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Potential zones for rainwater reserve in the face of climate change in a high Andean watershed

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ABSTRACT

Climate change is one of the main threats to the sustainable management of water in various regions of the world, especially in mountainous watersheds like the Mantaro River basin, located in the highland region of Peru. This basin is vital for agriculture and hydroelectric energy production in the area, but it faces significant challenges due to the variability of water resources and climate change. To mitigate these effects, there is a recognized need to identify suitable areas for the storage and distribution of rainwater. In this study, thematic maps of the basin were created using the technique of multi-criteria analysis, considering factors such as precipitation, soil type, slope, texture, and watershed order. Four climate change scenarios (RCP 2.5, RCP 4.5, RCP 6.0, and RCP 8.5) were also included to assess their impact on potential areas for rainwater harvesting. It was identified that approximately 54% of the lower lands in the basin, with a flat topography, are suitable for the implementation of rainwater harvesting systems. However, the low amount of precipitation in these areas, compared to the highlands, represents a significant challenge. Regarding the climate change scenarios, it was determined that under the RCP 2.5 and RCP 8.5 scenarios, the upper areas of the basin, which comprise approximately 11% of it, would be the most suitable for the implementation of these infrastructures. On the other hand, with the RCP 4.5 and RCP 6.0 scenarios, the mid-altitude areas, which cover about 35% of the basin, would be the most strategic.

Keywords: geographic information systems, suitability, hydrological cycle, water management, climate scenarios.

INTRODUCTION

The demographic increase, accelerated urbanization, intensive water use, improved living standards, pollution, changes in ecosystems, and hydrological variability (Chakkaravarthy, 2019) have led to a greater allocation of both surface and groundwater resources (FAO, 2007). Added to this are the effects associated with climate change. In our country, water availability is approximately 70.000 m³/inhabitant/year, which represents about 5% of global runoff. For example, in the coastal region, only 2% of the population has access to the resource (Aranda, 2015). In the highlands and jungle regions, due to changes in the rainfall regime, temperature, hydrological cycle, land use, and loss of vegetation cover, this percentage has been reduced (MINAGRI, 2016).

Specifically, in the Mantaro River basin, climate projections indicate a reduction in monthly precipitation during the rainy season, in addition to a progressive increase in evapotranspiration, causing water deficits and changes in hydrological components (Khare et al., 2016). On the other hand, the increase in rainfall intensity derived from climate change is linked to flooding and soil erosion events (Correa et al., 2016). It is worth highlighting that these phenomena will be maintained or even intensified, particularly in the central and northern parts of the basin, which will affect environmental sustainability and agriculture (Wongchuig et al., 2018).

In this regard, priority has been given to the so-called "cochas," which are natural or artificial water reservoirs, especially in mountainous areas, where rainwater is captured and stored. These serve as reservoirs for agricultural and domestic use during dry periods (Baiker & Kómetter, 2022), contributing to water retention in the soil, optimization of nutrient circulation, promotion of plant growth, and biomass production (Singh et al., 2013; Pala et al., 2021).

However, despite the promising potential of these systems, existing studies are limited in their ability to provide precise locations for water reserve sites, especially considering the diverse climate change scenarios and the specific geoenvironmental conditions of the Mantaro River basin. This gap in knowledge constitutes a significant barrier to the effective implementation of rainwater storage solutions. As a result, there is a critical need for further research to address these uncertainties and ensure the sustainability of water conservation strategies in the face of climate change.

This study seeks to fill this research gap by providing a comprehensive spatial analysis of potential rainwater reserve areas in the Mantaro River basin, considering multiple climate change scenarios and geoenvironmental factors. Geographic Information Systems (GIS) and remote sensing techniques were employed as key tools for this purpose, as they offer an efficient and cost-effective methodology for conducting detailed spatial analyses and mapping suitable intervention zones (Bera & Mukhopadhyay, 2023; Higuera Roa et al., 2023).

Given the complex challenges arising from climate change and other factors at both global and local scales, the purpose of this study was to identify potential zones for rainwater reserve in the face of climate change in the Mantaro basin, located in the high Andean zone. Despite the challenges posed by the limited availability of some data sources, the findings of this research hold significant potential to inform future studies and contribute to the development of sustainable water management strategies in the region.

MATERIALS AND METHODS

Establishment criteria

The criteria selected for the identification of potential zones were based on information compiled by the Food and Agriculture Organization of the United Nations (FAO), considering precipitation, slope, soil texture, land use capacity and watershed order (FAO, 2004). These were complemented with information from the literature to establish the classification and assignment of weights (Figure 1).

Precipitation

Precipitation plays a crucial role in hydrological dynamics and is influenced by various climatic factors. Given Peru's geographic diversity, 38 distinct climatic types have been classified using the Warren Thornthwaite climate classification method. These classifications reveal that the

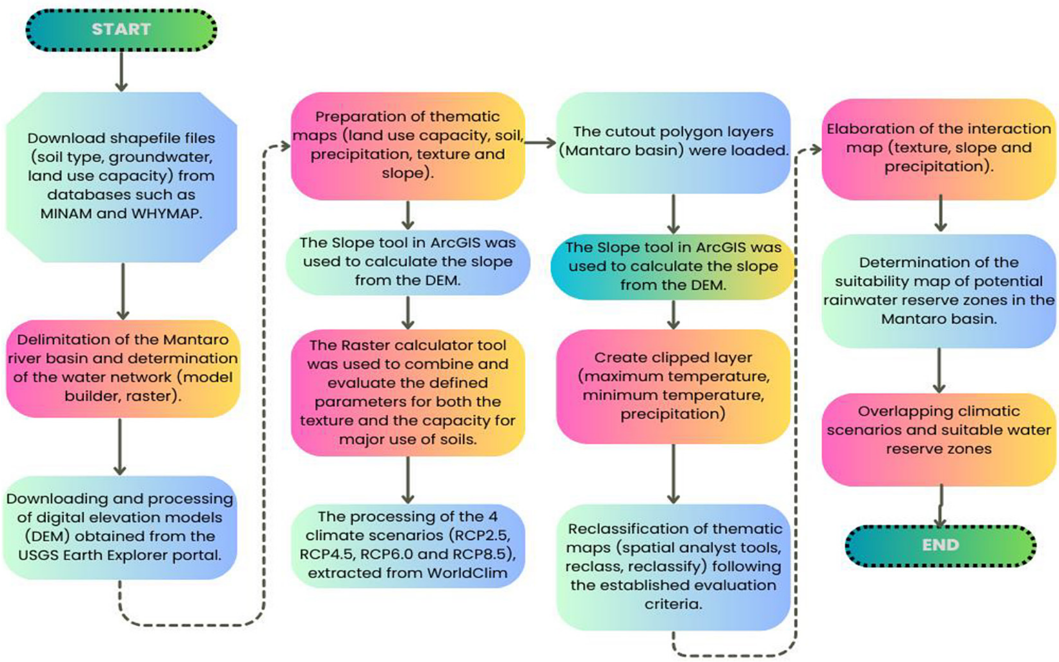

Figure 1. Methodological process for the identification of potential zones: Integration of FAO data and bibliographic review

most prevalent climates include arid and temperate conditions along the coastal region, characterized by limited rainfall; rainy and cold climates in the Andes, where precipitation is concentrated in specific seasons; and very rainy and hot conditions in the Amazon rainforest, contributing to significant runoff and erosion potential (Senamhi, 2015). Precipitation data are gathered from local weather stations to accurately assess their impact on water availability and soil moisture content within the watershed.

Historical meteorological data provided by Senamhi (National Meteorological and Hydrological Service of Peru), which offers daily precipitation records at different monitoring stations in the region, were used. With this data, iso-rainfall maps were generated using GIS software, which made it possible to identify the areas with the highest and lowest precipitation in the basin.

Slope

Slope is a critical factor in runoff generation and sediment transport. It influences not only the velocity of water flow, but also the sedimentation processes that occur within the watershed (Adham et al., 2016). The land classification guidelines D.S. N°017/2009-AG (MIDAGRI, 2009) classify slopes into seven ranges, from flat (0–2%) to very steep (> 30%). These classifications help determine appropriate land use practices and potential erosion risks. For example, areas with gentle slopes can promote infiltration and water retention, while steep slopes can increase runoff and landslide risk. Slope analysis was performed using digital elevation models (DEMs) to accurately derive topographic data.

The slope analysis was performed using a DEM with a resolution of 30 meters. Using GIS tools, the slope gradients in the watershed were calculated and classified into categories (low, medium and high) to evaluate their influence on runoff and infiltration capacity.

Increased land use capacity

Land use capacity and its associated impacts on infiltration and runoff can vary significantly depending on topography. In flat areas, infiltration capacity is high due to uniform water distribution and a less compacted soil structure, which is often enhanced by dense vegetation that improves permeability. On moderate slopes, infiltration rates are influenced by factors such as vegetation cover, soil texture, and soil management practices; however, these areas may be susceptible to erosion if not properly managed. Conversely, on steep slopes, infiltration is minimal due to rapid surface runoff and soil erosion, which compromises both water retention and absorption capacity. Studies show that denser vegetation correlates with higher infiltration rates and lower runoff (Adham et al., 2016; MIDAGRI, 2009). The assessment of land use capacity was conducted using field surveys and remote sensing techniques to evaluate vegetation cover and soil conditions.

To assess land use capacity, field surveys, Landsat and Sentinel satellite images, and remote sensing data were combined. The field surveys provided direct information on soil condition, crop types and agricultural practices, while the satellite images allowed for land use classification. In addition, remote sensing information was processed to identify areas with intensive crops, forested areas and urban areas.

Soil texture

Soil texture significantly influences infiltration rates and runoff patterns, as it determines the soil's ability to absorb and retain water. To classify the proportions of sand, silt, and clay, soil textural classes must be determined, as indicated by Ciancaglini, (2019). To assess land use capacity, field surveys, Landsat and Sentinel satellite images, and remote sensing data were combined. The field surveys provided direct information on soil conditions, crop types, and agricultural practices, while the satellite images allowed for land use classification. In addition, remote sensing information was processed to identify areas with intensive crops, forested areas, and urban zones. The data used for the analysis were obtained from databases provided by the Ministry of the Environment, ensuring that the information was accurate and up-to-date, allowing for a comprehensive assessment of the land use patterns and their potential for water harvesting within the watershed.

Table 1 provides a comprehensive overview of all the criteria considered, along with their respective values and scores that contributed to the multi-criteria analysis. This analysis integrates the various factors influencing water flow and catchment behavior, enabling a holistic understanding of the hydrological dynamics within the study area. The scoring system applied to each criterion

Table 1. Evaluation and classification criteria for land assessment

Criteria	Classification	Value	Importance
Basin order	Very high suitability	>7	9
	High suitability	7	8
	Medium suitability	6	7
	Low suitability	5	2
	Very low suitability	<4	1
Precipitation	Very rainy	<128	9
	Rainy	64–127	8
	Semi-dry	32–63	4
	Semi-arid	16–31	3
	Arid	>16	1
Slope	Flat to gently sloping	0–4	8
	Moderately sloping	4–8	7
	Steeply sloping	8–15	5
	Moderately steep	15–25	4
	Steep	25–50	3
	Very steep	50–75	2
	Extremely steep	>75	1
Major land use capacity	Soils suitable for clean cultivation (A)	Very high	9
	Land suitable for permanent crops (C)	High	8
	Land suitable for pasture (P)	Medium	7
	Land suitable for forest production (F)	Low	6
	Protected land (X)	Very low	5
Soil texture	Sand	Very low	3
	Loamy sand	Low	5
	Sandy loam	Medium	7
	Loam	High	9

allows for a comparative evaluation, facilitating decision-making in land use planning and water resource management (Table 2).

Climate scenarios

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) established four Representative Concentration Pathways (RCPs), which are characterized by their levels of radiative forcing (IPCC, 2014). These scenarios are essential for understanding the potential impacts of climate change under different levels of greenhouse gas emissions and the effectiveness of climate change mitigation policies. The key features of each RCP scenario are summarized below (Table 3):

Temperature and precipitation projections for each RCP scenario were obtained from global climate models (GCMs) and downscaled to reflect

Table 2. Assessment of importance based on assigned scores

Importance	Meaning	Explanation
1	Equal importance	The evidence is probable
3	Moderate importance	The evidence is unlikely
5	Strong importance	The evidence is moderately probable
7	Very high importance	The evidence is very probable
9	Extreme importance	The evidence is extremely probable
2,4,6	Intermediate values	

Note: Taken from (Bruins et al., 2002; Saaty, 1977).

Table 3. Climate scenarios

Scenario	Description
RCP 2.5	Very low CO_2 emissions led to an increase of T° = 2°C
RCP 4.5	Low CO_2 emissions cause T° increase = 2.4°C
RCP 6.0	Medium CO_2 emissions cause an increase of T° = 2.8°C
RCP 8.5	High CO_2 emissions cause T° increase = 4.3°C

local conditions in the Mantaro River basin. This data was then processed to represent the expected changes in temperature and precipitation patterns across the basin, providing insights into how climate change may influence regional weather conditions.

The projected temperature and precipitation changes were overlaid onto thematic maps of the identified rainwater harvesting areas. This spatial analysis allowed for the assessment of how different regions especially the highland and lowland zones would respond to climate projections under each RCP scenario, helping to identify areas that could experience more significant changes or risks.

The impacts of the RCP scenarios were evaluated by examining how changes in precipitation would affect water availability in the identified rainwater harvesting zones. For instance, under the RCP 2.5 scenario, areas experiencing slight increases in precipitation were deemed more suitable for rainwater harvesting, whereas the RCP 8.5 scenario, which predicted more extreme and erratic rainfall, highlighted the risks of erosion and runoff. These factors could significantly impact the feasibility of water storage in those regions.

By comparing all four RCP scenarios, the study identified regions that are likely to be more resilient to climate change, as well as those that are vulnerable to issues such as water scarcity, flooding, and erosion. The results of this analysis helped prioritize areas for the development of rainwater harvesting infrastructure, taking into account both current land use and the projected climate conditions in the future.

Groundwater

The identification of the primary source of groundwater in the Mantaro Basin was carried out using a global groundwater resources map created at a scale of 1:40,000,000 as part of the WHYMAP (World Hydrological Map of Groundwater Resources) project. This project is the result of a collaborative effort between several organizations, including UNESCO, the Commission for the Global Geological Map (CGMW), the International Association of Hydrogeologists (IAH), the International Atomic Energy Agency (IAEA), and the German Federal Institute for Geosciences and Natural Resources (BGR).

The WHYMAP data were processed using ArcMap software for detailed spatial analysis, enabling the visualization and assessment of groundwater availability within the basin. Integrating these data into the suitability analysis was essential for identifying areas with the highest groundwater potential, which served as an important criterion in selecting potential sites for water harvesting. The data provided valuable insights into the depth of aquifers, their storage capacity, and recharge rates.

This information was used to pinpoint areas with high aquifer recharge potential, particularly those with low slopes and permeable soils. Groundwater potential was considered a key factor in selecting optimal sites for rainwater harvesting, with priority given to areas that offer the highest groundwater storage capacity to ensure a sustainable water supply during drought periods.

RESULTS AND DISCUSSION

Precipitation

The monthly precipitation data compiled for the Mantaro River Basin, as illustrated in Figure 2, reveals important insights into the hydrological dynamics of the region. The basin is characterized predominantly by rainy areas, which play a vital role in determining the availability of water resources and the potential for infrastructure development related to water management.

The analysis reveals significant spatial variability across different zones of the basin. The arid zones are the smallest and experience low levels of precipitation. While water scarcity is unlikely in most of the basin, these areas may face challenges related to water quality and limited resource availability. In this case, rainwater

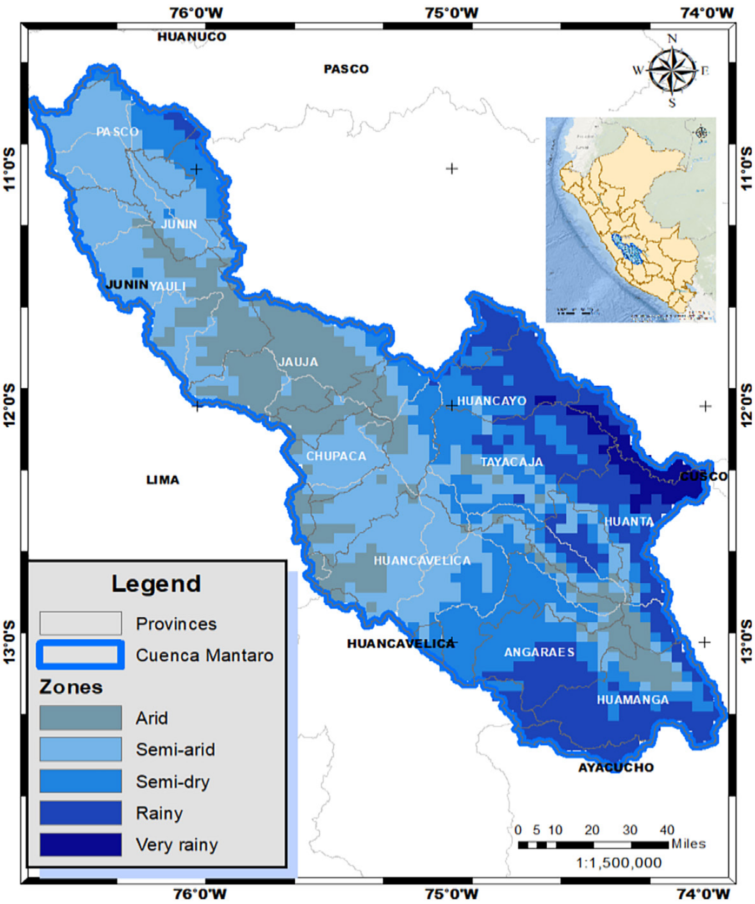

Figure 2. Precipitation presents in the Mantaro River Basin

harvesting may not be the primary strategy, but water conservation and treatment measures will be essential to ensure the long-term sustainability of water resources (Table 4).

On the other hand, the semi-arid zones are more prone to drought conditions, making rainwater harvesting a crucial strategy to mitigate the effects of intermittent dry spells. In these areas, designing water capture and storage systems, such as cisterns and diversion channels, will be key to ensuring water supply during dry periods and securing long-term water security.

The semi-dry zones are also vulnerable to fluctuations in precipitation. This variability can negatively impact agricultural productivity, highlighting the importance of implementing sustainable land management practices. Crop rotation and improving irrigation techniques are key strategies that should be promoted in these areas to maintain soil moisture and reduce vulnerability to drought. Rainwater harvesting in these areas must adapt to precipitation fluctuations, with flexible systems that can handle interannual variability.

Regarding the rainy zones, these areas represent a great opportunity for rainwater harvesting due to their high precipitation levels. Building capture infrastructure, such as rooftop water collection systems and cistern storage, can ensure a constant water supply throughout the year.

Table 4. Distribution of precipitation in the Mantaro Basin by rainfall category

Precipitation category	Area (km²)	Percentage of total area (%)
Zones areas	109.327	0.3153%
Semi-arid zones	396.866	1.1269%
Semi-dry zones	6731.884	19.1317%
Rainy zones	27298.341	78.9611%
Very rainy areas	119.428	0.3351%

Additionally, the high precipitation in these zones is crucial for aquifer recharge and maintaining local ecosystems, promoting biodiversity and ecological resilience.

Finally, the very rainy zones, though small, can pose risks associated with flash floods and erosion. Instead of focusing on rainwater harvesting, the focus in these areas should be on flood management. Retention reservoirs, dams, and preventive measures against erosion, such as reforestation, should be implemented to protect both communities and local infrastructure from the negative impacts of intense rainfall.

The Mantaro River Basin offers favorable conditions for water resource development, particularly in the rainy and semi-dry zones. However, the variability in precipitation across the basin emphasizes the need for an adaptive management approach. Rainwater harvesting systems must be flexible to respond to climate variability and ensure water availability in areas with lower precipitation. Additionally, flood risk management in the very rainy zones should be prioritized, using flood control strategies to mitigate potential damage. The combination of water capture infrastructure, sustainable land management practices, and adaptation strategies to climate change is key to ensuring the long-term sustainability of water resources in the Mantaro Basin.

Soils

The results of the soil distribution indicate that Leptosols are the most widespread soil type in the Mantaro River Basin, occupying 50.39% of the total area (46,111.983 km²). These soils are commonly found in mountainous areas or on steep slopes, which makes them more susceptible to erosion. They have a thin surface layer and high aluminum saturation, which reduces their natural fertility. Although are not ideal for agriculture due to their low nutrient retention, their ability to retain water is limited because of their underdeveloped structure and tendency to erode. However, in areas where conservation practices such as terracing and reforestation are implemented, water retention can be improved, and soil loss can be reduced. In these cases, rainwater harvesting may require systems that minimize runoff and promote infiltration.

On the other hand, Regosols occupy 37.23% of the area (34,103.878 km²) and are deeper than Leptosols, giving them a higher water retention capacity. Their medium texture and stability in various topographic positions make them suitable for groundwater recharge. Although their agricultural potential is limited, Regosols play a crucial role in water management, as they help ensure the availability of groundwater during dry periods. Regarding rainwater harvesting, Regosols can store more precipitation water compared to Leptosols, especially in areas where infiltration is adequate, making the implementation of more efficient water capture systems feasible.

Cambisols, although they represent only 12.38% (11,339.77 km²) of the basin, are more developed soils that can offer better conditions for agriculture, particularly in areas where the soil profile has undergone more significant development. Their greater depth and better structure favor water retention and nutrient storage, allowing Cambisols to have higher agricultural potential. This soil type can be especially suitable for implementing rainwater harvesting systems such as cisterns and diversion channels, as their infiltration capacity allows for more efficient and long-lasting water storage, which is essential for ensuring water security in these areas.

The predominance of Leptosols in the Mantaro River Basin may be related to geological and climatic factors that favor their formation, especially in mountainous areas (Figure 3). These young and underdeveloped soils are more susceptible to erosion, which increases the need for soil conservation practices to mitigate their impact on water availability. On the other hand, Regosols, being more stable and with higher water retention capacity, are key to groundwater recharge and can play a fundamental role in sustainable water management in the region. Finally, Cambisols, although limited in distribution, present greater potential for agriculture and rainwater harvesting. Proper management of these soils could improve both agricultural productivity and water security in areas where they predominate.

Soil texture

Regarding soil texture, at higher elevations, soil texture is predominantly sandy or loamy due to the presence of rocks and materials that have not consolidated during erosion processes (Figure 4).

Sandy soils cover approximately 3.38% (1,121.08 km²) of the basin, while loam soils make up 63.33% (21,000.82 km²). Silty soils constitute 19.15% (6,347.95 km²), and clay loam soils represent 3.35% (1,110.81 km²). Additionally, sandy clay loam soils account for 2.72%

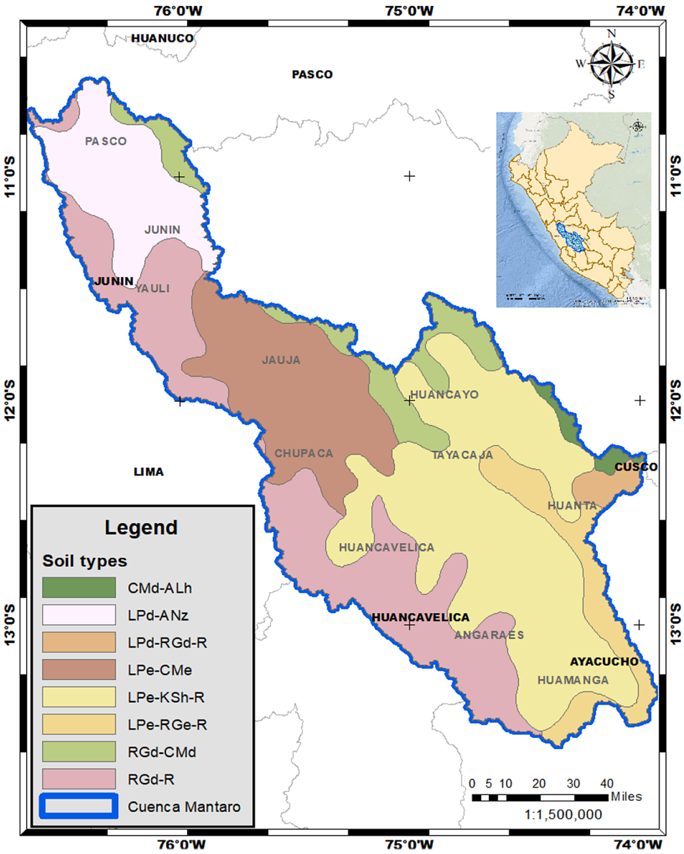

Figure 3. Soil types in the Mantaro River Basin

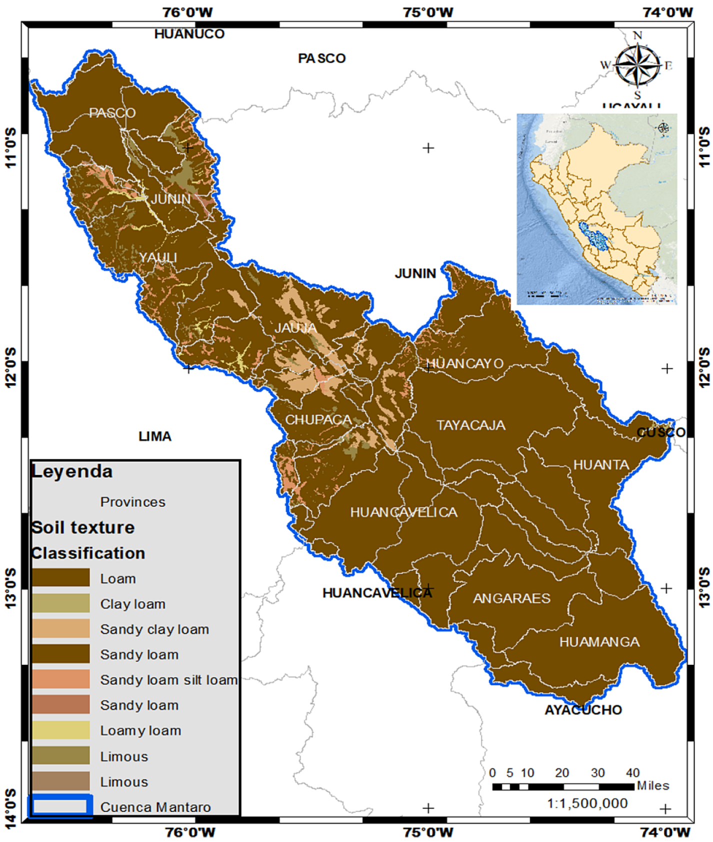

Figure 4. Texture of soils

(902.87 km²), and sandy loam soils occupy 3.35% (1,111.50 km²). Finally, sandy-loam and silty loam soils cover 1.86% (618.03 km²) and 4.92% (1,631.02 km²), respectively.

A study conducted by Garay & Ochoa (2007) evaluated the various textural categories in the basin and found that most sampled soils exhibited a tendency toward sandy clay loam and sandy loam textures. These findings suggest that soils with finer textures, such as silty and clayey soils, are more susceptible to the effects of rainfall due to their lower permeability, making them more prone to erosion. In contrast, coarser-textured soils like sandy loam or sandy clay loam are more prone to drought and frost, as their higher permeability can hinder water retention at the surface. This information is essential for understanding how different soil types respond to climatic events, offering valuable insights for the development of effective water resource management strategies in the region.

Further highlighting the complexity of factors influencing soil quality in the Mantaro River Basin, Correa et al. (2016c) noted the presence of additional textural varieties such as clayey sand, clay, and silt. This diversity underscores the edaphological richness of the region and its implications for soil properties. The variation in texture is crucial for determining how these soils can support or hinder rainwater harvesting, as finer-textured soils may need additional measures to manage water retention, while coarser soils might require strategies to capture and store water during dry spells.

The role of erosion risk is also critical, as factors like steep slopes, low vegetation cover, and intense rainfall exacerbate the basin's vulnerability to soil degradation. Varón et al. (2022) emphasized that erosion risk is significantly higher in areas with steep slopes and low vegetation cover, leading to further degradation of the soil and a reduction in its capacity to retain water. Understanding these variations in soil texture and the associated erosion risks is essential for sustainable land use planning and environmental management. It also has implications for the development of rainwater harvesting systems, which must account for these vulnerabilities.

Slope and capacity for major use of soils

The analysis of the Mantaro Basin reveals a variety of slope gradients that significantly affect both water availability and soil erosion. In Figure 5, it

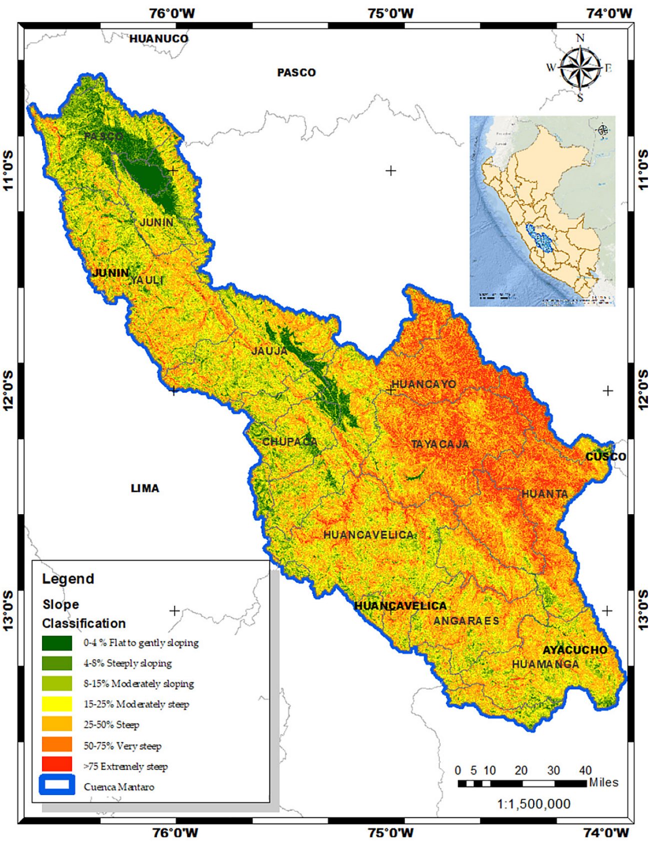

Figure 5. Slopes in the Mantaro Basin

can be seen that the steepest slopes are located in the lower part of the basin, with moderately steep slopes in the middle and slightly steep slopes in the upper areas. These topographic features directly influence the potential for rainwater harvesting, as steeper slopes are more prone to erosion and runoff. This can reduce the feasibility of implementing water storage systems unless mitigation measures, such as slope stabilization or the construction of retention ponds, are applied.

In terms of extent, the different slope classes in the Mantaro Basin are as follows: flat to slightly moderate areas cover 1,338.675 km², representing 3.99% of the basin; moderately inclined areas total 1,777.659 km² (5.30%); slightly steep areas cover 4,871.124 km² (14.52%); moderately steep areas encompass 6,535.819 km² (19.49%); steep areas occupy 11,799.067 km² (35.18%); very steep areas represent 5,313.400 km² (15.83%); and finally, extremely steep areas cover 2,910.195 km² (8.67%). This variability in slope gradients demonstrates the need for specific planning for each type of terrain, especially in areas with more pronounced slopes, where the risks of erosion and runoff are higher. As reported by Wongchuig et al. (2018b), the steep mountain slopes in the region contribute to the basin's vulnerability to erosion and runoff, highlighting the importance of addressing these issues in water resource planning. Additionally, it is essential to consider the specific characteristics of each slope type in water management and adaptation efforts.

The areas suitable for different land uses in the Mantaro Basin are as follows: land suitable for medium-quality grazing covers 14,339.139 km² (20.60%); land suitable for low-quality clean farming spans 28,067.580 km² (40.35%); land suitable for medium-quality forestry production covers 6,774.451 km² (9.73%); land suitable for low-quality permanent farming occupies 8,006.516 km² (11.50%); land suitable for medium-quality clean farming is 2,954.435 km² (4.24%); and protective lands cover 4,729.490 km² (6.80%).

Figure 6 illustrates that in higher altitude areas and along mountain slopes, forestry and watershed protection are the predominant land uses. In the intermediate zones, characterized by smoother topography, agricultural activities are the primary land use. In contrast, urban and industrial activities are prioritized in the low and flat areas.

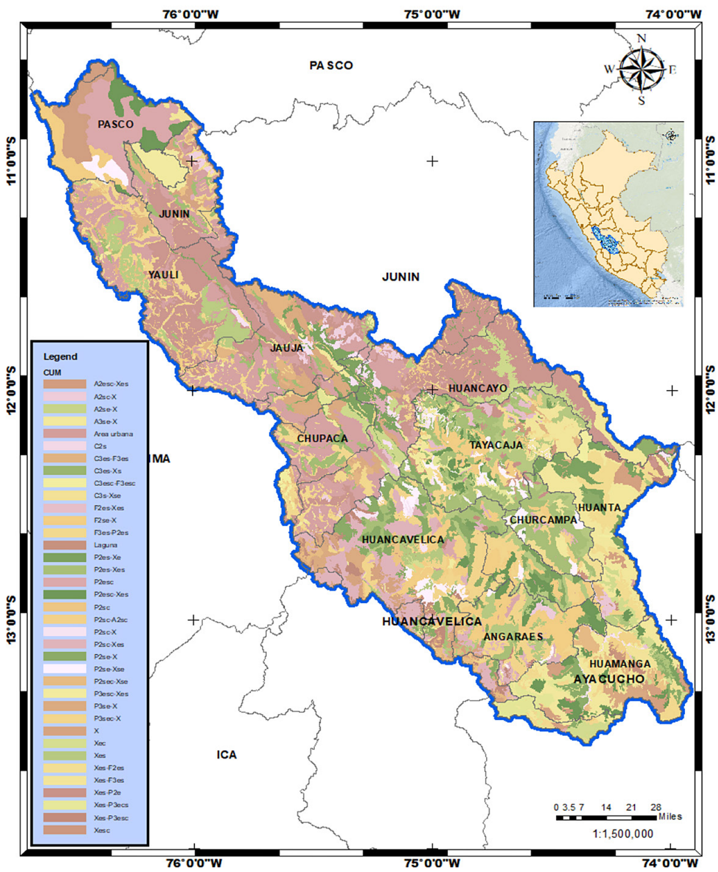

Figure 6. Capacity for increased land use in the Mantaro basin Groundwater

Regarding land use capacity, Espinoza et al. (2016) reaffirm the results of this research by indicating that in the lower zones, the soil is primarily used for agriculture, supporting the production of key crops such as prickly pear, potatoes, barley, olluco, and oca. The middle zone, which encompasses the valley, supports the cultivation of essential crops like potatoes, corn, carrots, barley, alfalfa, and artichokes. In the upper zones, including the headwaters, crops such as maca, fodder oats, potatoes, barley, olluco, and oca thrive, promoting the conservation of natural ecosystems.

Therefore, soil planning and management must be conducted in an integrated and sustainable manner. It is crucial to accurately record even minor variations in slope degree, particularly for effective erosion management, irrigation, and drainage (CIIFEN, 2019).

Groundwater

In the Mantaro Basin, there is a diversity of aquifers that vary according to altitude and geological characteristics. In the highlands, mountain aquifers predominate, which are fed mainly by precipitation and glaciers, the latter being a crucial source of water for local communities (Figure 7).

These mountain aquifers occupy an area of 6564.143 km² (15.98%). This variety of recharge sources contributes to the complexity of the hydrogeological system, highlighting the importance of comprehensively understanding and managing water resources in different geographical areas. In contrast, in the intermediate and lower areas, sedimentary aquifers prevail, which formed in deposits of alluvial and sedimentary materials. These aquifers are recharged mainly through the infiltration of rainwater and surface runoff. These findings for subterranean waters are supported by Delgado (2018), who in his report points out that the Mantaro Basin is mainly composed of aquifers, which are used for irrigation activities and domestic consumption. This reinforces the importance of understanding their dynamics and the need to implement sustainable management strategies to ensure their long-term availability.

Potential areas for rainwater harvesting

Considering the current conditions for rainwater storage in the Mantaro Basin, the most

Figure 7. Groundwater sources

suitable areas are located in the upper, middle and lower parts of the basin. The lower part of the basin is the most representative.

This sectorization was carried out using geographic and topographic data, which allowed the identification of the different zones that make up the basin. The specific locations that delimit each of its sections are detailed below (Table 5)

By overlaying the soil texture, slope, and precipitation layers, several zones are identified. The brown areas (12.3%) are characterized by soils with a texture of loam (in the upper basin, 4%), clay loam, clay loam sandy (in the middle basin, 3.5%), and sandy loam (in the lower basin, 4.8%). These zones have flat slopes (in the upper and middle basins, 8%) and steep slopes (in the lower basin, 4.3%). Precipitation zones include arid, semi-arid, and rainy areas (in the upper basin, 3.8%), arid, semi-arid, semi-dry, and rainy (in the middle basin, 3%), and arid, semi-arid, very rainy, and semi-dry (in the lower basin, 2.5%) (Figure 8).

Aquifers are present in all basins (3%). The predominant soil types are Leptosol dystrophic and Regosol dystrophic (in the upper basin, 3.8%), Eutric Leptosol (in the middle basin, 4%), and Eutric Leptosol, Dystrophic Regosol, and Dystrophic Leptosol (in the lower basin, 4.5%). Regarding land use, there are lands suitable for pasture with medium agro-ecological quality (in the upper basin, 4.5%), lands suitable for crops in the open with low agro-ecological quality, lands suitable for pasture with medium agro-ecological

Table 5. Division of the Mantaro Basin into functional zones

Sector	Upper limit	Lower limit
Upper Basin	Source of the river at the outflow of Lake Junín (10°52′0"S, 76°13′0"W)	Malpaso Reservoir (11°40′0"S, 75°21′0"W)
Middle Basin	Malpaso Reservoir (11°40′0"S, 75°21′0"W)	Tablachaca Reservoir (12°0′0"S, 74°50′0"W)
Lower Basin	Tablachaca Reservoir (12°0′0"S, 74°50′0"W)	Confluence with the Apurímac River (12°46′0"S, 73°48′0"W)

Note: Taken from (ANA, 2024).

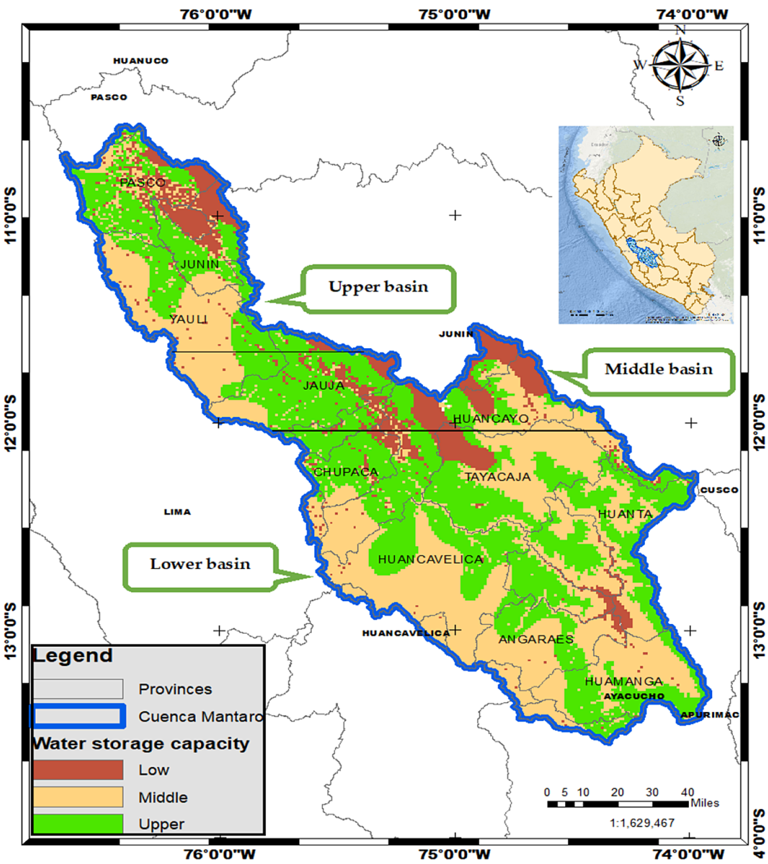

Figure 8. Water reserve zones

quality, and protection lands (in the middle basin, 4%), and lands suitable for crops in the open with low agro-ecological quality, lands suitable for permanent crops, protection lands, and lands suitable for pasture with low agro-ecological quality (in the lower basin, 3.8%).

The yellow areas (25.04%) are characterized by a silty, loam, and sandy loam texture (in the upper basin, 7%), clay loam sandy and loam (in the middle basin, 8%), and loam (in the lower basin, 10.4%). Slopes range from flat to moderately steep (in the upper basin, 7.5%), steep, flat, and moderately steep (in the middle basin, 8%), and moderately steep (in the lower basin, 4.54%).

Precipitation includes arid, semi-arid, and rainy zones (in the upper basin, 7%), arid, semi-arid, semi-dry, and rainy (in the middle basin, 7.5%), and arid, semi-arid, very rainy, and semi-dry (in the lower basin, 6.54%). Aquifers are present in all basins (2%). Soil types include Dystrophic Leptosol (in the upper basin, 8%), Eutric Leptosol (in the middle basin, 8%), and Dystrophic Leptosol, Eutric Leptosol (in the lower basin, 8.54%). Regarding land use, there are lands suitable for pasture with medium agro-ecological quality (in the upper basin, 8%), lands suitable for crops in the open with low agro-ecological quality, urban areas, and protection lands (in the middle basin, 7.5%), and protection lands, lands suitable for pasture with low agro-ecological quality (in the lower basin, 6.54%).

The green areas (62.66%) are characterized by loam, clay loam, sandy loam (in the upper basin, 20%), silty loam (in the middle basin, 15%), and loam (in the lower basin, 27.66%). Slopes are mostly flat and very steep (in the upper basin, 25%), moderately steep and flat (in the middle basin, 15%), and flat and moderately steep (in the lower basin, 22.66%). Precipitation zones include arid, semi-arid, and rainy (in the upper basin, 20.33%), arid, semi-arid, semi-dry, and rainy (in the middle basin, 25.33%), and arid, semi-arid, very rainy, and semi-dry (in the lower basin, 17%). Aquifers are present in all basins (27.66%).

The predominant soil types are Dystrophic Regosol (in the upper basin, 20%), Dystrophic Regosol (in the middle basin, 27.66%), and Dystrophic Regosol and Eutric Leptosol (in the lower basin, 15%). Regarding land use, there are lands suitable for pasture with medium agro-ecological quality (in the upper basin, 20%), lands suitable for pasture with medium agro-ecological quality, protection lands (in the middle basin, 15%), and lands suitable for pasture with low agro-ecological quality and protection lands (in the lower basin, 27.66%).

In the upper basin, areas with high water storage capacity are located in Pasco, Junín, and Yauli. In the middle basin, they are found in Jauja and Huancayo. In the lower basin, Chupaca, Tayacaja, Huanta, Huamanga, and Angaraes stand out. In the lower basin, these areas represent 54%, equivalent to 14107.61 km². In the middle basin, they represent 35% (3651.43 km²), and in the upper basin, 11% (566.32 km²). Additionally, in the lower basin, areas with medium water storage capacity constitute 44.5%, while those with low capacity only account for 1.5%.

Influence of minimum temperature

Figure 9 below shows the projections of the 4 future climate scenarios (RCP 2.5, RCP 4.5, RCP 6, RCP 8.5). Minimum temperatures will range from -1.7 °C (RCP 8.5) to -1.6 °C (RCP 2.5, 4.5 and 6), at their lowest level. While the highest levels, between 20° (RCP 8.5) and 20.1 °C (RCP 2.5, 4.5 and 6).

Regarding temperature and precipitation variations, different RCP scenarios project changes that will affect water availability and agricultural productivity. In the RCP 2.5 scenario, the increase in minimum temperatures will be slow, and the impacts on precipitation patterns will be less dramatic, making it easier to manage changes in water availability in a more controlled manner.

In the RCP 4.5 scenario, a moderate increase in temperatures is expected, accompanied by changes in precipitation patterns that could lead to prolonged droughts and more intense rainfall events, particularly in the upper and middle zones. This scenario presents additional challenges for water and agricultural management.

Therefore, in the RCP 8.5 scenario, which corresponds to a high-emission scenario, a significant increase in temperatures is projected, exacerbating the risk of droughts and extreme weather events such as flash floods. This scenario would place considerable pressure on water management systems and increase vulnerability in various parts of the basin.

The scenarios suggest that precipitation patterns will become more variable, with some areas experiencing more intense rainfall and others facing reduced precipitation during the dry season. The spatial distribution of suitable rainwater

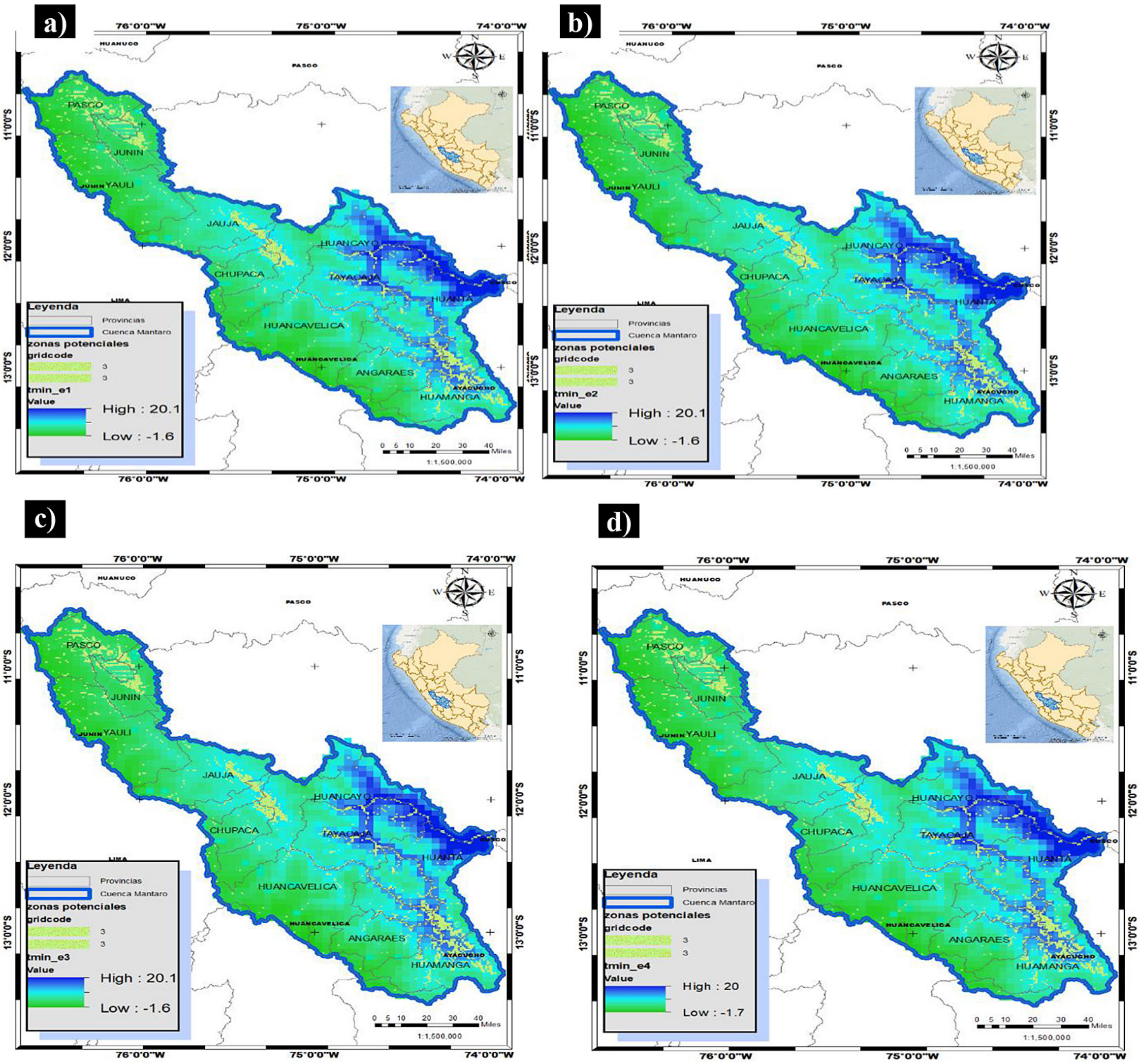

Figure 9. Zones vs minimum temperature scenarios a) RCP2.5 b) RCP4.5 c) RCP6 d) RCP8.5

harvesting sites will shift accordingly, highlighting the importance of implementing adaptive management strategies to ensure water security in the face of climate change. Therefore, taking into account the most adverse climate scenario (RCP 8.5), the 689 suitable areas would be reduced to only 315 (54.28%).

Influence of maximum temperature

In the case of maximum temperatures, Figure 10 shows that the minimum values vary between 9.2 °C (RCP 2.5), 9.3 °C (RCP 4.5), 9.5 °C (RCP 6 and 8.5), while the maximum values range between 30.4 °C (RCP 2.5 and RCP 4.5) and 30.5 °C (RCP 6 and RCP 8.5).

Whereas, the RCP 4.5 scenario implies moderate emissions, resulting in a gradual increase in temperature and alterations in precipitation trends. In contrast, the RCP 6.0 scenario implies moderately high emissions, which makes it a more worrisome scenario due to its impact on water availability and agriculture. The RCP 8.5 means a substantial increase in radiative forcing, temperature and the occurrence of extreme weather events, including accelerated glacier retreat and significant changes in precipitation patterns.

This could have serious implications for water availability and food security in the region. In that sense, in order to understand how much climate change could affect the establishment of rainwater reserve zones, four representative concentration pathways were included. As a result, the most relevant scenarios in this context are RCP 4.5 and RCP 8.5. The first one translates into changes in precipitation patterns, so that drought periods would be more intense and prolonged, as well as more intense rainfall events in certain seasons, affecting

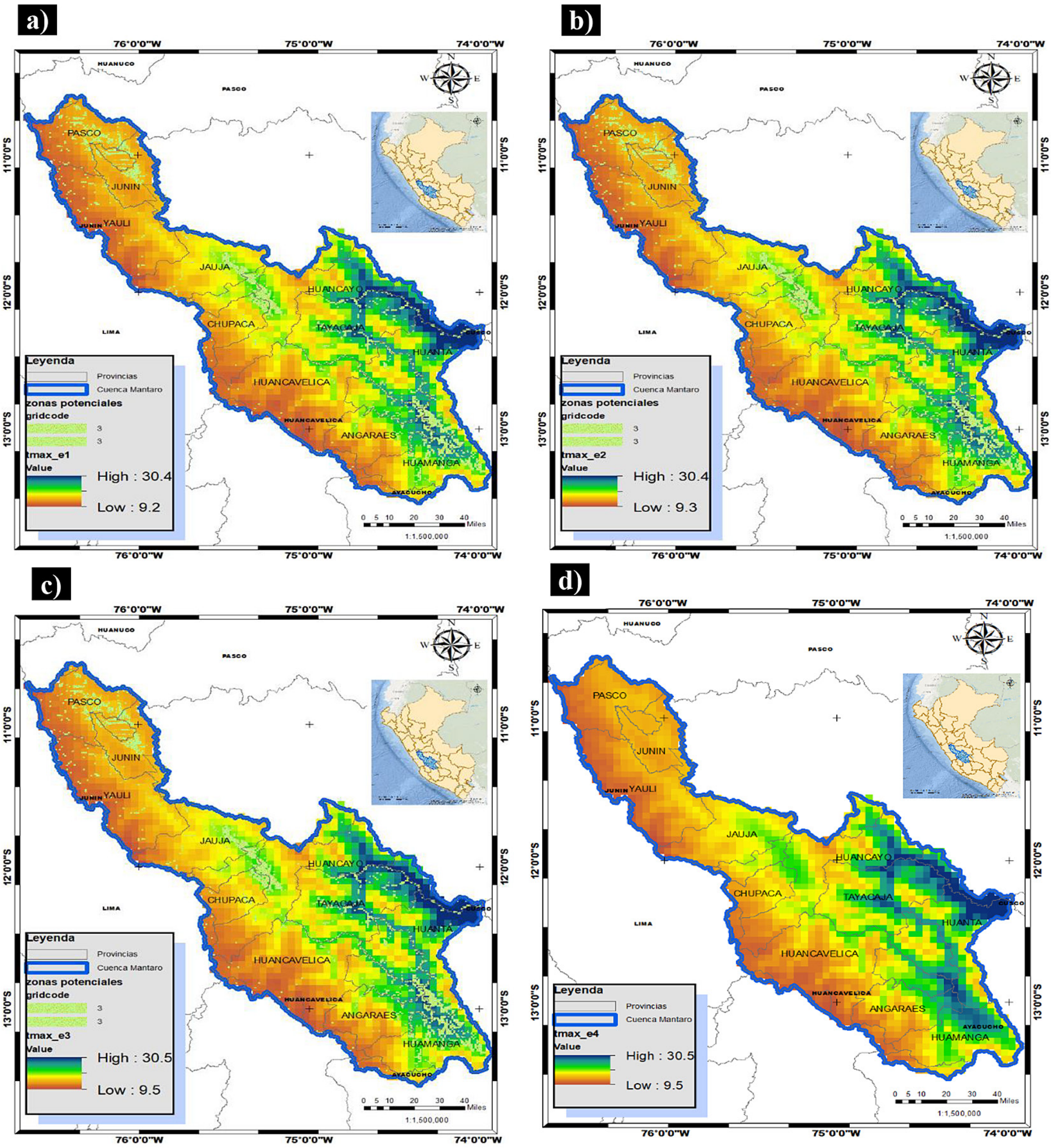

Figure 10. Zones vs. maximum temperature scenarios a) RCP2.5 b) RCP4.5 c) RCP6 d) RCP8.5

the availability and management of rainwater, putting the upper and middle zones at risk. Meanwhile, with the second, more prolonged droughts, rainfall variability and water stress would be expected.

As a result, the areas suitable for rainwater reserve will be reduced from 689 to 315 (54.28%), considering the most adverse scenario (RCP 8.5).

Influence of precipitation

Precipitation would increase significantly in intensity, especially in the lowlands and near the foothills of the Andes. Its importance lies in the fact that it contributes to the recharge of water bodies, which would favor its use in agricultural activities. In contrast, during the dry season this would decrease. This would increase significantly in intensity, especially in the lower basin, so that at its highest level it would oscillate between 257 mm (RCP 2.5), 255 mm (RCP 4.5) and 252 mm (RCP 6 and RCP 8.5).

Under RCP 4.5 and RCP 8.5, changes in precipitation patterns are expected, with more intense drought periods and extreme rainfall events in certain seasons. These shifts in precipitation patterns will directly impact the suitability of areas for rainwater harvesting. Regions currently suited for rainwater harvesting may become less reliable due to changes in precipitation timing and volume. Therefore, adaptive management strategies will be essential to optimize the use of available water resources and ensure the sustainability of rainwater harvesting systems (Figure 11). Thus, stormwater reserve areas would be reduced from 689 to 315 (54.28%) under the most adverse scenario (RCP 8.5).

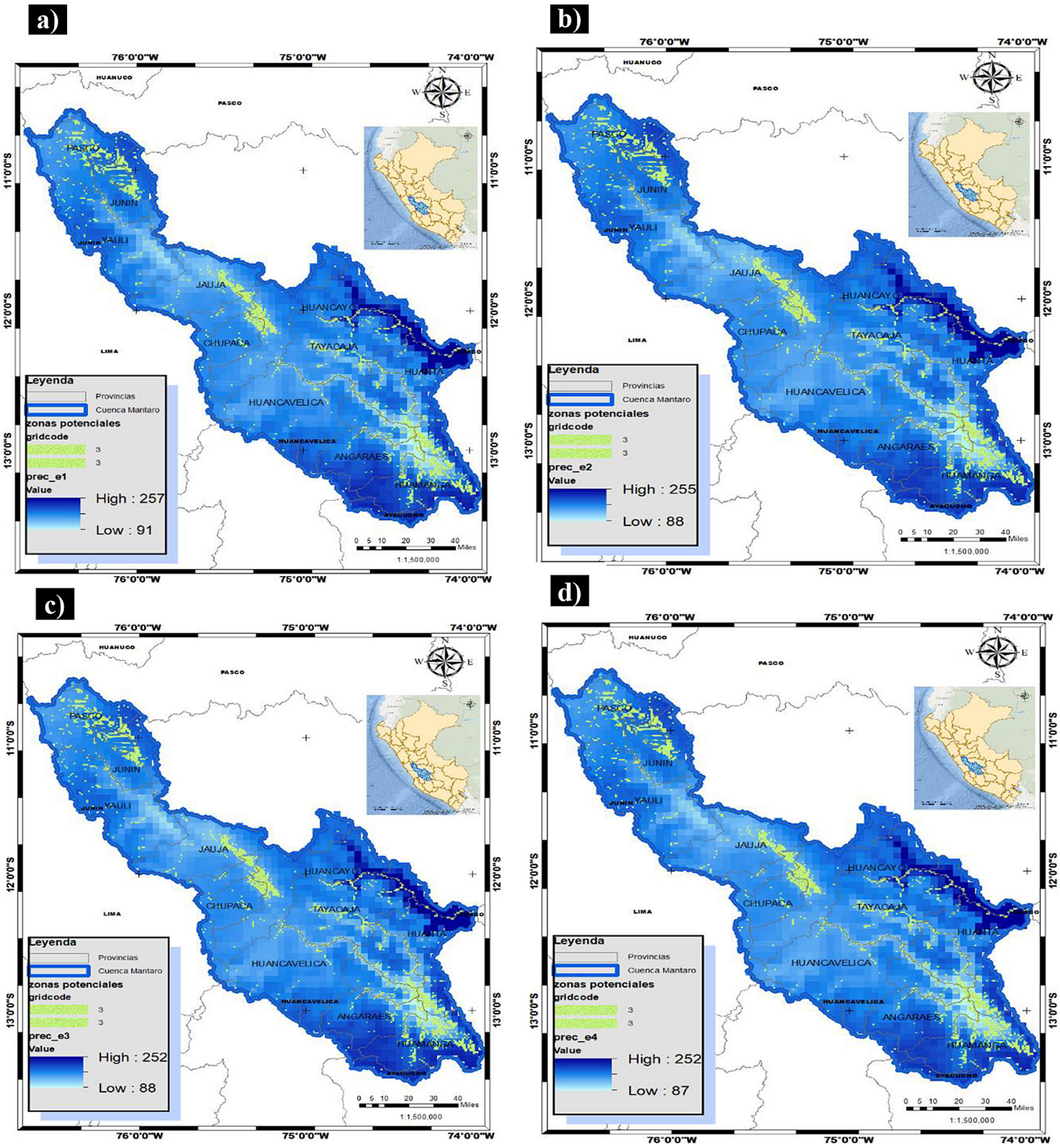

Figure 11. Precipitation vs scenarios a) RCP2.5 b) RCP4.5 c) RCP6 d) RCP8.5

This is consistent with the results of this research. Silva et al. (2006) and Ruedas et al. (2023) state that significant variability due to climate change is mainly related to the increase in temperature and the decrease in precipitation patterns. In this sense, farmers in the Mantaro Valley would find themselves in a situation of greater vulnerability. During the summer season, higher maximum temperatures are expected. In low, flat areas, these would exceed 30 °C, while in higher altitude areas, such as mountainous areas, they could vary between 20 and 25 °C. Winter will tend to be cooler. At higher elevations, especially in mountainous areas, maximum temperatures would hover between 15 and 20 °C. In general, maximum temperatures are expected to be between typical summer and winter values. Likewise Saavedra et al. (2020) the increase or decrease in precipitation due to changes in topography or land use can be controlled by the flow of humidity and its convergence, as is the case in the Mantaro Basin. Whereas Sotomayor (2010) in order to improve rainfall and temperature projections employed multivariate regression splines (MARS) and artificial neural network backpropagation (ANNB) establishing that the Mantaro river basin is an area exposed to high climatic variability due to geography and other yet unknown physical phenomena. This makes it difficult to forecast the monthly climate in the region. In this way Kumar et al. (2019) indicates that a better understanding of precipitation in the tropical Andes would be a great contribution to evaluate this variable and better forecast precipitation using numerical models.

CONCLUSIONS

The analysis of the Mantaro Basin identified areas with high potential for rainwater storage, evaluating key factors such as soil type and texture, slope, precipitation, and land use. The lower basin stood out as the region with the highest storage capacity, representing 54% of the total capacity, equivalent to 14,107.61 km², followed by the middle basin (35%) and the upper basin (11%). Within the lower basin, 54% has high storage capacity, while 44.5% has medium capacity and 1.5% has low capacity. This confirms that the lower basin is the most suitable for rainwater harvesting. Aquifers are the main source of groundwater in the basin, covering 84.02% of the total area (34,546.52 km²). Mountain aquifers, particularly in the upper and lower basins, depend on precipitation and glaciers, which cover 15.98% of the basin. These resources are crucial for groundwater recharge, especially in areas with limited precipitation.

However, under the RCP 8.5 climate scenario, a significant increase in temperatures and greater variability in precipitation patterns are projected, which could reduce the areas suitable for rainwater storage by 54.28%, intensifying the risk of prolonged droughts and water stress. The study has some limitations, such as the reliance on precipitation and soil data that may not fully capture local conditions. To improve accuracy, it would be beneficial to obtain more detailed data and consider different long-term climate scenarios (such as RCP 2.6 or RCP 4.5). Additionally, although soil type and texture were assessed, factors such as erosion and land use were not thoroughly addressed, which could affect the sustainability of rainwater harvesting systems, especially in areas with steep slopes or intensive agriculture.

Future research could expand this work by addressing key areas, such as conducting local studies with higher-resolution data on precipitation, soil types, and land use, to refine the identification of areas suitable for rainwater harvesting. It would also be relevant to investigate the impacts of climate variability, exploring how different climate scenarios, including variations in precipitation and seasonal temperatures, could further affect the distribution of areas suitable for rainwater harvesting, particularly in the context of prolonged droughts or extreme rainfall events. Regarding soils, detailed models of soil erosion and land management practices could be incorporated to assess the long-term viability of rainwater harvesting in different soil types and land uses, especially in the more sloped areas of the basin. Finally, it would be valuable to explore integrated approaches that combine rainwater harvesting with aquifer recharge and other water management strategies to enhance the resilience of the basin's water resources to climate change. These future research areas will be essential for refining water management strategies and ensuring the sustainable availability of water for both people and ecosystems in the Mantaro Basin, especially as climate change impacts continue to evolve.

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