was pre-processed in ArcGIS®10.5, with the help of the Spatial Analyst, 3D Analyst, ArcHydro Tools, and Geo-HMS Tools extensions. The Geo-HMS tool was used to pre-process the DTM, which consisted of filling depressions, defining flow directions (D8 algorithm [41]), flow accumulation, defining the synthetic drainage network by testing different thresholds, and outlining the watershed by setting the Canoinhas River as an outlet. The thresholds were evaluated by comparing water streams with the support of visual interpretation over high spatial resolution images (i.e., ~0.40 m) freely available from the State Government [56].

The spatial resolution chosen to apply the TWI model in the Canoinhas River watershed was 20 m, and to apply the HAND model, it was 5 m. The 20 m resolution is relative to the roughly horizontal 1:100,000 scale, and the 5 m resolution to 1:25,000. Both were from resampling the original 1 m DTM (relative to a 1:5000 horizontal scale). The 20 m resolution was an arbitrary choice to identify horizontal TWI entities in sufficient detail and considerably improve the computational performance. Interestingly, the original DTM of the watershed with a 1 m spatial resolution accounted for 46.08 GB in the Canoinhas River watershed, while the DEM of the TWI with 20 m resolution accounted for 1.44 GB with 3.6×10^6 cells.

To classify the landscape based on HAND, we empirically considered the possible effects of discretization and smoothing of the DTM [57], the probable effects of the vertical resolution, and the fractal dimension of the hydrographic network of the Canoinhas River watershed. According to Gharari et al. [18], a spatial resolution of 20 m would be enough to classify landscapes using the HAND model. In this way, a 20 m spatial resolution for identifying horizontal TWI entities and a 5 m spatial resolution for landscape classification would be compatible resolutions with environmental analyses for planning purposes at a regional scale.

The different spatial resolutions from datasets were disregarded since the tabulation of the pair of information was considered using the zonal statistics tool available in a GIS. Specific aspects are discussed in forthcoming sections.

3.4. Topographic Wetness Index (TWI)

The TWI model was processed according to Quinn et al. [41] and subsequently classified according to the propensity of a cell for water accumulation on the surface or soil saturation (Table 4).

Table 4. Classes of the TWI values and propensity for water accumulation on the surface or soil saturation.

Class	Characteristics	Water Accumulation Propensity/Soil Saturation
−0.56 to 6.40	Small contributing area and steep slopes	Low
6.40 to 8.00	Average contributing area and average slopes	Average
8.00 to 25.69	Large contributing area and low local slopes (flatter areas)	High

A TWI parameter is assigned to each MDT cell. Cells with the same TWI show the same tendency for water accumulation or soil water saturation. The scale and resolution of the data affect the distribution of the TWI statistics in the landscape [13,58]. A horizontal resolution corresponds to the elementary size of a surface measured by a remote sensor [57] and should be sufficient to capture the minor features identifiable in the object space to portray them unmistakably [34,53]. In practical terms, geographic features that identify areas of water accumulation or soil saturation result from grouping neighboring cells with the same value.

At high MDT resolutions, 1 m, for example, the slight variations in the local slope parameter β (Equation (1)) between neighboring cells can assign quite a different TWI to each, with the cells having a similar a parameter. This can generate an inconsistency in the information about the areas prone to water accumulation, since this effect depends on the water table, of which no significant variations are expected at short distances. The floodplain areas (lowlands), which tend to present the highest TWI values, may present a large variation in the TWI, without significant variation in soil moisture [11,59]. This effect can exist in finer scales (or large scales), where small variations in relief can be perceived without necessarily being proportional to small variations in soil moisture. This effect also tends to produce an overabundance of TWI in the landscape without necessarily aiding in identifying zonal features of interest to decision-making processes at the regional planning level. Therefore, data and information saturation can impede the extraction of relevant information. Thus, the dimensions of the spatial domain of the problem and the most appropriate horizontal resolution have to be observed to show the geographical features of interest. Even in course scales (or small scales), it is possible to extract relevant information from the terrain for practical purposes [60]. For example, Gharari et al. [18] used a 10 m resolution for the TWI model to compare it with the HAND. The HAND model presented the best performance.

3.5. Height above Nearest Drainage (HAND)

The HAND model can be applied in any terrain and translate hydrological meanings [8]. The model has received great attention from researchers due to its simple concept, relatively simple implementation, availability in open-source software like TerraHidro [61], and large application possibilities.

The HAND model [7] was presented to outline the structural units of the hydrological landscape to map terra-firme environments in the Cuieiras Biological Reservation (Amazon), based on the shuttle radar topographic model (SRTM) DEM. These classes were subsequently validated by Nobre et al. [8] over an area in the lower Rio Negro watershed (Amazonia) using a set of field observation points. The most evident signs of the structural units of the hydrological landscape are lowland, valley side, and upland [5]. However, other classes may be needed to describe these units better such as waterlogged, ecotone, slope, and plateau [8]. Interestingly, the class intervals to outline the structural elements of the hydrological landscape have still been scarcely studied in the literature. Furthermore, the transitions between the classes are usually not abrupt, and the attribution of a point of the landscape to a certain class would imply the use of diffuse techniques [18]. In this paper, we used the thresholds suggested by Rennó et al. [7] and Nobre et al. [8], whose results are shown in Table 5.

Table 5. The HAND classes for classifying the hydrological landscape in the Canoinhas River watershed.

Class	Hydrological Landscape Unit
HAND $<$ 5.3 m	Floodplain
5.3 $\leq$ HAND $\leq$ 15 m	Ecotone
HAND $>$ 15 m and $\geq$7.6% slope	Slope/Hillslope
HAND $>$ 15 m and $<$7.6% slope	Plateau

Source: adapted from Rennó et al. [7].

Floodplains are located at the lowest heights of the terrain, close to the natural drainage channels, presenting low slopes and a groundwater table close to the surface, which can saturate the land [5,8]. Ecotones represent smooth concave surfaces of transition between the floodplains and hillslopes, which mark the vadose regions [62] (i.e., the first landscape entities in which the soil is unsaturated, far from the channels). Slopes or hillslopes mark the surfaces with a height gradient in the landscape, which are well-drained and strongly interact with surface runoff. Plateaus are distributed in the high regions of the landscape, generally surrounded by hillslopes and with low slopes.

We chose these classes for the Canoinhas River watershed due to the greater number of classes and the general topographic characteristics of the watershed, especially the fact that 63% of the area of the watershed is composed of flat (slopes up to 3%) and slightly undulating terrain (slopes ranging from 3 to 8%), which would indicate the possibility of there being clear vadose zones (Figure 1).

Considering that the model's basic premise is the vertical distance of a point on the landscape from the nearest drainage channel, one has to assume that the model is sensitive to the number of channels generated by the channel definition operation on the DTM. This is a very common operation, which has the contributing area of the first grid cell as a user-defined parameter to which the channel is assigned. The area threshold (AT) parameter affects the degree of fractal discretization of the synthetic hydrographic network. Therefore, the AT of 0.5 km^2 was adopted, corresponding to 0.035% of the total area of the Canoinhas River watershed. This value is the approximate mean of the watershed area of a sample set of sources of first-order natural water courses recognized in high-resolution orthoimages available for the entire Santa Catarina State and are freely available for the general community [56].

The features attributed to the natural hydrographic network were identified by analyzing the form, size, tone, color, texture, and pattern [53]. The aim was to keep the geometric structure of the synthetic hydrographic network as close as possible to the natural geometric structure [18]. Therefore, the samples for calculating were based on AT, and the synthetic hydrographic network generated produced a set of linear features originating in the first pixel attributed to the flow accumulation algorithm.

Regarding the spatial resolution of the MDT, it is assumed that the better the resolution, the more accurate the vertical distances corresponding to the HAND. Furthermore, if the model is used to determine the extent of flood zones, it is valid to consider the best resolution available, especially in urban areas. However, the model here in this paper was only used to classify the hydrological landscape at the planning level, which could perhaps be sufficient for the 10 m resolution as used by Gharari et al. [18]. Therefore, we opted for the 5 m resolution resampled from the 1 m MDT.

3.6. Spatial Relationships

Spatial relationships are properties of spaces that do not undergo variations with their deformation. For example, a sub-watershed always belongs to its main watershed, independently of the distortions of scale. Similar affirmations can be made for relationships of continencies, intersections, contours, proximities, and adjacencies. These properties are studied in topology and used for validating data, modeling the integrated behavior of different features, data editing productivity, and query optimization [25].

The classes of features identified in the TWI and HAND morphological models, land use, and slope maps were assessed regarding spatial relationships. The relationships explored in this study were intersection, buffer clip, symmetrical differences, and proximity. These operations are used in GIS by means of predicates or mathematical operations such as the Euclidian distance between geometries of different classes, for example. Predicates are functions for comparing a given condition between pairs of features belonging to different classes coded as points, lines, or polygons. These functions can return a TRUE (T) condition when the condition under analysis is met or FALSE (F) otherwise.

The GIS approach used in this study (ArcGIS 10.5.1) adopts the dimensionally extended nine intersections model (DE-9IM [63]). The DE-9IM matrix presents nine possibilities of spatial relationships involving the features' interior, exterior, or edge. Point-type features have an interior and exterior but no edges. Similar to polygon-type features, line-type features have an interior, exterior, and edge. The final configuration of the matrix will be used to return the features of the classes involved in the operation or parts that satisfy the conditions expressed in the matrix, which can then be analyzed separately from the rest. The intersection operation returns the intercept features, which helps identify features that somehow share the same space, whether fully or partially. Their original geometries are maintained, which differs from the clip operation. This builds a group of features using the boundaries of other features and only returns the geometry relative to the portion in common. In both the intersection and clip operations, the attributes of both features can be kept in the resulting features. The buffer operation is normally used to analyze the area around features, especially regarding the proximity, continence, or intersection. The symmetrical difference operation chooses non-overlapping parts of the geometries, which operate inversely from the intersection. It is useful, for example, when excess information needs to be eliminated from the analysis, leaving only that which is actually of interest.

The operations above-mentioned were applied in the environmental assessment of the watershed. The operationalized classes of polygon features were land use, slope, TWI, HAND, the order of the channels, and the areas around the points of origin of the first-order channels. As the Brazilian Forest Act prescribes, these points are supposed to be the sources of the main watercourse [64]. In addition, areas of 0–15 m, 0–30 m, 0–50 m, and 0–100 m around the synthetic drainage features of the watershed were also defined. Finally, the surrounding features thus defined were operated with the features from the land use classes.

4. Results and Discussion

4.1. Topographic Wetness Index (TWI)

The TWI values vary considerably over the landscape according to the geomorphological characteristics of the terrain [65,66]. This is due to TWI parameters *a* and *tan β* (Equation (1)), where *a* depends on the position of a point on surface, being near or far from the watercourse, and *tan β* depends on the slope. Values of *a* are expected to be higher the closer points are to the watercourse, since *a* has a superficial dimension. Parameter *a* also depends on the relief conformation because the shape of the watershed area A (Equation (1)) varies with relief configuration. The parameter *β* is essentially a parameter linked to the relief configuration. Therefore, the slope distribution in the watershed should affect the occurrence and distribution of *tan β* in the landscape. In this regard, the geometric signatures show that the watershed presents 40.8 hectares of highly mountainous relief, 12.2% of highly undulating and mountainous relief, and the average slope is 0.09 m.m^{-1}. About 63% of the watershed area is on flat and gently undulating relief. This reveals that the relief of the watershed is quite diversified and well-distributed in the range from 0 to 20% slope (Table 6).

Table 6. Slope classes in the Canoinhas River watershed [67].

Slope (%)	Class	km^2	%
0–3	Flat relief	378.6	26.3
3–8	Slightly undulating relief	532.7	37.0
8–20	Undulating relief	345.4	24.0
20–45	Highly undulating relief	176.9	12.2
45–75	Mountainous relief	6.6	0.5
>75	Highly mountainous relief	0.0	0.0
	Total	1440.2	100

Some studies have shown that the TWI values that indicate prone to developing water accumulation or soil saturation in the landscape are above 8.0 [17,18,65,66]. For example, Figure 4 shows TWI variations ranging from −0.56 to 25.69, with a mean of 6.00 and a standard deviation of 3.00.

A TWI ranging from −0.56 to 6.40 represents 49.1% of the watershed, whereas 6.40 to 8.00 with 27.5%, and 8.00 to 25.69 with 23.2%, respectively. Similarly, DuPage city's values varied from −7 to 29.5 and from −5 to 288 in Will County [17]. Values below 6.00 were considered by Meles et al. [59] as very dry regions, those from 6.00 to 8.60 as dry, and those above 16.60 as moderately wet to very wet. Values above 8.00 were validated in the field by Schier [66] as being prone to flooding in the city of Lages, SC, Brazil.

Mapping the dry and wet zones of the landscape provides relevant information from a regional and local planning point of view. Drylands reveal regions available for land use for agricultural, forestry, and urban activities. However, these regions may be prone to mass movements during extreme precipitation events or be the first regions of the watershed to suffer water deficit during periods of drought. For example, we witnessed during the drought that hit the state in 2020 in the Canoas River watershed Management Committee that the cities located in the headwaters, close to the watershed, were the ones that suffered most from the lack of water, requiring effective help and assistance actions from the authorities. Wetlands, on the other hand, indicate areas that tend to be better able to withstand periods of drought. Indeed, Biffi and Neto [67] demonstrated that during a drought in 2005, the lower-lying areas of the relief in the apple production region of Santa Catarina State exhibited higher production levels than the higher-lying areas.

In general, terrains in the State of Santa Catarina tend to present a predominance of areas with little tendency for water accumulation/soil saturation in watersheds due to the predominance of steeper slopes. For example, in the case of the Canoinhas River watershed, 38% of the area with a flat terrain (slopes from 0 to 3%) presented TWI geometric signatures higher than 8.00, representing only 10% of the total area of the watershed. The fact that not all areas with slopes from 0 to 3% presented a TWI > 8 does not imply that these areas are not prone to water accumulation/soil saturation, especially if they are located close to drainage channels, where the water table is expected to be closer to the surface. Hence, adding the topographic variable HAND helps categorize the landscape based on the vertical distance between a point on the surface and the nearest drainage, making it an important consideration.

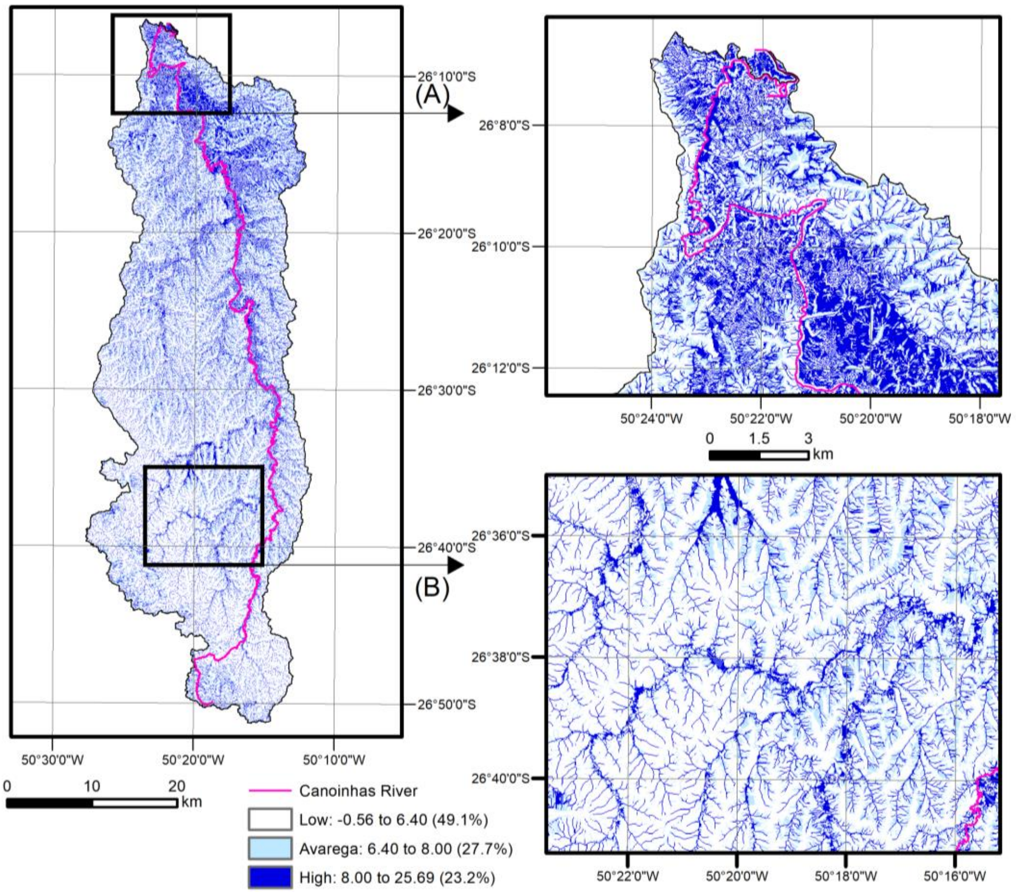


Figure 4. The TWI spatial distribution in the Canoinhas River watershed. The larger-size TWI spatial entities are located in the lower part of the watershed (**A**), while the smaller entities are located in the higher regions (**B**).

4.2. Height above Nearest Drainage (HAND)

The relative gravitational potential of a water particle is determined in the HAND model by the vertical distance to the nearest drainage. Various results were found by Nobre et al. [8] for the Rio Negro River watershed in Amazonia. The predominantly sedimentary constitution of that region found 20.9% of the area occupied by floodplains, 26.9% by ecotones, 9.1% by hillslopes, and 24.8% by plateaus. In the Canoinhas River watershed, we found 4.74% occupied by floodplains, 2.67% by ecotones, 38.04% by hillslopes, and 54.55% by plateaus (Table 7; Figure 5).

Table 7. Hydrological landscape classes in the Canoinhas River watershed.

Class	Hydrological Landscape Unit	Area (km^2)	%
HAND < 5.3 m	Floodplain	68.33	4.74
5.3 ≤ HAND ≤ 15 m	Ecotone	38.42	2.67
HAND > 15 m and ≥7.6% slope	Hillslope	547.93	38.04
HAND > 15 m and <7.6% slope	Plateau	785.64	54.55

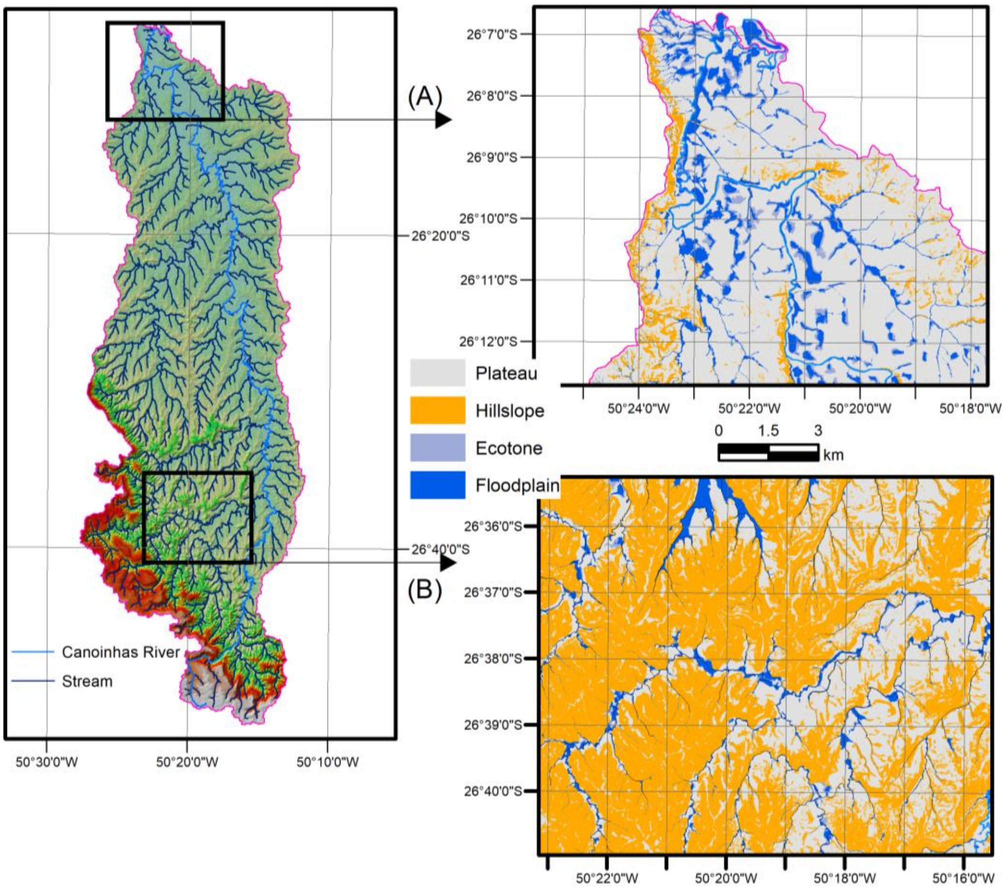


Figure 5. The HAND model classes in the Canoinhas River watershed. The lower region of the watershed has a wide area of plateaus and floodplains (**A**), while the higher regions have a predominance of hillslopes (**B**).

These results may be influenced by the DTM resampling from higher to lower resolutions due to the joint effect of discretization and smoothing [57]. However, the immediate consequence is the loss of detailed information on the relief and, consequently, on identifiable spatial entities, especially through the discretization effect.

The quality of the vertical variable is also a point to be considered. Smoothing the DTM tends to reduce the altimetric amplitude and with that, there is a loss of vertical accuracy. Smoothing should also affect the presumed gravitational gradients and runoff paths to the nearest channel. Thus, better altimetric determinations of the gravity gradients and of the extent of the surface runoff are expected in DTMs with higher spatial and vertical resolutions.

The fractal dimension of the hydrographic network of a watershed [60] makes the HAND model dependent on the area threshold (AT, presented in Section 3.5) to generate a channel [18]. The AT affects the size of the network similarly to the effect commonly associated with changes of scale in maps [60]. In a hydrographic network with a Hortonian structure [68], the channels' orders parametrize the channels' average lengths and watershed areas. Thus, morphometric parameters such as bifurcation ratio, length ratio, and the ratio of areas between the channels of contiguous orders are affected by the degree of fractal discretization of the synthetic hydrographic network extracted from a DTM. The algorithm considers the AT as an area value arbitrarily attributed as an injunction factor regarding the flow accumulation model. The z attributes of the flow accumulation DEM express the number of cells that flow to each cell of a DTM.

In a typical hydrological landscape, the subsurface water sheet tends to lie closer to the topographic surface on the floodplains and further away from the plateaus [5,69]. The continuity or not of that sheet throughout the landscape depends on the composition of the soil profiles. In general, water accumulation or soil saturation in the landscape is expected on the floodplains and plateaus due to the low slopes of the terrain, leading to expected susceptibility to flooding and sediment depositions on the floodplains.

The geometric signatures of floodplains appeared in the Canoinhas River watershed throughout the entire hydrographic network (Figure 6). The most expressive floodplain signatures tend to be closer to the higher-order channels, which would be expected due to the lowest slope class characteristics of the watershed. These signatures can guide the planning of land occupation, whether for agricultural activities or urban occupation, for example.

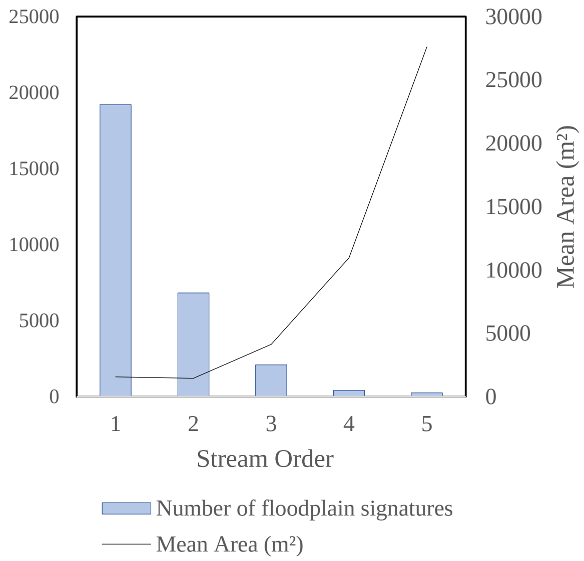


Figure 6. Geometric signatures of the floodplain class throughout a 100 m buffer from the Canoinhas River watershed hydrographic network.

The geometric signatures of the hillslopes were shown to be quite diversified in form and size. It is common to find fragments of hillslopes surrounded by plateaus on the same slope. This occurs due to changes in the local slope used to classify the model. These fragments can even be considered irrelevant from the viewpoint of the environmental analysis of the watershed, since few or no specific decision-making processes would be expected in adhering to this level of analysis.

4.3. Zones with a Propensity for Water Accumulation/Soil Saturation and Hydrological Landscapes Classes

The occurrence of zones with a high propensity for water accumulation or soil saturation (TWI > 8) concerning the HAND classes has been studied in the literature. Unlike the HAND model, whose manifestation of the vertical distances in the model depends on the degree of fractal discretization of the synthetic hydrographic network, the TWI model is manifested throughout the whole watershed precisely because the parameter depends solely on variables of the relief (a and β). The degree of fractal discretization of the synthetic hydrographic network may be responsible for some regions of the watershed that could be classified as floodplains (more discrete) being classified as hillslopes or plateaus (less discrete), which can add bias in the TWI occurrence analysis in the classes of the hydrological landscape. With this caveat, it was observed that in the Canoinhas River watershed, there is a tendency for the most prominent water accumulation or soil saturation entities to lie close to the higher-order channels (Figure 7).

There is a tendency for an exponential increase in the floodplain areas and the areas with high water accumulation or soil saturation as the order of the channels increases. This may be explained by the fractal dimension of the hydrographic network, the cumulative order of the channels using the Strahler method in measuring the ramifications, and the erosion, transportation, and fluvial sedimentation processes. The sedimentary areas tend to occupy the lowest regions of the relief and contribute to the formation of the floodplains as structural units of the hydrological landscape. These zones should receive special attention in the watershed's environmental planning due to their riparian importance or their tendency to flood.

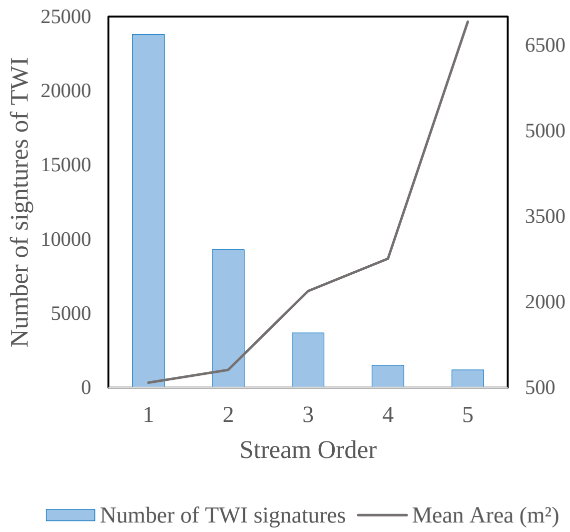


Figure 7. Geometric signatures of TWI throughout the 100 m buffer from the Canoinhas River watershed hydrographic network show the zones that are highly prone to developing water accumulation or soil saturation on the floodplains.

The areas prone to developing water accumulation or soil saturation were distributed throughout all units of the hydrological landscape (Figure 8). The plateau areas were the most indicated areas prone to developing water accumulation or soil saturation, followed by the floodplains, hillslopes, and ecotones. The means of the areas indicate that the number of geometric signatures followed that same trend. This shows the importance of plateaus as structural elements of the landscape for surface water storage. The hillslopes were also shown to be relevant as landscape units with a tendency to accumulate water. These regions can contain topographic footprints that indicate wetlands or waterlogged zones, which can play a relevant ecological role in the watershed. From an urban occupation perspective, these zones are potential areas of flooding caused by surface runoff from intense rainfall, hence the need to pay attention to local micro-drainage systems [70,71].

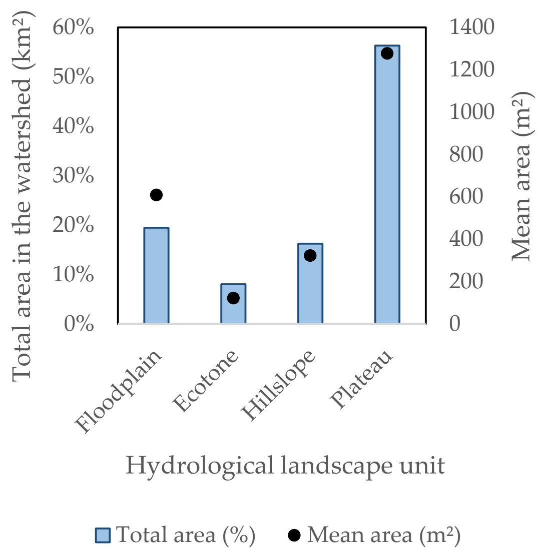


Figure 8. Geometric areas associated with a high propensity for developing water accumulation or soil saturation in the units of the hydrological landscape in the Canoinhas River watershed.

4.4. Land Use

Land use factors have been employed as parameters for assessing the levels of environmental degradation or preservation [31–33,72,73]. Some of these factors are recognized as modifying agents of the hydrological responses of the watershed and can act over water infiltration and percolation in the ground, surface, and subsurface runoff, and evapotranspiration, among others. As a result, the hydric balance of the watershed can be affected, the storage capacity of the aquifers can be reduced, and the occurrence of natural disasters from landslides, mudslides, and flooding can be intensified.

The image classification of the Canoinhas River watershed produced geometries associated with agriculture, water bodies, urban areas, fields, forests, and planted forests. The geometric signatures of the respective classes appeared throughout the whole spatial domain of the watershed and the structural units of the hydrological landscape (Figure 9). The Forest class is the one that covers the most significant part of this domain, occupying 33% of the total area of plateaus and 61% of the hillslope area. However, there is a clear decreasing trend in the geometric signatures of this specific class further away from the hydrographic network, up to around 50 m (Figure 9).

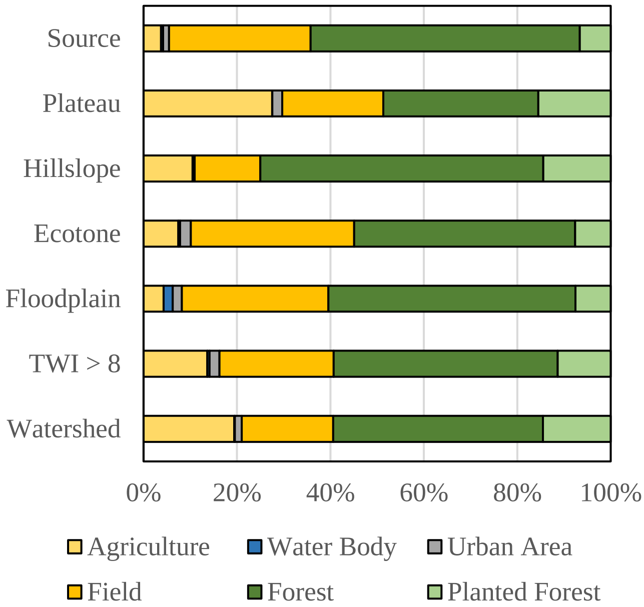
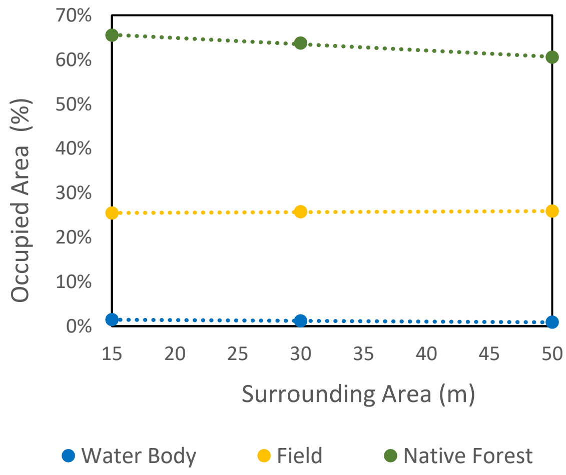


Figure 9. Land use in the Canoinhas River watershed in the classes of the hydrological landscape, and in the areas prone to developing water accumulation or soil saturation.

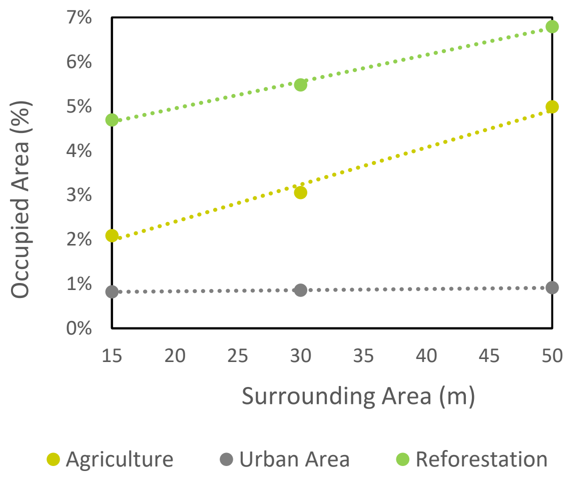
The Field class is the second most frequent and represents, together with the Forest and Water classes, the most sensitive geographical entities from an environmental quality and preservation viewpoint. This shows that the Canoinhas River watershed still has wide vegetated areas that warrant attention from a preservation viewpoint and wide field areas subject to agroforestry exploitation. Most field and native forest areas are distributed on floodplains, ecotones, and hillslopes. A substantial portion is also situated in areas prone to water accumulation or soil saturation.

Agriculture, Urban Areas, and planted forests represent the geographical entities associated with anthropogenic activities in the watershed. The geometric signatures of the agriculture class occupy 19% of the total area of the watershed, and the planted forest class occupies 15%. Agricultural activities are also found in 4% of the surrounding areas within 50 m of the source areas of the watershed. These areas are still occupied by entities of the planted forest (7%), grasslands (30%), and forests (58%).

The areas occupied by agriculture entities and planted forest classes around the hydrographic network tend to increase with distance, while the areas occupied by the forest class tend to decrease (Figure 10). A drainage network is a component of the morphological subsystem of the watershed that scarcely alters its position, geometry, and attribute characteristics, thus being considered fixed bases in the landscape and potentially applicable as both horizontal and vertical references of alterations in the state of the GIS of the chosen watershed. Thus, the hydrographic network is a potential indicator of the behavior of dynamic geographic systems such as the expansion or contraction of anthropogenic activities that are spatial in scope in one urban area [74].



(**a**)



(**b**)

Figure 10. Areas occupied by the geometric signatures of land use in the 0–15 m, 0–30 m, and 0–50 m surrounding areas in the Canoinhas River watershed. Land use consists of classes of natural use (**a**) and classes with human activities (**b**).

The Urban Area class in the Canoinhas River watershed occupies a small total area. However, it is found on floodplains, ecotones, and plateaus and in areas prone to developing water accumulation or soil saturation. The plateaus can be considered as safe environments for urban equipment in terms of the risks of flooding disasters. On the other hand, the floodplains and areas prone to developing water accumulation/soil saturation warrant attention concerning the macro- and micro-drainage systems, especially in the vectors of urban expansion. Low-impact development (LID) measures should be considered to mitigate the effects of localized flooding caused by intense rainfall in the consolidated areas where the occupation has reached an irreversible state and address water quality in urban ecosystems [69–78].

4.5. Further Research Perspectives

Land use factors have been employed to assess environmental degradation or preservation [31–33]. Some of these factors are recognized as modifying agents of the hydrological responses of the watershed and can act over water infiltration and percolation in the ground, surface, subsurface runoff, and evapotranspiration, among others. As a result, the hydric balance of the watershed can be affected, the storage capacity of the aquifers can be reduced, and the occurrence of natural disasters from landslides, mudslides, and flooding can be intensified.

The relationship between water and landscape is a natural relationship for shaping the land surface, sustaining lives, and conditioning human activities. Hydro-based hydrological models such as TWI and HAND bring in their conceptual framework assumptions of this relationship, which can be explored practically for regional or local planning purposes to pursue environmentally sustainable development. They can be applied from a DEM since their conceptual basis rests on the physical functions of water on the land, its geographical position in the terrain, and its energy potential in the landscape. These models are conceptual abstractions built using the hydrological landscapes' structural units that form the watershed's geomorphology.

Interestingly, these models can be used to recognize landforms that condition the behavior of cascading systems such as the hydrological cycle, the dynamics of land use by cities, agriculture, cattle ranching, and planted forests, among others, for example, to preserve sensitive ecological zones and prevent the occurrence of disasters caused by floods from extreme runoffs, debris flows, and mass movements. Therefore, the water–landscape relationship can be explored with these models without the need for scientific modeling of the cascade hydrological systems, whose complexity sometimes makes its application unfeasible in countries like Brazil due to the lack of specialists or reliable data for effective modeling of the systems.

Regional-scale maps have been found to be incompatible with local urban analysis as it demands detailed DEMs for more accurate TWI and HAND models. Therefore, further assessments should consider, for example, the efficacy of the HAND model to represent the flood extent in flat areas under high spatial resolution DEMs such as those extracted from high point density cloud points acquired by airborne LIDAR.

Furthermore, a sensitivity effect of algorithms to define flow direction and flow accumulation from DEM, since the HAND model is spatially dependent on the channel's flow paths, is also needed. On the other hand, the TWI model tends to show a superabundance of water accumulation/soil saturation in high-resolution DEM. Therefore, efforts may drive toward a better choice of DEM resolution or DEM cell size to delineate features on the landscape that better represent the phenomena, and therefore helps land managers and environmental agencies support decisions for better use of the environment.

5. Conclusions

This research evaluated HAND and TWI morphological models as an important source of information on the geomorphological agents that condition the anthropogenic activities in the structuring units of the landscape. Our results showed that geometric signatures of the TWI emerged through all of the structural units of the hydrological landscape, with values between -0.56 and 25.69, where values above 8.0 represent areas prone to developing water accumulation or soil saturation. The plateau areas were the ones that most indicated that condition, followed by the floodplains, hillslopes, and ecotones. In such areas, plateau areas are suggested as structural elements of the landscape for surface water storage. However, this distribution depends on local relief characteristics, and more detailed studies are strongly encouraged.

In the Canoinhas River watershed, there is a tendency for the largest geometric signatures of water accumulation or soil saturation entities to be located close to the higher-order channels, along with the largest geometric signatures of the floodplains. The area around the drainage network within 50 m of these channels showed that the areas occupied by entities of the Agriculture and Planted Forest classes tended to increase with distance, while the areas occupied by the Forest class tended to decrease. On the other hand, the Grasslands, Urban Areas, and Water-related classes remained stable. Some agricultural and forestry activities were also found within 50 m of the source areas, which shall be considered in the future by environmental agencies.

HAND and TWI are hydrological-based models that are relatively simple to formulate but have robust assumptions, which can be applied based on available DEMs. Their conceptual basis rests on the physical functions of water on the land, its geographical position in the terrain, and its energy potential in the landscape. These models are ultimately conceptual abstractions built using the hydrological landscapes' structural units that form the watershed's geomorphology.

Studying how land and water are related in morphological models like HAND and TWI can help us better understand and evaluate watersheds using freely available remote-sensing data sources. Factors like terrain, soil, and water quality all play a role in how people use the land and could drive decision-makers to use the landscape better. Hydrological-based models can be an easy way to analyze how all of these different factors interact and where environmental agencies must pay some attention.

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References

1. MacMillan, R.A.; Jones, R.K.; McNabb, D.H. Defining a Hierarchy of Spatial Entities for Environmental Analysis and Modeling Using Digital Elevation Models (DEMs). *Comput. Environ. Urban Syst.* **2004**, *28*, 175–200. [CrossRef]
2. Rahmati, O.; Kornejady, A.; Samadi, M.; Nobre, A.D.; Melesse, A.M. Development of an Automated GIS Tool for Reproducing the HAND Terrain Model. *Environ. Model. Softw.* **2018**, *102*, 1–12. [CrossRef]
3. Keller, E.; Adamaitis, C.; Alessio, P.; Anderson, S.; Goto, E.; Gray, S.; Gurrola, L.; Morell, K. Applications in Geomorphology. *Geomorphology* **2020**, *366*, 106729. [CrossRef]
4. Gruber, S.; Peckham, S. Land-Surface Parameters and Objects in Hydrology. *Dev. Soil Sci.* **2009**, *33*, 171–194. [CrossRef]
5. Winter, T.C. The Concept of Hydrologic Landscapes. *J. Am. Water Resour. Assoc.* **2001**, *37*, 335–349. [CrossRef]

6. Beven, K.J.; Kirkby, M.J. A Physically Based, Variable Contributing Area Model of Basin Hydrology. *Hydrol. Sci. Bull.* **1979**, *24*, 43–69. [CrossRef]
7. Rennó, C.D.; Nobre, A.D.; Cuartas, L.A.; Soares, J.V.; Hodnett, M.G.; Tomasella, J.; Waterloo, M.J. HAND, a New Terrain Descriptor Using SRTM-DEM: Mapping Terra-Firme Rainforest Environments in Amazonia. *Remote Sens. Environ.* **2008**, *112*, 3469–3481. [CrossRef]
8. Nobre, A.D.; Cuartas, L.A.; Hodnett, M.; Rennó, C.D.; Rodrigues, G.; Silveira, A.; Waterloo, M.; Saleska, S. Height above the Nearest Drainage—A Hydrologically Relevant New Terrain Model. *J. Hydrol.* **2011**, *404*, 13–29. [CrossRef]
9. Cuartas, L.A.; Tomasella, J.; Nobre, A.D.; Nobre, C.A.; Hodnett, M.G.; Waterloo, M.J.; de Oliveira, S.M.; von Randow, R.d.C.; Trancoso, R.; Ferreira, M. Distributed Hydrological Modeling of a Micro-Scale Rainforest Watershed in Amazonia: Model Evaluation and Advances in Calibration Using the New HAND Terrain Model. *J. Hydrol.* **2012**, *462–463*, 15–27. [CrossRef]
10. Mattila, U.; Tokola, T. Terrain Mobility Estimation Using TWI and Airborne Gamma-Ray Data. *J. Environ. Manag.* **2019**, *232*, 531–536. [CrossRef]
11. Guan, M.; Liang, Q. A two-dimensional hydro-morphological model for river hydraulics and morphology with vegetation. *Environ. Model. Softw.* **2017**, *88*, 10–21. [CrossRef]
12. Mohamedou, C.; Tokola, T.; Eerikäinen, K. LiDAR-Based TWI and Terrain Attributes in Improving Parametric Predictor for Tree Growth in Southeast Finland. *Int. J. Appl. Earth Obs. Geoinf.* **2017**, *62*, 183–191. [CrossRef]
13. Drover, D.R.; Jackson, C.R.; Bitew, M.; Du, E. Effects of DEM Scale on TWI Spatial Distribution Effects of DEM Scale on the Spatial Distribution of the TOPMODEL Topographic Wetness Index and Its Correlations to Watershed Characteristics. *Hydrol. Earth Syst. Sci. Discuss* **2015**, *12*, 11817–11846. [CrossRef]
14. Rózycka, M.; Migoń, P.; Michniewicz, A. Topographic Wetness Index and Terrain Ruggedness Index in Geomorphic Characterisation of Landslide Terrains, on Examples from the Sudetes, SW Poland. *Z. Fur Geomorphol.* **2017**, *61*, 61–80. [CrossRef]
15. Riihimäki, H.; Kemppinen, J.; Kopecký, M.; Luoto, M. Topographic Wetness Index as a Proxy for Soil Moisture: The Importance of Flow-Routing Algorithm and Grid Resolution. *Water Resour. Res.* **2021**, *57*, e2021WR029871. [CrossRef]
16. Riittersfl, K.H.; O'neill, R.V.; Jones, K.B. Assessing habitat suitability at multiple scales: A landscape-level approach. *Biol. Conserv.* **1997**, *81*, 191–202. [CrossRef]
17. Ballerine, C. *Topographic Wetness Index Urban Flooding Awareness Act Action Support Will and DuPage Counties*; Illinois State Water Survey—Prairie Research Institute—University of Illinois: Champaign, IL, USA, 2017; Volume 22.
18. Gharari, S.; Hrachowitz, M.; Fenicia, F.; Savenije, H.H.G. Hydrological Landscape Classification: Investigating the Performance of HAND Based Landscape Classifications in a Central European Meso-Scale Catchment. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 3275–3291. [CrossRef]
19. Dantas, A.A.R.; Paz, A.R. Use of HAND Terrain Descriptor for Estimating Flood-Prone Areas in River Basins. *Rev. Bras. Ciências Ambient.* **2021**, *56*, 501–516. [CrossRef]
20. Bayat, M.; Ghorbanpour, M.; Zare, R.; Jaafari, A.; Thai Pham, B. Application of Artificial Neural Networks for Predicting Tree Survival and Mortality in the Hyrcanian Forest of Iran. *Comput. Electron. Agric.* **2019**, *164*, 104929. [CrossRef]
21. Gao, Y.; Yao, L.; bin Chang, N.; Wang, D. Diagnosis toward Predicting Mean Annual Runoff in Ungauged Basins. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 945–956. [CrossRef]
22. Simon, H.A. *The New Science of Management Decision*, 1st ed.; Harper and Row: New York, NY, USA, 1960.
23. Chorley, R.; Kennedy, B. *Physical Geography: A System Approach*; Prentice-Hall: London, UK, 1971.
24. Neto, S.L.R.; Rodrigues, M. A Taxonomy of Strategies for Developing Spatial Decision Support Systems. In *Systems Development Methods for Databases, Enterprise, Modelling, and Workflow Management*; Wojtkowski, W., Wojtkowski, W., Wrycza, S., Zupancic, J., Eds.; Kluwer Academic/Plenum: New York, NY, USA, 1999; pp. 139–155.
25. Longley Paul, A.; Goodchild, M.F.; Maguire, D.J.; Rhind, D.W. *Sistemas e Ciência Da Informação Geográfica*, 3rd ed.; Bookman: Porto Alegre, Brasil, 2013.
26. Neto, S.L.R.; Sá, E.A.S.; Debastiani, A.B.; Padilha, V.L.; Antunes, T.A. Efficacy of Rainfall-Runoff Models in Loose Coupling Spacial Decision Support Systems Modelbase. *Water Resour. Manag.* **2019**, *33*, 889–904. [CrossRef]
27. Densham, P.J. Spatial Decision Support Systems. In *Geographical Information Systems. Vol. 1: Principles*; Wiley: Hoboken, NJ, USA, 1991; pp. 403–412. [CrossRef]
28. Kobiyama, M.; Mendonça, M.; Moreno, D.A.; Marcelino, I.P.V.d.O.; Marcelino, E.V.; Gonçalves, E.F.; Brazetti, L.L.P.; Goerl, R.F.; Molleri, G.S.F.; Rudorff, F.d.M. *Prevenção de Desastres Naturais Conceitos Básicos*; Organic Trading: Rosebery NSW, Australia, 2006; ISBN 858775503X.
29. Tram, V.N.Q.; Somura, H.; Moroizumi, T.; Maeda, M. Effects of Local Land-Use Policies and Anthropogenic Activities on Water Quality in the Upstream Sesan River Basin, Vietnam. *J. Hydrol. Reg. Stud.* **2022**, *44*, 101225. [CrossRef]
30. Pandey, S.; Kumar, P.; Zlatic, M.; Nautiyal, R.; Panwar, V.P. Recent Advances in Assessment of Soil Erosion Vulnerability in a Watershed. *Int. Soil Water Conserv. Res.* **2021**, *9*, 305–318. [CrossRef]
31. Sisay, G.; Gitima, G.; Mersha, M.; Alemu, W.G. Assessment of Land Use Land Cover Dynamics and Its Drivers in Bechet Watershed Upper Blue Nile Basin, Ethiopia. *Remote Sens. Appl.* **2021**, *24*, 100648. [CrossRef]
32. Wang, Y.; Liu, X.; Wang, T.; Zhang, X.; Feng, Y.; Yang, G.; Zhen, W. Relating Land-Use/Land-Cover Patterns to Water Quality in Watersheds Based on the Structural Equation Modeling. *Catena* **2021**, *206*, 105566. [CrossRef]

33. Ross, E.R.; Randhir, T.O. Effects of Climate and Land Use Changes on Water Quantity and Quality of Coastal Watersheds of Narragansett Bay. *Sci. Total Environ.* **2022**, *807*, 151082. [CrossRef] [PubMed]
34. Pike, R.J. The Geometric Signature: Quantifying Landslide-Terrain Types from Digital Elevation Models I. *Math Geol.* **1988**, *20*, 491–511. [CrossRef]
35. Schröder, B. Pattern, Process, and Function in Landscape Ecology and Catchment Hydrology—How Can Quantitative Landscape Ecology Support Predictions in Ungauged Basins? *Hydrol. Earth Syst. Sci.* **2006**, *10*, 967–979. [CrossRef]
36. Hengl, T.; Evans, I.S. Mathematical and Digital Models of the Land Surface. *Dev. Soil Sci.* **2009**, *33*, 31–63. [CrossRef]
37. Bishop, M.P.; Young, B.W.; Huo, D. Geomorphometry: Quantitative Land-Surface Analysis and Modeling. In *Reference Module in Earth Systems and Environmental Sciences*; Elsevier: Amsterdam, The Netherlands, 2018.
38. Mao, W.; Yang, J.; Zhu, Y.; Ye, M.; Liu, Z.; Wu, J. An Efficient Soil Water Balance Model Based on Hybrid Numerical and Statistical Methods. *J. Hydrol.* **2018**, *559*, 721–735. [CrossRef]
39. van Buuren, M.; Kerkstra, K. The Framework Concept and the Hydrological Landscape Structure: A New Perspective in the Design of Multifunctional Landscapes. Available online: https://doi.org/10.1007/978-94-011-2318-1_10 (accessed on 30 September 2022).
40. Neto, S.L.R.; Biffi, L.J. Aplicação de Um Modelo Linear Local Na Determinação de Alturas Ortométricas Referidas Ao Sistema Geodésico Brasileiro. *Bol. Goiano Geogr.* **2016**, *36*, 157–176. [CrossRef]
41. Quinn, P.K.B.; Chevallier, P.; Planchon, O. The Prediction of Hillslope Flow Paths for Distributed Hydrological Modelling Using Digital Terrain Models. *Hydrol. Process.* **1991**, *5*, 59–79. [CrossRef]
42. Ambroise, B.; Beven, K.; Freer, J. Toward a Generalization of the TOPMODEL Concepts: Topographic Indices of Hydrological Similarity. *Water Resour. Res.* **1996**, *32*, 2135–2145.
43. Dušek, J.; Dařenová, E.; Pavelka, M.; Marek, M.V. Methane and Carbon Dioxide Release from Wetland Ecosystems. In *Climate Change and Soil Interactions*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 509–553. [CrossRef]
44. Tarboton, D.G. A New Method for the Determination of Flow Directions and Upslope Areas in Grid Digital Elevation Models. *Water Resour. Res.* **1997**, *33*, 309–319.
45. Nobre, A.D.; Cuartas, L.A.; Momo, M.R.; Severo, D.L.; Pinheiro, A.; Nobre, C.A. HAND Contour: A New Proxy Predictor of Inundation Extent. *Hydrol. Process.* **2016**, *30*, 320–333. [CrossRef]
46. Momo, M.R.; Pinheiro, A.; Severo, D.L.; Cuartas, L.A.; Nobre, A.D. Desempenho Do Modelo Hand No Mapeamento de Áreas Suscetíveis à Inundação Usando Dados de Alta Resolução Espacial. *Rev. Bras. Recur. Hídricos* **2016**, *21*, 200–208. [CrossRef]
47. Bhatt, C.M.; Srinivasa Rao, G. HAND (Height above Nearest Drainage) Tool and Satellite-Based Geospatial Analysis of Hyderabad (India) Urban Floods, September 2016. *Arab. J. Geosci.* **2018**, *11*, 600. [CrossRef]
48. Santa Catarina. Plano de Recursos Hídricos Da Bacia Hidrográfica Do Rio Canoinhas e Afluentes Catarinenses Do Rio Negro. Available online: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/964417/1/BPD-46-2004-Santa-Catarina-.pdf (accessed on 30 September 2022).
49. EMBRAPA SOLOS Distribuição Geográfica Dos Solos Do Estado de Santa Catarina. Available online: https://www.fapesc.sc.gov.br/wp-content/uploads/2021/02/pgrh-canoinhas_produto_3_etapa_c_final_rev21jul2020.pdf (accessed on 30 September 2022).
50. AMPLANORTE. Plano de Desenvolvimento Regional Do Planalto Norte Catarinense. 2017. Available online: https://www.amplanorte.org.br/cms/pagina/ver/codMapaItem/74869 (accessed on 30 September 2022).
51. Rao, P.; Wang, Y.; Liu, Y.; Wang, X.; Hou, Y.; Pan, S.; Wang, F.; Zhu, D. A Comparison of Multiple Methods for Mapping Groundwater Levels in the Mu Us Sandy Land, China. *J. Hydrol. Reg. Stud.* **2022**, *43*, 101189. [CrossRef]
52. Souza, C.M.; Shimbo, J.Z.; Rosa, M.R.; Parente, L.L.; Alencar, A.A.; Rudorff, B.F.T.; Hasenack, H.; Matsumoto, M.; Ferreira, L.G.; Souza-Filho, P.W.M.; et al. Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. *Remote Sens.* **2020**, *12*, 2735. [CrossRef]
53. Avery, T.E. *Interpretation of Aerial Photographs*, 3rd ed.; Burgess Publishing Company: Minneapolis, MN, USA, 1977.
54. Souza, C.F.; Liesenberg, V.; Schimalski, M.B.; Casemiro Soares, P.R. Evaluating the Monetary Environmental Compensation over a Hydroelectric Power Plant Based on Opportunity Cost Simulation, GIS, and Remote Sensing Images. *Remote Sens. Appl.* **2021**, *23*, 100573. [CrossRef]
55. Costa, J.d.S.; Liesenberg, V.; Schimalski, M.B.; de Sousa, R.V.; Biffi, L.J.; Gomes, A.R.; Neto, S.L.R.; Mitishita, E.; Bispo, P.d.C. Benefits of Combining Alos/Palsar-2 and Sentinel-2a Data in the Classification of Land Cover Classes in the Santa Catarina Southern Plateau. *Remote Sens.* **2021**, *13*, 229. [CrossRef]
56. SDS. *Levantamento Aerofotogramétrico Do Estado de Santa Catarina. Secretaria de Estado Do Desenvolvimento Econômico e Sustentável*; ENGEMAP: Assis, Brazil, 2013.
57. Wolock, D.M.; McCabe, G.J. Differences in Topographic Characteristics Computed from 100- and 1000-m Resolution Digital Elevation Model Data. *Hydrol. Process.* **2000**, *14*, 987–1002. [CrossRef]
58. Wolock, D.M.; Price, C.V. Effects of Digital Elevation Model Map Scale and Data Resolution on a Topography-Based Watershed Model. *Water Resour. Res.* **1994**, *30*, 3041–3052. [CrossRef]
59. Meles, M.B.; Younger, S.E.; Jackson, C.R.; Du, E.; Drover, D. Wetness Index Based on Landscape Position and Topography (WILT): Modifying TWI to Reflect Landscape Position. *J. Environ. Manag.* **2020**, *255*, 109863. [CrossRef] [PubMed]
60. Gyasi-Agyei, Y.; Willgoose, G.; de Troch, F.P. Effects of Vertical Resolution and Map Scale of Digital Elevation Models on Geomorphological Parameters Used in Hydrology. *Hydrol. Process.* **1995**, *9*, 363–382. [CrossRef]

61. Camara, G.; Vinhas, L.; Ferreira, K.R.; de Queiroz, G.R.; de Souza, R.C.M.; Monteiro, A.M.V.; de Carvalho, M.T.; Casanova, M.A.; de Freitas, U.M. *TerraLib: An Open Source GIS Library for Large-Scale Environmental and Socio-Economic Applications*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 247–270. [CrossRef]
62. Nobre, A.D. A new landscape classification: The HAND Model. Available online: https://hess.copernicus.org/preprints/8/C2446/2011/hessd-8-C2446-2011.pdf (accessed on 30 September 2022).
63. ESRI. *ArcGis Release 10.5.1*; ESRI: Redlands, CA, USA, 2017.
64. Bonamigo, A.; Schimalski, M.B.; Soares, P.R.C.; Liesenberg, V.; de Souza, T.R.; Boesing, T.L.S. Variação Nas Áreas de Preservação Permanente Em Imóveis Rurais Do Planalto Sul Catarinense Segundo as Leis N° 4.771 e 12.651. *Cienc. Rural* **2017**, *47*, 1–6. [CrossRef]
65. Gharari, S.; Fenicia, F.; Hrachowitz, M.; Savenije, H.H.G. Land Classification Based on Hydrological Landscape Units. *Hydrol. Earth Syst. Sci. Discuss* **2011**, *8*, 4381–4425. [CrossRef]
66. Schier, D.T. Avaliação Do Índice Topográfico de Umidade Para Detecção de Zonas Urbanas Inundáveis. Master's Thesis, Universidade do Estado de Santa Catarina, Lages, Brazil, 2020.
67. Biffi, L.J.; Neto, S.L.R. Spatial Behavior of the Agronomic Variables of the Fuji Apple during Two Years in the Planalto Serrano of Santa Catarina State. *Rev. Bras. Frutic* **2008**, 975–980. [CrossRef]
68. Scheidegger, A.E. Horton's Law of Stream Numbers, 3rd ed. *Water Resour. Res.* **1968**, *4*, 655–658. [CrossRef]
69. Tan, Z.; Li, Y.; Zhang, Q.; Liu, X.; Song, Y.; Xue, C.; Lu, J. Assessing Effective Hydrological Connectivity for Floodplains with a Framework Integrating Habitat Suitability and Sediment Suspension Behavior. *Water Res.* **2021**, *201*, 117253. [CrossRef]
70. Sieker, H.; Klein, M. Best Management Practices for Stormwater-Runoff with Alternative Methods in a Large Urban Catchment in Berlin, Germany. *Water Sci. Technol.* **1998**, *38*, 91–97. [CrossRef]
71. Braune, M.J.; Wood, A. Best Management Practices Applied to Urban Runoff Quantity and Quality Control. *Water Sci. Technol.* **1999**, *39*, 117–121. [CrossRef]
72. Pereira, B.W.d.F.; Maciel, M.d.N.M.; Oliveira, F.d.A.; Alves, M.A.M.d.S.; Ribeiro, A.M.; Ferreira, B.M.; Ribeiro, E.G.P. Land Use and Water Quality Degradation in the Peixe-Boi River Watershed. *Ambiente Água* **2016**, *11*, 472–485. [CrossRef]
73. Wroblescki, F.A.; Bertol, I.; Wolschick, N.H.; Bagio, B.; Santos, V.P.d.; Bernardi, L.; Biasiolo, L.A. Assessed Impact of Anthropization on Water and Soil Quality in a Drainage Basin in Southern Brazil. *Rev. De Ciências Agroveterinárias* **2021**, *20*, 74–85. [CrossRef]
74. Neto, S.L.R.; Cordeiro, M.T.A. Análise Do Comportamento de Sistemas Urbanos Por Meio de Componentes de Sistemas Hidrológicos. *GEOUSP Espaço E Tempo* **2015**, *19*, 142–155. [CrossRef]
75. Ice, G. History of Innovative Best Management Practice Development and Its Role in Addressing Water Quality Limited Waterbodies. *J. Environ. Eng.* **2004**, *130*, 684–689. [CrossRef]
76. Tingsanchali, T. Urban Flood Disaster Management. In *Proceedings of the Procedia Engineering*; Elsevier Ltd.: Amsterdam, The Netherlands, 2012; Volume 32, pp. 25–37.
77. Woods Ballard, B. *Construction Industry Research and Information Association. The SuDS Manual*; CIRIA: London, UK, 2016.
78. Maidment, D.; Rajib, A.; Lin, P.; Clark, E.P. *National Water Center Innovators Program Summer Institute Report 2016*; National Water Center: Tuscaloosa, AL, USA, 2016.