

Hydrological regulation capacity of soils and its application in water and biodiversity conservation

Carlos Castro^{1,*}, Yolima Agualimpia² Robinson José García Gavilán³

¹Universidad Internacional de Investigación México, Postdoctoral program, 77533, Cancún-México

* Corresponding Author Email: carlos.castro@uiimex.edu.mx - ORCID: [0000-0003-3125-8349](https://orcid.org/0000-0003-3125-8349)

²Universidad Distrital Francisco José de Caldas, 111711, Bogota-Colombia

Email: yagualimpia@udistrital.edu.co - ORCID: [0000-0002-4262-954X](https://orcid.org/0000-0002-4262-954X)

³Universidad Internacional de Investigación México, Postdoctoral program, 77533, Cancún-México

Email: robinson.garcia@uiimex.edu.mx - ORCID: [0009-0005-0929-3844](https://orcid.org/0009-0005-0929-3844)

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Abstract: The importance of soil in maintaining environmental flows and preserving biodiversity has been underestimated in many cases. However, research that takes an eclectic approach that considers both water and soil has demonstrated the importance of this information. It is essential to recognize the hydrological characteristics of a region by including soil variables, which are accessible to everyone. This will not only improve our understanding of water availability in a region, but will also lay the foundation for continued monitoring of this vital resource. In this context, an inclusive and precise conceptual approach has been developed to understand the water cycle and its spatial variation. The main objective of this research has been the creation of a technical instrument that allows evaluating the capacity of lands to store and regulate rainwater at a regional level. This instrument seeks to generate detailed information on wet and dry areas, as well as propose an interpretation based on spatial patterns. These patterns will allow the identification of lands that present a greater risk of desertification, thus offering a valuable tool for the sustainable management of natural resources.

1. Introduction

To advance research oriented towards sustainable alternative land uses, addressed by the Soils and Ecology research group of the Agustín Codazzi Geographic Institute, a multidisciplinary team of specialists was formed. This team collaborated in the co-construction of an indicator designed to analyze the moisture retention capacity of soils. The purpose of this indicator was to offer solutions to previously identified problems related to the yield and quality of water resources in the middle sector of the Sumapaz river basin in Cundinamarca [1].

The group achieved significant progress by identifying sectors of the Cuja river basin in the municipality of Fusagasugá that require special management practices. These practices aim to minimize the socio-environmental impact affecting the river, a problem addressed in several academic investigations, especially those integrating soil and hydrology aspects [2].

In this research, previous advances in knowledge are leveraged to integrate them into a multiscale model. This model aims to analyze the water capacity of lands using information from general soil surveys, which have national coverage. This allows complementing the reports of the National Water Study in Colombia. This integration enables researchers to consider soil as an essential environmental component in regulating flows for the conservation of river ecosystems [3], thus becoming a module that improves the resolution of information provided by the Institute of Hydrology, Meteorology and Environmental Studies [4].

The technical devices necessary for monitoring water resources demand a structure that enables data integration, using variables, indicators, and indices. This integration is fundamental to synthesize

information related to soil and water, thus allowing the obtainment of the spatial variation of the water resource. This approach facilitates a detailed analysis at the municipal level in Colombia, contributing to progress in controlling socio-environmental demand.

The analysis presented below constitutes a subsequent step to the examination of natural channel hydraulics, which is part of water systems and falls within the scope of basin morphometry. This analysis aims to integrate runoff data, which is a product of the National Water Study [4].

At a regional level, at a 1:100,000 scale, soil information consists of variables adjusted to the representation scale. These variables are gradually being refined, contributing to the purification of information previously used in defining sustainable alternative uses [5].

The application of spatial analysis techniques using indicators is fundamental to understanding both spatial and temporal dynamics. By reducing the complexity of representation to a select set of variables, decision-making based on data collected in general studies is facilitated. This approach is supported by a rational logic backed by experience acquired through specialized knowledge in soils.

For this research, soil hydrophysical properties are defined as those relief and soil characteristics that influence the initial entry of water into the soil (sorptivity), clay migration and accumulation (pore plugging), the vertical water infiltration rate (infiltration), lateral water movements through macropores (hydraulic conductivity), and in general, water movement, whether represented through numerical values or interpretations based on soil profile morphology.

2. Materials and Methods

The criteria used to define the regional scale are based on the interpretive approach provided by the expert in analyzing soil morphology and pedogenetic processes observed in the field for each pedological unit (considering climatic, topographic, and parental material aspects). This criterion is reflected in the soil map legend and, specifically, in the integration of Soil Cartographic Units.

Based on the aforementioned criteria, the land water capacity index analysis relies on specific soil variables, which are grouped according to the following classification:

- Hydrophysical variables that identify:
- Water evacuation in the lands
- Water storage in the lands

It is important to note that soil is composed of various layers or horizons, known as genetic horizons, identified with the nomenclature A, B, and transitional to C; the latter excludes the underlying material from which the soils formed. In another context, Campy and Macaire (1989) defined superficial formations as the set of transformed or altered geological materials, which, in the case of soil surveys, encompass the Cr horizons and their transitional elements down to the soil-originating material, representing the deepest part of the soil studied by pedologists [6]

2.1. Hydrophysical Variables of Water Evacuation

Variables related to water evacuation are intrinsically linked to both the slope degree and relief shape, within the landscape context. Furthermore, with the pedological approach, these variables relate to soil granulometry, expressed through textural classes.

These variables can be contrasted both in digital terrain models and hydro-pedological balances, which integrate monthly precipitation data along with textural groups and effective soil depth.

In the context of water evacuation in the soil, hydrophysical possibilities are examined and evaluated through two vectors that facilitate interpreting water movement in terms of magnitude and direction. Moreover, this process can be studied by analyzing the soil profile morphology.

Two flow directions were examined. The first of these is interpreted as the removal of surface waters, determined by the recognition of the natural drainage of the soil, the study of colors, and soil mottling. The second shows the movement of water within the soil, interpreted as internal drainage, which groups different types of textures that have similar drainage to water that theoretically produces runoff when field capacity is exceeded. This cartographic level also covers other physical tests used to measure water dynamics, such as infiltration rate and water movements in pores. These tests are closely related to

textural classes and soil structure. The criteria used to evaluate dynamic water conditions are linked to the "permanence of water in the soil" and its possibilities of deep percolation.

Conceptual analyses prior to the research, which use sustainability indicators, have indicated the need to include a third variable acting as a mediator (a relationship between three variables). Therefore, the soil moisture regime variable is introduced, which is reported in soil surveys.

A value is assigned to each analyzed variable, in accordance with the experience and theoretical knowledge of the soil survey team, following the protocol established by qualitative methods [7]. The natural drainage variables are ordered, starting with those that retain water and have lower values, up to those that facilitate high infiltration rates and lead to runoff or, failing that, to surface runoff, caused by steep slopes.

Within the framework of this research, it is initially assumed that soil variability is adequately represented within the established limits. This assumption is necessary as it forms the basis upon which the subsequent morphological analysis will be developed. It is considered that there are no transitional soils between different drainage classes, which simplifies the analysis and allows for a clearer classification of soil characteristics.

The limit defined for this analysis corresponds to the soil cartographic unit, which has been previously determined during the soil survey. This delimitation provides a coherent spatial framework for evaluating the properties of the soil in question. Furthermore, the distribution of soil profile qualities according to the cartographic phases established during the initial mapping is taken into account.

Among the variables considered in this analysis are erosion, slope, stoniness, waterlogging, and flooding. These characteristics have been meticulously mapped during the soil survey to provide a complete understanding of the edaphic environment. The inclusion of these variables allows for a comprehensive assessment of the soils within the defined cartographic unit, facilitating the identification of significant patterns and trends. It is important to emphasize that this methodological approach is based on the premise that the cartographic information and represented soil characteristics are accurate and reliable. It is expected that this analysis will contribute significantly to the understanding of soil variability in the study area and serve as a basis for future research and applications in the field of soil science and natural resource management. It is important to recognize that soil cartographic units comprise a variety of pedological components that exhibit a diversity of hydrophysical properties. It is fundamental to understand and assimilate these mapped conditions for an accurate assessment of the soil in question. For example, soil profiles with limited water capacities tend to be associated with characteristics such as steep slopes or stony areas. These conditions can restrict the soil's capacity to retain water and can influence its drainage capacity. On the other hand, soil profiles with high water capacities are typically found in flatter terrains, where they may be susceptible to waterlogging or flooding due to the accumulation of water on the surface or in the soil profile. By understanding how the hydrophysical properties of the soil relate to the mapped terrain conditions, valuable information can be obtained about the distribution and behavior of soils in the landscape. This understanding is fundamental for the sustainable management of natural resources and for informed decision-making in various areas, such as agriculture, soil conservation, and land use planning. Two flow directions were examined. The first of these is interpreted as the removal of surface waters, determined by the recognition of the natural drainage of the soil, the study of colors, and soil mottling. The second shows the movement of water within the soil, interpreted as internal drainage, which groups different types of textures that have similar drainage to water that theoretically produces runoff when field capacity is exceeded. This cartographic level also covers other physical tests used to measure water dynamics, such as infiltration rate and water movements in pores. These tests are closely related to textural classes and soil structure. The criteria used to evaluate dynamic water conditions are linked to the "permanence of water in the soil" and its possibilities of deep percolation. Conceptual analyses prior to the research, which use sustainability indicators, have indicated the need to include a third variable acting as a mediator (a relationship between three variables). Therefore, the soil moisture regime variable is introduced, which is reported in soil surveys. A value is assigned to each analyzed variable, in

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Established Variables and Values

Table 1. Natural drainage and its water evacuation value [1].

Natural drainage	Value
Swampy	1
Very poor	2
Poor	3
Imperfect	4
Moderate	5
Good	6
Excessive	8
Not identified	0

Natural drainage is linked to the presence or absence of water tables in the soil, a characteristic determined from the modal soil profile. In this profile, redoximorphic conditions reflected in the appearance of gray or red colors are analyzed (Figure 1). The interpretation of water movement in the

soil, known as internal drainage, is closely linked to the textural class of the soil and its geomorphological position within the landscape.

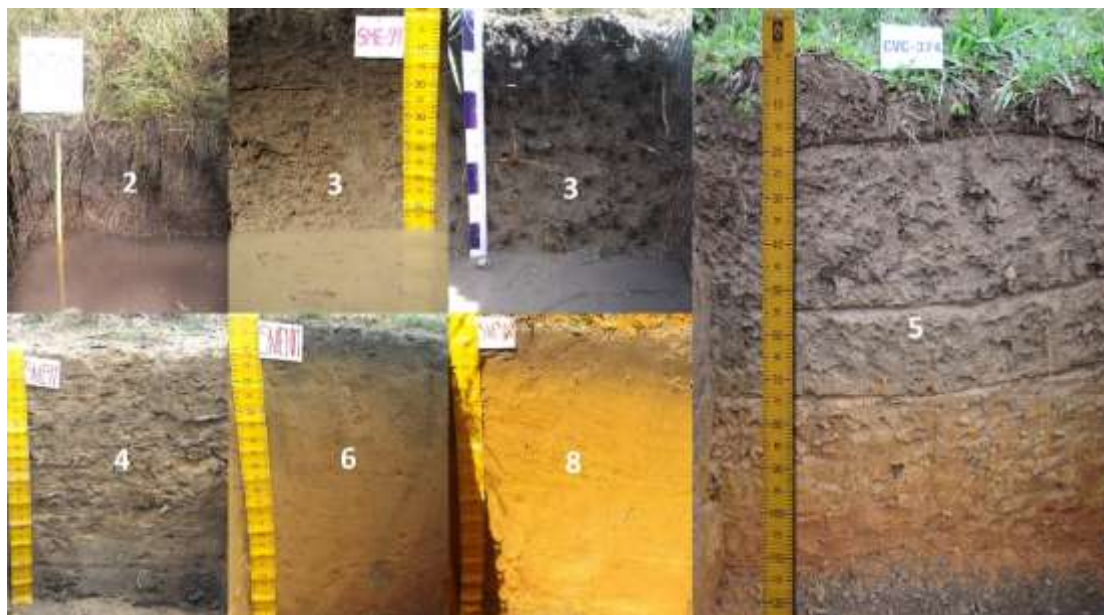


Figure 1. Soil profiles with different natural drainages.

Table 2. Internal drainage and water evacuation values [1].

Internal drainage	Value
Very slow	1
Slow	2
Medium	3
Fast	4
Very fast	5
Without drainage	0

In the description of the soil profile, other important elements were also taken into consideration, such as the color and consistency of the aggregates in a wet state. These aspects add depth to our understanding of the physical properties of the soil and can provide valuable information about its composition and structure.

Furthermore, compaction indices were observed during the soil survey, which were recorded as part of the profile description. This observation is fundamental, since soil compaction can have important repercussions on its water retention capacity, root aeration, and soil biological activity.

By considering these elements in conjunction with the hydrophysical properties and the mapped terrain conditions, a more complete and detailed picture of the soil under study is obtained. This information is essential for understanding its functioning and for designing effective soil management and conservation strategies.

Water Loss Indicator (WLI)

The indicator is derived from the analysis of variables that evaluate water loss in the soil. It is used to perform a qualitative assessment of the natural state through which the soil eliminates water, both in its surface form, depending on the degree of slope, and in water losses caused by high infiltration rates, which refer to water movements within the profile. The latter are associated with the pedogenetic footprint recorded in the internal morphology of the soils.

$$WLI = Cal_{ND} \times Cal_{ID} \quad (1)$$

Where: WLI is the water loss indicator (dimensionless) Cal_{ND} is the numerical value of natural drainage (Table 1) Cal_{ID} is the numerical value of internal drainage (Table 2)

The categories for the interpretation of the water loss indicator are detailed in Table 3.

Table 3. Water Loss Indicator [1].

WLI	Class
< 9	Low
9 – 18	Moderate
> 18	Fast

Water Evacuation Indicator (WEI)

The Water Evacuation Indicator provides a precise understanding of the current water loss conditions. It establishes a comparison between the water lost on the surface, influenced by vegetation cover, and that lost by deep percolation, determined by the textural groups of the soil. Additionally, it qualitatively evaluates water retention by analyzing the soil moisture regime.

To develop this indicator effectively, it is essential to establish the categories of the controlling elements, which include the Hydrological Protection Index (HPI) and the weighting values of clay contents, represented by the indicator known as the Buol Textural Coefficient - BTC [8].



Figure 2. Natural forest and pasture covers (Photograph: Carlos Castro, 2015)

Table 4 shows the Hydrological Protection Index values corresponding to each type of vegetation cover. Figure 2 shows the reclassification of covers according to the HPI.

The relationship between the Hydrological Protection Index (HPI) and its impact on water evacuation is based on the evaluation of the discrepancy between maximum protection, a purely ecological concept, and current land use. The latter implies analyzing surface evacuation taking into account the present vegetation cover, as reflected in the concept of the Water Evacuation Indicator (WEI).

Table 4. Hydrological Protection Index (HPI) Values by Vegetation Cover [5]

COVER	HPI
FORESTS	
- Dense natural forests	1.0
- Sparse natural forests	0.9
PASTURES	
- Natural pastures	0.6
- Association of pastures, scrubs, and forest relicts	0.8
PASTURES-CROPS	
- Association of crops, stubble, pastures	0.7
OTHER TYPES OF VEGETATION	
- Mangrove vegetation	1.0

WATER BODIES (Swamps, wetlands, marshes)	1.0
SPECIAL TYPES OF VEGETATION	
- Clean savanna	0.2
- Shrub savanna	0.4
- Xerophytic vegetation	0.1
- Paramo vegetation	1.0
WATER BODIES (Natural and artificial, continental and marine)	
- Lakes, lagoons, reservoirs, dams, free surfaces	1.0
WASTELANDS	
- Exposed rocks, rocky outcrops, eroded miscellaneous, sand blankets, and lands desertified by salinization	0.1
- Bare soils, rocky outcrops with very sparse vegetation relicts	0.1

The presence of weighted clay in the solum provides a solid basis for estimating water infiltration rates, i.e., vertical water movements in the soil. This premise is supported by the theoretical concept that the most significant infiltration losses occur in soils with sandy textures, while soils with high clay contents have a greater water retention capacity. Therefore, it is reasonable to assume that soil water retention will be considerably better in these textures. Table 5 provides a description of the textural groups, clay contents, and the factors used to calculate the water and mineral reserve.

Buol et al. (1975) introduced the concept of textural groups to distinguish between the surface layer and the subsequent 25 cm, which they called 'Type', and between the subsequent 25 and 50 cm, which they called 'Subtype' [8]. This granulometric analysis was carried out with the purpose of evaluating the possibilities of use and management of soil fertility.

Table 5. Buol Textural Coefficient (BTC), weighted clay contents, and factor value [1].

BTC	Weighted clay contents (%)	Values
Clayey	greater than 35%	0.7
Medium	between 18 and 35%	0.5
Sandy	less than 18%	0.3

The clay weighting values are determined through laboratory analysis of the profiles identified by the Soil Cartographic Unit, as well as the measurement of the horizon thicknesses in relation to the total thickness of the solum. The formula used for this calculation is as follows:

$$CWV = \frac{Cl_i \times T_i}{TT} \quad (2)$$

Where: CWV is the clay weighting value Cl_i is the clay percentage in horizon i T_i is the thickness in cm of horizon i TT is the total thickness of the solum in cm

Soil Moisture Regime Factor

For this study, the moisture regime is defined as a hydrophysical characteristic that evaluates the presence or absence of water in the control section of the soil profile. Its unit of measurement is expressed in days, indicating the periods in which said section is wet or dry throughout a year. It is determined by observing evidence in the soils, reflecting the climatic conditions during their formation and their location within the landscape.

Table 6. Soil moisture regimes [9,10]

MOISTURE REGIME	YEARS	CONTROL SECTION (cumulative days)	CONTROL SECTION DRY (consecutive days)	CONTROL SECTION WET (cumulative days)	CONTROL SECTION (consecutive days)
AQUIC	10/10			Saturated	Few days

PERUDIC	>5/10	< 90 (3)	< 45 summer (1)	> 180 (2)	> 90 (2) / > 45 winter (4)
UDIC	>5/10	< 90 (3)	< 45 summer (1)	> 270 (4)	
USTIC	>5/10	< 90 (3)	< 45 summer (1)	> 180 (2)	> 90 (2) / > 45 winter (4)
XERIC	>5/10		> 45 summer (1)	> 180	
ARIDIC	>5/10	> 180 (1)		< 180 (2)	< 90 (2)
TORRIC	>5/10	> 180 (1)		< 180 (2)	< 90 (2)

Summer = During the 4 months following the summer solstice Winter = During the 4 months following the winter solstice (1) = Dry in all parts of the control section (2) = Moist in some or all parts of the control section (3) = Dry in some or all parts of the control section (4) = Moist in all parts of the control section

The soil moisture regime emerges as a fundamental indicator that allows evaluating the climatic and topographic conditions present during the soil formation process, being a direct reflection of the prevailing climate experienced throughout its development. This essential indicator characterizes water availability, playing a critical role in regulating water losses and accumulations in the soil. These interactions leave a marked impression on the morphology of the soil profile. By analyzing this morphology, we can discern the dynamic processes that have taken place both in the past and in the present over the years (see Table 6 for detailed reference).

According to the analyses carried out in collaboration with recognized experts in the field of agrology, weighted values are assigned to the soil moisture regime, which are ordered from those with less drainage to the soils with the highest percolation indices (see Table 7 for detailed reference).

Table 7. Factor According to Soil Moisture Regime [1].

Classes	Moisture factor value
Aquic	1
Perudic	2
Udic	3
Ustic	4
Aridic	5
Torric	6
Xeric	7

The Water Evacuation Indicator (WEI) is finally calculated using the following formula:

$$WEI = Val_{ND} + [1.1 - HPI(Val_{ID} \times BTC)] \times SMR_{factor} \quad (3)$$

Where: Val_{ND} is the weight given to the natural drainage of the soil (Table 1). HPI is the hydrological protection index based on vegetation cover (Table 4). BTC represents the weighted values of the Buol textural coefficient (Table 5). SMR_{factor} is the moisture regime factor (Table 7). Table 8 shows the ranges of the water evacuation index and its corresponding interpretation within the analyzed space.

2.2. Hydrophysical Variables of the Water Storage Index

The water storage index is defined as the inherent capacity of a soil to regulate water flow, encompassing both the retention and accumulation of water from rainfall [1]. The variables used for this purpose are closely related to the depth and composition of the soil strata, factors that ultimately determine the solum's capacity to retain and conserve rainwater, along with its nutrients [2].

Table 8. Categories used in the interpretation of the Water Evacuation Indicator (WEI)

WEI Ranges	Interpretation
< 5	Very Slow

5 - 7	Slow
7 - 10	Moderate
10 - 20	Fast
> 20	Very fast

Source: [1]

The hydrodynamic variables under analysis are based on the physical properties of the horizons resulting from soil formation, with a particular focus on the superficial strata and the depth of the edaphic profile [1]. In essence, the objective is to specify the thickness of the soil horizons (A, B, and transitional C horizons).

The third important element in this relationship is the analysis of the stratum's permeability, information obtained from the soil profile that indicates the consistency of the C, Cr horizon, or type of stratum. This information is fundamental for inferring the possibilities of water loss or storage in the soil.

Storage Variables and their Categories

The evaluation of water retention characteristics in soils can be carried out using the categories defined in the Soil Classification Manual of the United States Department of Agriculture [9] or in the Soil Survey Manual of the Agustín Codazzi Geographic Institute [10]. These categories, with their respective classes detailed in Table 6, provide a starting point for the evaluation. However, it is possible to expand the repertoire of classifications by considering other compositions documented in previous soil research, as well as by making direct field observations through verification boreholes.

Stratum Composition Indicator (SCI)

Information about the parental material of soils, collected through agrological studies, constitutes an important aspect in the analysis of the substrates that gave rise to these soils. This material refers to the geological substrate, which may be covered by Quaternary deposits, thick mantles of volcanic ash, or colluvial debris in certain cases. To accurately understand the predominant nature of the underlying material, it is fundamental to consult specialized sources in structural geology. This is because soil survey works are often limited to a maximum depth of 120 cm, which highlights the importance of accessing detailed geological information for a complete interpretation of the edaphic environment (Figure 3).



Figure 3. Geological substrate (Photograph: Carlos Castro, 2015)

To create categories, a substrate type classification was performed (Table 9).

Table 9. Substrate class rating [1].

SUBSTRATE CLASS	RATING
Clayey and volcanic ashes	10

Lacustrine and organic materials	9
Marly	8
Calcareous or mixed	7
Gypsiferous	6
Silty	5
Sandy	4
Stony	3
Schistose	2
Gravelly	1

The first three substrate types, from clayey to marly, are classified within the clayey category. The following three, from calcareous to silty, are placed in the medium category. Finally, the last four, from sandy to gravelly, are included in the coarse category.

When information on structural geology and the composition of the stratum supporting the soil is available, especially when the latter corresponds to a coarse category, it is feasible to delineate aquifer recharge zones. These areas acquire significant relevance in projecting potential groundwater reserves in the future.

Solum Thickness Indicator (STI)

Solum thickness is defined as the set of horizons or layers found before the upper limit of the saprolite, which is the rock or parental material that gave rise to the soils.

Below are the thickness indicators used for analyzing water storage in the lands:

Table 10. Solum thickness indicator rating [1].

DEPTH TO STRATUM (cm)	RATING
Less than 50	1
Between 50 and 100	2
Greater than 100	3

Soil Consistency in Wet State

A fundamental factor in mediating this balance is the consideration of the weighted value of the consistency of soil horizons in cases of divergent characteristics, or the evaluation of the value of the soil layer or substrate in the absence of compactions that hinder water movement within the profile. This information is meticulously recorded in the morphological description of the profiles, focusing mainly on the horizons close to the parental material, such as Cr, saprolite, or the underlying material.

Table 11 details the values assigned to each of the wet soil consistency categories for the different soil horizons.

Table 11. Weighting factor by wet consistency class [1].

WET CONSISTENCY CLASS	FACTOR VALUE
Loose	1
Very friable	2
Friable	3
Firm	4
Very firm	5
Extremely firm	6

The factor to be weighted according to the consistency class and the horizon thickness is calculated using the following formula:

$$WCV = \sum \left(\frac{V_i \times T_i}{TT} \right) \quad (4)$$

Where: WCV is the weighted value of wet consistency V_i is the consistency factor value in each horizon (according to Table 11) T_i is the thickness in cm of each horizon i (data from the modal soil profile) TT is the total thickness of the solum in cm (data from the modal soil profile)

Composite Storage Indicator (CSI)

The Composite Storage Indicator (CSI) is defined as the intrinsic relationship that exists between the storage capacity present in soils, which varies according to the different solum thickness ranges and substrate composition.

$$CSI = Val_{SCI} + Val_{STI} \quad (5)$$

Where: CSI is the composite storage indicator Val_{SCI} is the numerical value of the substrate composition indicator (Table 9) Val_{STI} is the numerical value of the solum thickness indicator (Table 10)

Table 12 presents a summary of the interpretation of the combined variables of stratum and solum thickness, fundamental information for the characterization of water storage in the soil.

Table 12. Interpretation of the composite storage indicator [1].

CSI	COMBINATION OF VARIABLES	CLASS
> 25	Fine and deep strata (greater than 100 cm.)	High
12 - 25	Medium strata depth between 50 and 100 cm. or fine composition strata less than 100 cm.	Moderate
< 12	Coarse strata with depth greater than 50 cm. or medium composition strata at 50 cm. and less	Low

Actual Storage Indicator (ASI)

The Actual Storage Indicator (ASI) is defined as the relationship between the substrate composition and the solum thickness, where natural storage is directly influenced by the weighted consistency factor of all horizons identified to a depth of less than 150 cm.

$$ASI = (Val_{Substrate} \times 0.6) + (Val_{SThick} \times 0.4) \times WCV \quad (6)$$

Where: $Val_{Substrate}$ is the substrate value (Table 9) Val_{SThick} is the solum thickness value (Table 10) WCV is the weighting factor of the substrate consistency (Table 11)

This indicator can experience dynamic changes over time due to land overexploitation or tillage practices that generate plow layers or land compaction. These layers, both in theory and in practice, reduce infiltration rates and can be reflected in the weighted consistency values of soil aggregates, which ultimately results in a decrease in water storage indices.

Table 13 presents the interpretations of the actual water storage interpreted for each soil profile represented in the Soil Cartographic Unit.

Table 13. Interpretation of the actual water storage indicator in the soil [1].

RANGES	INTERPRETATION
< 15	Very low
15 - 20	Low
20 - 30	Moderate
30 - 50	High
> 50	Very high

Water Capacity Index (WCI)

It is defined as the capacity of lands to retain water in the solum, which is determined by hydrophysical variables that balance water storage and retention. This capacity is necessary to identify aquifer recharge

sites. The land water capacity index provides vital information on subsurface water flow and its capacity to regulate water in the solum [1].

The obtained index arises from the interaction between the storage and evacuation indicators, providing specific information for each taxonomic or cartographic unit on the soil's water retention capacity. This knowledge is fundamental for understanding its utility in terms of plant support, ecosystem maintenance, and agricultural applications.

Final formula:

$$WCI = \frac{ASI}{WEI} \quad (7)$$

Where: *WCI* is the soil water capacity index *ASI* is the Actual Storage Indicator *WEI* is the Water Evacuation Indicator in Lands

Table 14 offers interpretations of the land water capacity index, which uses the hydrological protection indices represented in the vegetation cover as a dynamic analysis unit. As vegetation cover decreases, regulatory effects are diminished, resulting in a reduction of infiltration rates. This situation can lead in the long term to an accelerated water shortage in watersheds, progressively leading to land desertification and increasing erosive processes caused by surface runoff. Furthermore, this index is sensitive to the decrease in soil storage indices due to the presence of compacted layers, which hinder water infiltration and promote increases in runoff flows.

Table 14. Interpretation of the land water capacity index [1].

WCI Ranges	Water capacity interpretation
< 0.75	Extremely low
0.75 – 1.00	Very Low
1.00 – 1.50	Low
1.50 – 2.80	Moderate
2.80 – 6.00	High
> 6.00	Very high

3. Results and Discussions

The methodology presented above represents an innovative proposal to evaluate the water retention capacity of soils. It is based on the cartographic information available on the Colombian platform and the open data provided by the Agustín Codazzi Geographic Institute. The cartography generated from this process is revealed as an invaluable tool for enriching geographic descriptions at the municipal level, which contributes significantly to land use planning and procedures related to the creation and updating of multipurpose cadasters. The information presented is contextualized within the regional scale at the municipal level. However, it is necessary to highlight that it can be refined to more detailed scales through the use of soil surveys at larger scales. In this sense, its versatility stands out as a valuable instrument for soil data management, with direct applications in territorial development and strategic planning of environmental management. The methodology in question focuses on the analysis of the municipality of Ayapel, located in the department of Córdoba, in the lowest region of La Mojana. Its main objective is to carry out an exhaustive characterization of the water capacity of this territory, comparing it with the hydric soil analyses previously carried out by the Agustín Codazzi Geographic Institute, in collaboration with the Alexander Von Humboldt Institute.

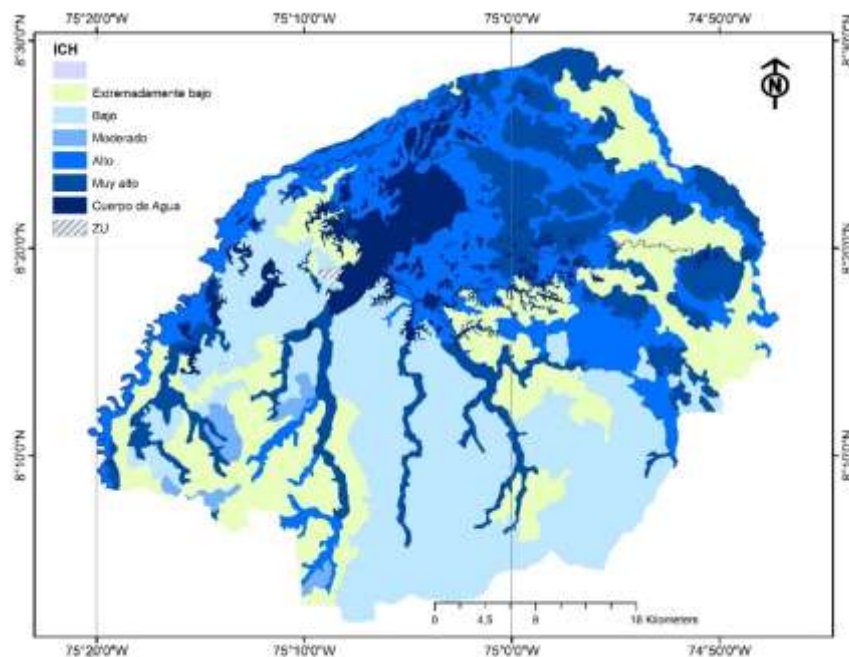


Figure 4. Distribution of the water capacity of lands in the municipality of Ayapel in the department of Córdoba.

The materialization of the regional analysis of the water capacity of the municipality of Ayapel is presented in Figure 4. This figure shows the distribution of the hydric characteristics of the lands, which clearly reveal the pattern of runoff and water accumulation from the southern sector to the north, as well as the identification of the lands most susceptible to prolonged drought periods, represented in yellow color. This methodology represents a regional vision at a 1:100,000 scale and is presented as a significant contribution for the interpretation of relevant hydrophysical variables at that scale. Its objective is to define the availability of surface water for the ongoing multipurpose cadaster in Latin American countries.

4. Conclusions

Obtaining spatial information on the water storage capacity of soils, from morphological data at a general scale of 1:100,000, represents the first step in defining the hydrological characteristics of municipalities in Colombia. This initiative, led with researchers from the Geography Sub-directorate of the Agustín Codazzi Geographic Institute, seeks to integrate these data into municipal land-use planning guidelines. By better understanding how topography and soil composition interact with the water cycle, it is possible to move towards a more effective and sustainable management of our water resources at the local and regional levels.

The spatial analysis of water footprints present in soil morphology not only reveals an innovative approach to understanding our geography, but also fosters the creation of new technical-scientific tools that enrich the territorial planning process at the municipal level. This approach, rooted in a life-centered geography, establishes a framework for interpreting soil cartographic data more comprehensively.

By integrating these water footprints into soil cartography, novel applications are generated that transcend geographic representation. These applications are especially valuable in the context of the multipurpose cadastre, where the relevance of environmental issues becomes increasingly important. Furthermore, these tools act as mediators between productive lands and environmentally sensitive areas, helping to prevent soil degradation and mitigate desertification risks. This approach not only promotes a more efficient management of our resources, but also fosters harmony between human development and environmental preservation. It is considered that this approach emerges as a methodology in

constant development, open to continuous testing and refinement, with the purpose of becoming a reliable and versatile technical instrument for researchers with both an environmental and productive focus. It is based on the experience acquired both in professional practice and in the academic field, merging theoretical knowledge with practical application. This tool, which is available to the knowledge society, is nourished by a wide range of resources available on online platforms, including data in spatial formats such as shapefiles and detailed descriptions of soil profiles. By making use of these information sources, its usefulness is enhanced and its capacity to address a variety of challenges related to land and natural resource management is enriched. Furthermore, it is important to emphasize that this methodology is not only limited to the academic sphere, but is also conceived as a practical and applicable tool in the professional field. Its flexibility and adaptability allow its integration into various contexts and projects, thus promoting interdisciplinary collaboration and knowledge exchange. The methodology under consideration represents a bridge between theory and practice, between research and action, providing a solid framework to address environmental and productive challenges comprehensively and sustainably in the digital age.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
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References

- [1] Castro, C. E., Moncada, J., Camilo, Z., Castelblanco, J., Saavedra, F., Espinel, A., & Gaviria, M. (2004). *Diagnóstico y alternativas de solución para mejorar el rendimiento y calidad del recurso hídrico en la cuenca media del río Sumapaz* [Trabajo de grado, Universidad Santo Tomás]. Bogotá.
- [2] Agualimpia, Y., & Castro, C. (2016). Análisis de posibles conflictos entre usos agrícola, rural, urbano y ambiental de los suelos. *Revista Ingeniería y Región*, 16(2), 85-94. <https://journalusco.edu.co/index.php/iregion/article/view/1303/2541>
- [3] Agualimpia, Y., & Castro, C. E. (2021). Hacia el ordenamiento del territorio. El eclecticismo del agua y el suelo: suelos hidroconductores (SHC). Caso microcuenca de la quebrada Barbillas, Colombia. En Y. D. C. Agualimpia Dualiby, M. G. González Pérez, F. Jalomo Aguirre, & E. X. M. García García (Comps.), *Agua, ciudad y territorio*. Universidad de Guadalajara y Universidad Francisco José de Caldas; Typo Taller. <http://ambiental.udistrital.edu.co:8080/libro-agua-ciudad-y-territorio>
- [4] IDEAM - Instituto de Hidrología, Meteorología y Estudios Ambientales. (2018). *Estudio Nacional del Agua*.
- [5] IGAC - MADS Instituto Geográfico Agustín Codazzi y Ministerio de Ambiente y Desarrollo Sostenible. (2007). *Definición de usos alternativos y sostenibles para la ocupación de las tierras a nivel nacional (Colombia)*. Bogotá.
- [6] Campy, M., & Macaire, S. S. (1989). *Geologie des formations superficielles*. Masson.
- [7] Gibbs, G. (2012). *El análisis de datos cualitativos en investigación cualitativa* (Colección Cualitativa, U. Flick, Dir.). Morata.
- [8] Buol, S. W., Sánchez, P. A., Cate, R. B. Jr., & Granger, M. A. (1975). Soil fertility capability classification: A technical soil classification system for fertility management. En *State Univ., Raleigh, N. C.* (pp. 126-145).
- [9] USDA - United States Department of Agriculture. (2022). *Keys to Soil Taxonomy* (13.^a ed.). Natural Resources Conservation Service. <https://www.nrcs.usda.gov/sites/default/files/2022-09/Keys-to-Soil-Taxonomy.pdf>
- [10] IGAC - Instituto Geográfico Agustín Codazzi. (2021, 11 de mayo). *Levantamiento de suelos a diferentes escalas*. Subdirección de Agrología. Código: PC-GAG-05.