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# Strategies for increasing water availability and improving water use efficiency in Latin America and the Caribbean

IHP - VIII Technical Paper No. 43

Latin America and the Caribbean

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Published in 2021 by the United Nations Educational, Scientific and Cultural Organization, 7, place de Fontenoy, 75352 Paris 07 SP, France, and the UNESCO Office in Montevideo, Luis Piera 1992, Mercosur Building, 2nd floor, Montevideo, 11200, Uruguay



Editor of the IHP-LAC Technical Series: Miguel de França Doria

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Cover photo: Henry Abel Vergara

Graphic design: Ser Gráficos

Cover design: Ser Gráficos

Assistant editor: Maria Clara Cremona, Sabrina Cupeiro, Camila Tori

Translation: Soledad Insiburo, Lourdes Martino

SC-2020/PHI-LAC/43

SUMMARY

# What strategies to choose to overcome the challenge of water management?


Climate change, new patterns of land use, deforestation and urbanisation, among others, make water management in Latin America and the Caribbean a challenge of significant complexity. Population growth also plays an important role: the region's population has grown steadily since 1950, to over 650 million today, adding pressure in terms of water availability.

Despite this scenario, efforts have been made at all levels. Discover in this publication the work on research and technology to improve water management and use in Latin America and the Caribbean, how progress has been made in the recovery of techniques, what their strengths and weaknesses are, and what countries can do to adopt them.

This publication is aimed primarily at technicians and decision-makers who have an impact on public policies, strategic plans and management, as well as all those who interact in water resource management.


Recent strategies have led to a 95% increase in access to improved water sources and an 83% improvement in sanitation in the region.

*"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"*

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# Preface

Water management in Latin America and the Caribbean is increasingly complex, especially in the context of climate change and its impact on different factors such as population growth, increases in the areas under irrigated agriculture, development, and industrialization, among others. Several successful initiatives have been developed and implemented to address these issues and enhance sustainable water management. However, many of these are not being adequately promoted in the region.

UNESCO's Intergovernmental Hydrological Programme (IHP) for Latin America and the Caribbean (IHP-LAC) has joined forces under the framework of the G-WADI Program with the Regional Water Center for Arid and Semi-Arid Areas of Latin America and the Caribbean (CAZALAC)—current G-WADI LAC secretariat—and the "Water security and climate change adaptation project in Peruvian glacier-fed river basins" (RAHU Project), to gather information on traditional and modern techniques for sustainable water management to address these gaps. The seminar "Towards sustainable water management in Latin America and the Caribbean: sharing experiences on methods to preserve, increase availability and improve water-use efficiency" on August 5th and 6th, 2019, in Lima, Peru, was organized for this purpose.

More than 20 Latin American researchers, experts, and professionals gathered in this event to discuss water management in the region and present techniques and technologies to increase water-use efficiency in the region and its environmental and sustainable management under the complex scenarios resulting from global changes. This seminar made it possible to compile and share knowledge and experiences on different sustainable water management methods with those interested in sustainable water use and develop and discuss reliable and authoritative reviews.

This publication showcases the research and technology trends towards efficient water use in Latin America and the Caribbean, the progress in the development or adoption of techniques that enable sustainable water use, the strengths and weaknesses of the methods identified, and the potential for these techniques to be embraced in different parts of the region. These methodologies could be replicated, extrapolated, or adapted to local contexts, which could also contribute to implementing Goal 6 of the Agenda for Sustainable Development towards universal access to safe drinking water and sanitation and towards SDG target 6.4, which focuses on achieving water use efficiency in all sectors, ensuring the sustainability of freshwater extraction and supply.

The future we want hinges, to a large extent, on how we manage water resources. The best approach to tackle water scarcity and make it available to the entire population is to improve water use efficiency. I hope this publication can bolster that process.

Abou Amani
Secretary, Intergovernmental Hydrological Programme (IHP)
Director Division of Water Sciences, UNESCO

# Strategies for increasing water availability and enhancing water-use efficiency in Latin America and the Caribbean

*Miguel de França Doria[1], Magali García[2], Gabriel Mancilla[3]*

Overall, there is water abundance across the Latin American and Caribbean region: approximately 13,000 km3/year or almost 30% of the planet's renewable water resources. In this region, we can find the largest basin (the Amazon), the largest transboundary aquifer (the Guaraní), the longest wetland (Pantanal) and the widest estuary on the planet (the Plata), as well as almost all of the tropical glaciers (in the Andes) and critical lake systems (e.g., Titicaca, Mar Chiquita, Atitlán). The natural wealth, water variability and rich biodiversity and culture contribute significantly to the region's economic development, thanks to crucial virtual water exports to areas with more shortages. The distribution of water resources in the region is still quite heterogeneous, and there are significant disparities between and within Latin American and Caribbean countries. Also, several basins are affected by seasonal variability. There are also nearly 4.5 million km$^3$ of arid and semi-arid areas in the region, including the world's most arid non-polar desert, the Atacama. The geographic distribution of human beings and productive activities matches that of water resources. However, this is not a perfect match, and about a quarter of the population lives in basins with water shortages.

During the past decades, significant changes have taken place following global trends. The region's population has almost increased four-fold since 1950, when there were around 169 million people, to about 650 million today. As a result, the amount of water resources per capita has dropped almost four times. There has been a growing concentration of the population during this period. The urban population increased from 40% to 80%. Despite this growth, there has been significant progress in water access, and currently, more than 95% have access to improved water sources, and 83% have access to improved sanitation (WWAP, 2019). One of the critical changes in land use that has implications for water resources is the deforestation of vast areas, associated with increased erosion and sedimentation in many basins. About 10% of rivers suffer from severe organic pollution (BOD> 8 mg/l), and only about 20% of wastewater is treated (IANAS, 2019). Climate change poses great challenges for the region due to the significant increase in droughts and floods and hurricanes and rising sea levels that impact the Caribbean's coastal areas and islands' water resources. The last few decades have seen the rapid retreat of Andean glaciers. Many Andean glaciers have reached the "peak water", and meltwater runoff will continue to decrease in the future (UNESCO and GRID-Arendal, 2018).

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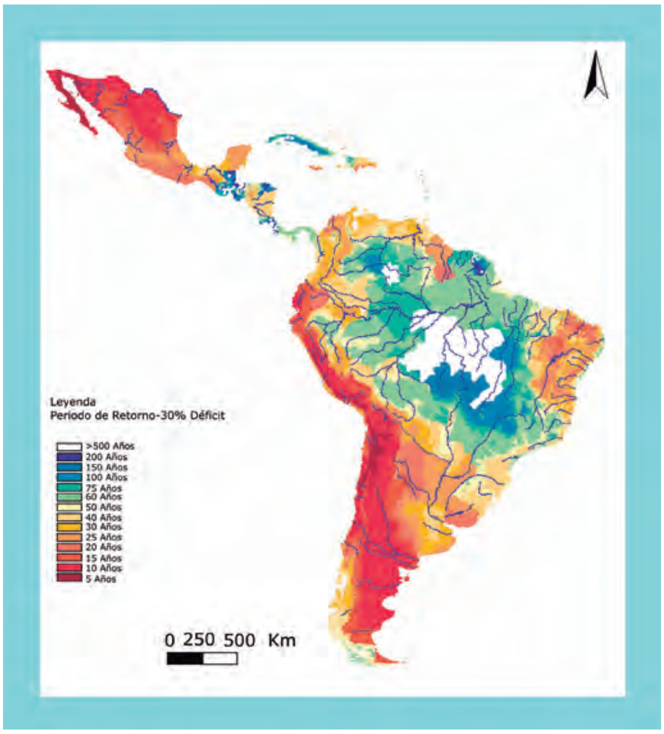
Mean recurrence of annual rainfall equivalent
to a 30% compared to normal values




Source: UNESCO, 2018.

In light of such a complicated context, increasing water availability and enhancing water-use efficiency—and its environmental, social, and economic components—are considered priorities for the region's sustainable development (FAO, 2018). Target 6.4 of Sustainable Development Goal 6, which seeks to ensure access to water, its sustainable management and sanitation for all, aims to: "By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity." The indicator used for monitoring water use efficiency (6.4.1) under this target has been defined with an economic perspective as the value added over time per unit of water used, expressed in USD/$m^3$, for the agricultural, industrial, and service sectors. The indicator is calculated as the sum of efficient water use in each sector, weighted by the percentage of water used in each sector. Reference values for this indicator were recently determined and show an average efficiency of 15 USD/$m^3$ at the global level, with substantial differences between countries and regions of the world (FAO, 2018). Central and South Asia have the lowest efficiency (2 USD/$m^3$) and Oceania the highest (50 USD/$m^3$). Based on this indicator, water use efficiency in Latin America and the Caribbean is currently estimated at 13 USD/$m^3$, slightly below the world average. As in other regions, the agricultural sector is the primary water resource user and the least economically efficient.

Other targets of the Sustainable Development Goal 6 include universal access to safe drinking water and the protection and restoration of water-related ecosystems. In Latin America and the Caribbean, the ecosystem services are considered one of the region's main assets. Although they are not market goods, they make a vital contribution to our survival and are essential to economic development. The Sustainable Development Goals are profoundly interconnected, and this is particularly true for water. Without universal access to water and sanitation and the sustainable management of this resource, it is not possible to achieve any of the other Goals, such as poverty eradication (SDG 1), zero hunger (SDG 2), good health (SDG 3), gender equality (SDG 5) or the preservation of life below water (SDG 14).

Domestic data in Latin America and the Caribbean for the water use efficiency indicator (WUE) in the agriculture, MIMEC (mining and quarrying; manufacturing; electricity, gas, steam and air conditioning supply; constructions), and service sectors, and the percentage (P) of water used by each sector considering total use

| Country | WUE Agriculture (USD/m³) | WUE MIMEC (USD/m³) | WUE Services (USD/m³) | P Agriculture (%) | P MIMEC (%) | P Services (%) | WUE (USD/m³) |
|---|---|---|---|---|---|---|---|
| Antigua and Barbuda | 2.4 | 70.3 | 120.6 | 16 | 22 | 63 | 91.2 |
| Argentina | 0.2 | 35.5 | 53.3 | 74 | 11 | 15 | 12.1 |
| Barbados | 0.7 | 98.8 | 160.6 | 68 | 8 | 25 | 47.7 |
| Belize | 0.2 | 8.9 | 56.4 | 68 | 21 | 11 | 8.4 |
| Bolivia | 0.2 | 256.2 | 75.7 | 92 | 2 | 7 | 9.1 |
| Brazil | 0.3 | 34.5 | 53.8 | 55 | 17 | 28 | 21.2 |
| Chile | 0.2 | 15.6 | 71.0 | 83 | 13 | 4 | 4.8 |
| Colombia | 0.6 | 29.1 | 36.1 | 54 | 19 | 27 | 15.5 |
| Costa Rica | 0.8 | 40.7 | 45.7 | 57 | 11 | 32 | 19.7 |
| Cuba | 0.2 | 25.0 | 35.8 | 65 | 11 | 24 | 11.5 |
| Ecuador | 0.5 | 45.6 | 28.8 | 81 | 6 | 13 | 6.7 |
| El Salvador | 0.2 | 29.1 | 27.5 | 68 | 10 | 22 | 9.2 |
| Guatemala | 0.8 | 22.5 | 33.2 | 57 | 18 | 25 | 12.9 |
| Guyana | 0.2 | 31.8 | 21.2 | 94 | 1 | 4 | 1.5 |
| Haiti | 0.2 | 56.7 | 19.1 | 83 | 4 | 13 | 4.6 |
| Honduras | 0.2 | 29.5 | 20.0 | 73 | 7 | 20 | 6.2 |
| Jamaica | 0.4 | 41.3 | 31.0 | 55 | 9 | 35 | 15.1 |
| Mexico | 0.2 | 47.9 | 52.0 | 77 | 9 | 14 | 11.9 |
| Nicaragua | 0.3 | 36.9 | 18.6 | 77 | 5 | 19 | 5.4 |
| Panama | 0.3 | 947.5 | 53.2 | 43 | 1 | 56 | 39.1 |
| Paraguay | 0.1 | 39.5 | 28.5 | 79 | 6 | 15 | 6.9 |
| Peru | 0.5 | 208.0 | 66.3 | 89 | 2 | 9 | 11.0 |
| Dominican Republic | 0.2 | 24.7 | 41.4 | 80 | 8 | 12 | 7.1 |
| Suriname | 1.0 | 10.8 | 35.2 | 70 | 22 | 8 | 5.9 |
| Trinidad and Tobago | 1.7 | 105.8 | 45.6 | 4 | 34 | 62 | 63.9 |
| Uruguay | 0.2 | 80.4 | 43.2 | 87 | 2 | 11 | 6.8 |
| Venezuela | 0.4 | 212.0 | 26.2 | 74 | 4 | 23 | 13.7 |

Source: FAO, 2018.
WUE = water-use efficiency
MIMEC = mining, and quarrying; manufacturing; electricity, gas, steam, and air conditioning supply; constructions

In terms of SDG 5 and gender equality, the gap can be observed at several levels and in the many sectors that use water. In this regard, Latin America and the Caribbean differ from other regions (UNDESA, 2010). For example, most (80%) women in the region work in the service sector, and nearly 75% of the agricultural sector professionals are men. This helps explain why in Latin American and the Caribbean, the percentage of men responsible for water collection is higher than that of women in rural and urban areas. However, the stronger presence of women in the service sector—the most water-efficient sector—should be addressed with greater participation in water management and governance positions. More women should be trained on water issues, and we should generate conditions that promote women's engagement in water management. It is also necessary to promote adequate conditions for women in sectors where they are a minority, even in essential aspects such as rural sanitation.

SDG 6 targets also show interconnection (UNESCO-CODIA, 2019). Sustainable development is only possible when environmental, social, and economic components are addressed as one. Thus, it is vital to consider three pillars, which focus on the following practical solutions for the region: (1) techniques that preserve and increase the availability of water, (2) techniques that improve water-use efficiency in the agriculture sector, and (3) techniques aimed at managing and preserving water for ecosystems. These pillars were discussed at the seminar "Towards Sustainable Water Management in Latin America and the Caribbean: sharing experiences on methods to preserve, increase availability and improve water-use efficiency" (Lima, August 5-6, 2019), organized by the Intergovernmental Hydrological Program (IHP), the Regional Water Center for Arid and Semi-Arid Areas of Latin America and the Caribbean (CAZALAC) and the "Water security and climate change adaptation in Peruvian glacier-fed river basins" project (RAHU). The discussions and conclusions of this seminar are presented below.

## Techniques that preserve and increase the availability of water

The initial discussion was devoted to describing a case study of a primary phase project that will measure the retreat of Peruvian glaciers, water availability for human consumption, and the needs of ecosystems in the Andean region. There was a particular focus on the need for increased understanding of the water dynamics of glacier-dependent ecosystems and the buffering and regulation potential of intermediate ecosystems such as peat bogs. It was concluded that not enough information is available for many glacier water systems in the Andes since research has focused on a few specific glaciers, most of which are non-tropical. Tropical glaciers are part of water systems intensively used by ecosystems and by productive urban and rural areas. Therefore, if we want to evaluate their potential to increase water availability, or at least maintain current levels, it is necessary to know these systems in detail. For this purpose, in the specific case presented, a glacio-hydrological model will be developed, contemplating adaptation strategies to water scarcity to increase local water availability and achieve long-term water security. During the discussion, different suggestions were made on the need to integrate the system's stakeholders and users to avoid frequent conflicts.

Later on, there was a mention of the importance of glacier-regulated flows and high Andean wetlands, not only for glacier-dependent systems in high-altitude areas but also for the affected basins in lowland areas. The discussions also addressed the use of alternative technologies—in this case ancestral— for aquifer recharge through the recovery of old infrastructure that, with great accuracy and well located, can recharge crucial aquifers downstream, taking advantage of the local geology and the potential storms in the basins' high areas.

It was pointed out that due to the intrinsic nature of Amazonian hydrology—such as remoteness, the difficulty of access, etc.—there are few studies and limited hydrological characterization. Since it is highly unlikely there will be field information from weather stations in the area available, it is crucial to consider alternative techniques to produce descriptive data to inform water availability management. In this context, studies were presented on regionalization, modeling, and indirect estimation of hydrological patterns in glacier-dependent basins, covering different types of ecosystems, such as equatorial mid-altitude peat bogs, Amazon basins, etc.

The actions currently being carried out to increase water availability in urban contexts close to depleting their natural resources were also discussed. Sometimes the only option is resorting to other basins with accurate dimensioning. However, working only from a supply perspective reaches less than desirable limits since the indiscriminate use of water resources increasingly causes water stress in urban areas. As a result, it was decided to include part of the Seminar's recommendations to focus not only on the availability but also on the urgent need to rationalize the demand for water at the global level.

Under this perspective, it was agreed that determining water availability and increasing it depends strongly on the information available. The general notion is that the availability of data, studies, and research is quite limited, and that is the context in which water security must be managed. Most studies in the area—in terms of its meteorology, climate, and water resources—show high uncertainty regarding the resource's current availability. There will be much less security in the future. Therefore, there is a clear need for data collection, assimilation, reconstruction, or other techniques that, based on available technologies, can produce more accurate information to adopt measures to increase water availability.

The quality of water was also addressed during the presentations. Most Latin American and Caribbean (LAC) cities depend on already polluted sources, water bodies such as aquifers or rivers. Water availability can also be increased through the restoration of these sources. In this region, urban wastewater discharges increase due to population growth and the expansion of water supply and sanitation services. The increase in urban wastewater is caused by the urban population's growth and a higher per capita water use. However, less than 60% of these facilities are connected to sewage systems. Reports published by different institutions warn that in most of the region, the increase in the population with access to sanitation has not gone hand in hand with an increase in wastewater treatment, in general this is due to financial limitations.

Despite the great potential for direct, safe, and planned water reuse in the region, most wastewater is discharged, unused, into the sea or waterways where it is reused downstream indirectly and often unintentionally on hundreds of thousands of hectares of crops, posing severe risks to human health and the environment.

Two of the presentations showed pilot research and techniques to identify and treat water pollution. Water eutrophication was specifically described for deepwater bodies where both surface contamination and the significant accumulation of immobilized nutrients must be taken into account. This complicates water treatment because these nutrients are released slowly and re-contaminate surface water, which water treatment plants must consider. Different solutions were analyzed as well as a technology related to the use of monitoring and simultaneous treatment devices, although costs continue to be a limitation. However, many cities in LAC may be forced to invest in this type of facility in the future, making it clear there is an urgent need for research and technology development in this area.

The need to explore more technologies to increase water availability in the region was also raised during the discussion. Some of the much-needed alternatives already underway include: treating domestic wastewater by direct and indirect means, which can be reused for irrigation, aquifer recharge, or non-consumptive domestic uses. Aquifer recharge should be a priority, especially in regions with significant amounts of precipitation but in concentrated periods. For this purpose, it is crucial to develop technologies that allow intense hydrological monitoring, combined with indirect technologies such as remote sensors that, with technological advances, offer more and better features.

## Techniques that improve water-use efficiency in agriculture

The session outlined the outcomes of different actions adopted to reduce water losses in agriculture and/or increase the water-use efficiency of cultivated systems. As discussed, crop and irrigation water-use is crucial when discussing food security in the region since much of agriculture is developed on a rain-fed basis, making it more vulnerable to climate change. It will soon be necessary to expand the area under irrigation, but with an increased water-use efficiency, since food supply is not compatible with limited water resources that are poorly or inefficiently managed.

The session started with five presentations that showed techniques or research related to reducing water use to produce the same biomass or crop products. Advances in research and practical implementation of two successful cases of agricultural water productivity improvement were introduced. One sought to improve water-use efficiency in fodder production through hydroponic culture. The other addressed a more efficient use of water in greenhouses and its connection to photosynthetic activity in areas affected by intense direct radiation. The intensive use of water to farm smaller areas was feasible, especially for vegetables and fodder, although production costs may still be high. However, the relatively frequent emergencies due to extreme adverse events in the LAC region shows the need for swift actions that lead to quick results, similar to those presented.

The presentations also covered efficient water-use monitoring through patented water control facilities in canals and field monitoring sensors that could save significant amounts of water, even in extensive large-scale crops. Overall, savings of around 50% were reported across the different experiences, which shows that either through improved monitoring or innovative techniques, conditioned environments, and agroclimatic monitoring of soil water parameters, such water-use savings are achievable. In terms of the physiological aspects, the potential of the great diversity of crops in the Americas was addressed. There was a mention of South American crops with unique physiological mechanisms that make them drought resilient and adaptable. This opens up the possibility for crop production in extremely dry conditions and/or the genetic use of those characteristics for extremely efficient water use.

In terms of the social aspects, one of the presentations allowed for an exchange of ideas and impressions on the need to support social organizations in charge of water control, highlighting the commitment of local communities and indigenous peoples to monitor and control water rights for irrigation and water-use efficiency from a local knowledge perspective. By involving local communities, indigenous peoples, and citizens in implementing water-use efficiency actions, we could improve water balance in LAC basins. This is because water is the pillar around which many communities developed, and by coming together, they could preserve balance and governance and increase water-use efficiency.

It was also agreed that these communities must produce useful information. Their knowledge and practices provide critical insights into how natural events manifest and affect communities and what local resources should manage the associated risks. A clear example was the conservation and upkeep of ancient canals that preserve water balance in the basin surrounding the city of Lima.

Other experiences currently underway in Latin America and the Caribbean were also brought up, although they were not presented. These were mainly related to the agro-ecological management of agricultural production, the integration of agricultural management into global environmental agreements such as the Koronivia Joint Work on Agriculture, into agricultural biotechnology initiatives, and the massification of farming systems with provisions for inputs such as irrigation and appropriate and sustainable fertilization practices, among others.

## Techniques aimed at managing and preserving water for ecosystems

The presentations in this session focused on several demonstrations that show that water maintenance and preservation for ecosystems are feasible in the region. At the same time, there is little research and few results available, least of all long-term monitoring. Moreover, the precious experiences had to face severe data constraints due to the lack of regular monitoring in most LAC aquifers. A comparative study showed that the extent of water gains for deep aquifer recharge or ecosystem use is generally wise. In most cases, no measurements are made, and, therefore, there is no available data. Thus, in general, the actions' effectiveness cannot be quantitatively demonstrated comparatively.

Water governance was also addressed to evaluate a proposal for water monitoring in a basin directly affected by atmospheric events, mainly by El Niño, the most critical global atmospheric-oceanic event in the LAC region.

Monitoring could lead to more efficient management. This would reduce the ecosystem stress caused by large extractions for irrigation and other uses, thus reducing even further, under ENSO events, the availability of water in the region's basins where water use is already in a critical state.

In all cases, the communities have shown interest in participating in monitoring and preservation initiatives, agreements, and other related actions. As noted in the rest of the sessions, the technical issues and proposals depend largely on stakeholder engagement, without whom the sustainability and feasibility of these measures would be compromised. But the lack of preexisting information makes it difficult to assess effectiveness, as there is no baseline information to compare the results or proposals.

Finally, the limited amount of research and results in this field of knowledge, although integrated with more global studies, would require a special focus on water management.

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# Increasing water security in the context of glacier shrinkage in the Vilcanota-Urubamba basin

*Fabian Drenkhan,[1] Wouter Buytaert,[2] Pedro Rau[3] and Walescka Cachay[4]*

**Abstract**

In the Peruvian Andes, year-round streamflow from tropical glaciers supports human livelihoods and ecosystems further downstream. However, the rapid shrinking of glaciers, combined with high human and natural vulnerability, increases the potential of water-related risks. In this context, the project *Water security and climate change adaptation in Peruvian glacier-fed river basins* (RAHU) aims to collect new data and integrate modeling of glaciers and water-related processes in the Vilcanota-Urubamba basin in southern Peru. Therefore, a focus has been put on participatory hydrological monitoring of glaciated and high-Andean wetland-covered sub-basins in close collaboration with Peruvian and British research teams, as well as local and regional policy-making and water use groups. The collected data represent a crucial input for an improved understanding of the hydrological role of glaciers and Andean peat bogs in the context of downstream water availability to increase long-term water security in the region.

**Keywords:** Glacier shrinkage, water security, participatory monitoring, natural infrastructure, adaptation, Cusco.

## Introduction

In the tropical Andes, climate change impacts are evidenced by the sharp reduction in glacier coverage. The area loss rate is approximately 1-2% annually (Rabatel *et al.*, 2013; Vuille *et al.*, 2018). Estimations of the potential glacier progression towards the end of the 21st century suggest a substantial rise in the snow line and, consequently, in the Equilibrium Line Altitude (ELA) from about 200 m (RCP2.6) to 700 m (RCP8.5) in the tropical Andes (Réveillet *et al.*, 2015; Schauwecker *et al.*, 2017; Drenkhan *et al.*, 2018; Vuille *et al.*, 2018; Cuesta *et al.*, 2019).

This would imply a full shrinkage of glaciers located below 5,400-5,700 m a.s.l. (Rabatel *et al.*, 2013) and, probably, the loss of a significant part of the water stored (Réveillet *et al.*, 2015; Drenkhan *et al.*, 2019). These possible impacts of glacial retreat put water security for human subsistence and ecosystems in the Andean region at risk (Buytaert *et al.*, 2017; Vuille *et al.*, 2018). On the one hand, water supply is affected as the ice mass in heavily glaciated sub-basins decreases: river flow may be subject to time-space reductions (e.g., in the dry season and headwaters) and lead to more significant variability in an increasingly rain-fed regime (Kaser *et al.*, 2010; Baraer *et al.*, 2012). On the other hand, greater demand for water resulting from the growth of irrigated agriculture, hydropower production, and population and urbanization processes leads to more significant stress on water resources (Buytaert, De Bièvre, 2012; Drenkhan *et al.*, 2019).

In Peru, where we can find the largest tropical glacier area in the world (~70%), glacier coverage has decreased substantially in the past five decades (~54%), from about 2,400 km² in 1962 to

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1,285 km² in 2016 (INAIGEM, 2018). Its physical, natural, and cultural characteristics make it a complex region of study. Also, the interrelations between water supply and demand variables are multidimensional and, therefore, large uncertainties remain (Drenkhan *et al.*, 2015)including climate change, glacier shrinkage, and socioeconomic forces related to demographics, agroindustrial development, and hydroelectricity generation, pose new hydrological risks for human livelihoods. However, these hydroclimatic and socioeconomic drivers of water resource change are often poorly quantified and interconnected, while data scarcity poses challenges in these regions. Here we review the state of knowledge for two major catchments in the Peruvian Andes, which hold the largest tropical glacier mass worldwide: the Santa River (Cordillera Blanca. There are also substantial limitations on the availability of reliable, long-term, glacio-hydrological, and socio-economic data (Huggel *et al.*, 2015). Thus, there is little understanding of the processes and connections between climate change, glacier shrinkage, water security, and local adaptation capacity (Salzmann *et al.*, 2013; Huggel *et al.*, 2015). In this context, it is necessary to adopt a comprehensive and interdisciplinary approach to understand these processes and their impacts and to implement appropriate science-based adaptation strategies for an uncertain future. Furthermore, the multiple water conflicts prevailing in Peru clearly show the need for water governance with an adaptation-based management approach that is more participatory, safe, and sustainable (Lynch, 2012; Drenkhan *et al.*, 2015)including climate change, glacier shrinkage, and socioeconomic forces related to demographics, agroindustrial development, and hydroelectricity generation, pose new hydrological risks for human livelihoods. However, these hydroclimatic and socioeconomic drivers of water resource change are often poorly quantified and interconnected, while data scarcity poses challenges in these regions. Here we review the state of knowledge for two major catchments in the Peruvian Andes, which hold the largest tropical glacier mass worldwide: the Santa River (Cordillera Blanca.

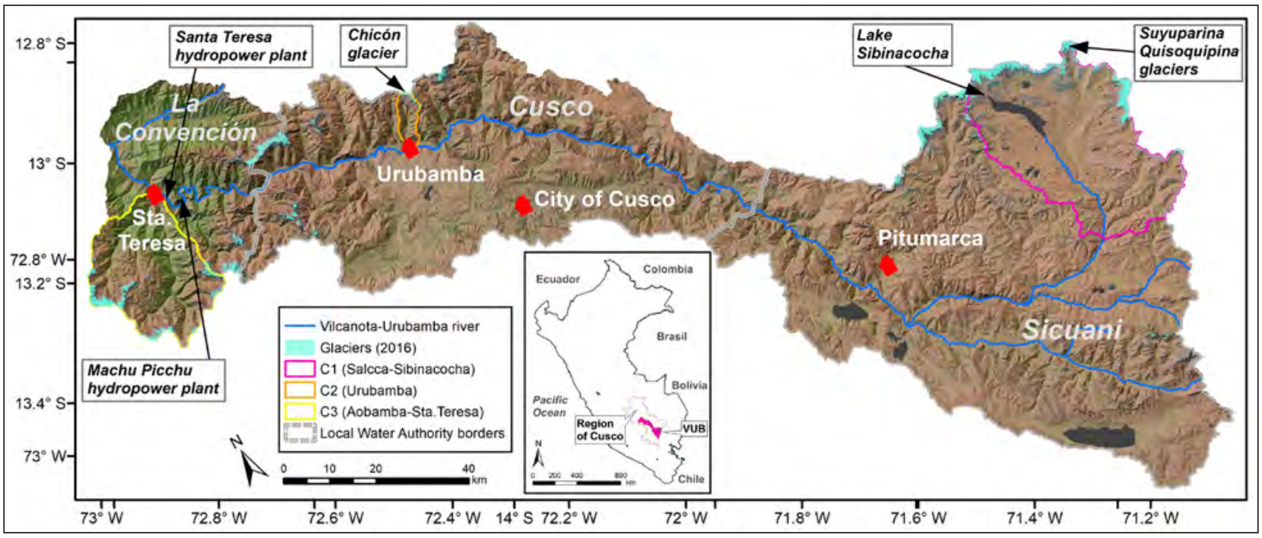
In this framework, the new international project “Water security and climate change adaptation in Peruvian glacier-fed river basins” (RAHU) aims to address these challenges through an international research consortium (Peru and UK) and local policymakers’ engagement. The objective is to develop a glacio-hydrological model integrating adaptation strategies to water scarcity to inform decision-making in implementing adaptation measures to sustain and increase local water availability and achieve long-term water security.

## Materials and methods

### *Area of study*

The RAHU study area is located in the Vilcanota-Urubamba basin (Cusco, Figure 1). The Vilcanota Mountain Range is the second-largest tropical glacier fragment globally, spreading across 34% (~255 km²) of the glacier surface in Peru (INAIGEM, 2018). An important part (~84 km²) of this mountain range is located in the Vilcanota-Urubamba River Basin, which also includes parts of the Urubamba Mountain Range (~18 km²) and the Vilcabamba Mountain Range (~39 km²) downstream (Drenkhan *et al.*, 2018). Glacial annual contribution to the surface runoff of the Vilcanota-Urubamba River in the heavily glaciated headwaters is quite significant (from 35% to more than 50%), decreasing towards the Valle Sagrado (<10%) and the lower basin (<4%) (Buytaert *et al.*, 2017). However, the considerable glacial shrinkage rate of 1.3%/year in area and 0.7% in volume observed during the past four decades shows a substantial loss of ice and water of about 1.7 km³ and 1.5 km³, respectively (Drenkhan *et al.*, 2018). The Vilcanota-Urubamba basin spreads over a total area of 11,048 km² at 6,372 m a.s.l. (Nevado Ausangate, highlands) down to the mouth near Santa Maria at 1,180 m a.s.l.

**Figure 1.** Combined view of the Vilcanota-Urubamba basin and the three sub-basins (C1, C2 y C3), glacier coverage, largest populated centers and regions of the *local Water Authorities*




Source: Modified from Drenkhan et al. (2018)

There is a semi-arid high Andean climate at the basin headwaters with a pronounced dry season in the southern winter (May-September) (e.g., C1, Figure 1). In contrast, downstream (e.g., C3, Figure 1), there is a transition through montane rainforests to the tropical forest (Figure 2). This means that human livelihoods at the basins' headwaters are potentially affected by extended droughts. Towards the end of this century, the potential decrease of 19-33% in precipitation in the highlands during the wet season (Neukom *et al.*, 2015)climate models have often limited capabilities to adequately simulate the precipitation variability on small spatial scales. Also, their validation is hampered by typically very low station density. In the Central Andes of South America, a semi-arid high-mountain region with strong seasonality, zonal wind in the upper troposphere is a good proxy for interannual precipitation variability. Here, wecombine instrumental measurements, reanalysis and paleoclimate data, and a 57-member ensemble ofCMIP5model simulations to assess changes in Central Andes precipitation over the periodAD1000–2100. Thisnewdatabase allows us to put future projections of precipitation into a previously missing multi-centennial and pre-industrial context. Ourresults confirmthe relationship between regionalsummerprecipitation and 200 hPa zonal wind in the Central Andes, with stronger Westerly winds leading to decreased precipitation. The period of instrumental coverage (1965–2010 could worsen this situation. In contrast, downstream, there is a greater risk of landslides and mass removals resulting from torrential rains. The different events in the Sacsara and Aobamba river basins, in the extreme climatic year of 1998, illustrate this fact with the loss of most of the Santa Teresa population center and the critical Machu Picchu hydropower plant (Carlotto, Cárdenas, Fidel, 2007).

Figure 2. Vilcabamba range (C3)

Photo: Fabian Drenkhan.

Water security is at risk, not only because of the expected reduction and more significant variability in the water supply but also because of the strong growth in water demand and high human vulnerability (Buytaert *et al.*, 2017; Drenkhan *et al.*, 2019). Almost half (43.2%) of the Cusco region population does not have access to the public drinking water system, which is noticeably above the national average (32.6%). In households without permanent access to water, it is mainly women who have to procure it elsewhere, making them the most vulnerable group in health, productivity, and education opportunities (INEI, 2018b). Between 1993 and 2017, the population's average annual population growth in the basin (~838,500 inhabitants) was 1.3%. There is a stark difference in gradient between the city and the province. While rural areas (55% of the population) register an annual depopulation of 0.4%, urban areas (45%) grow significantly at a rate of 2.2% per year (INEI, 2018a). Agriculture covers about 12% (1,318 $km^2$) of the basin area (Figure 3), of which half (674 $km^2$) is managed with gravity or, to a lesser extent, spray irrigation (INEI, 2013). The expansion of agriculture is clear in different parts of the basin; there has been an increase in irrigated areas in the middle basin for export crop production (*cf.* Drenkhan *et al.*, 2019). The Machu Picchu I/II/III and Santa Teresa I hydropower plants, located on the Vilcanota River near the town of Santa Teresa (Figure 1), have an installed capacity of 290 MW at a required flow of 61 $m^3/s$ and play an essential economic and political role in the Cusco region. However, locals consider hydropower production quite controversial. The construction of the Salcca Pucará hydropower plant (152 MW) with two reservoirs was finally not possible due to the lack of a social license, and the Santa Teresa II project (268 MW, C3, Figure 1) is still the object of a major dispute as locals fear a shortage of water for agricultural, domestic and tourist-recreational use (Drenkhan *et al.*, 2015) including climate change, glacier shrinkage, and socioeconomic forces related to demographics, agroindustrial development, and hydroelectricity generation, pose new hydrological risks for human livelihoods. However, these hydroclimatic and socioeconomic drivers of water resource change are often poorly quantified and interconnected, while data scarcity poses challenges in these regions. Here we review the state of knowledge for two major catchments in the Peruvian Andes, which hold the largest tropical glacier mass worldwide: the Santa River (Cordillera Blanca.

Figure 3. Agriculture around the Sacred Valley (C2)

Photo: Fabian Drenkhan.

### *Methodology proposed*

The RAHU project aims to better understand the spatial-temporal propagation of the glacial pattern within the terrestrial water cycle in a context of water security and how glacial streamflow interacts with other water bodies, such as the high Andean wetlands (peat bogs). It will focus on monitoring different (glaciated and non-glaciated) sub-basins using the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA) (Célleri *et al*., 2009) methods to identify and scale hydro-glacial and human impacts on the basins. There is vast, 10-year experience with iMHEA's monitoring method, covering more than 20 sites in Venezuela, Colombia, Ecuador, Peru, and Bolivia (Buytaert *et al*., 2014; Ochoa-Tocachi *et al*., 2016; Ochoa-Tocachi, Buytaert, De Bièvre, 2018). Three different types of experimental micro-basins will be monitored under these principles: one dominated by glacial streamflow (type 1), one by high Andean wetlands (peat bogs) (type 2), and one by other coverage (type 3, with minimal influence of glacier or wetland).

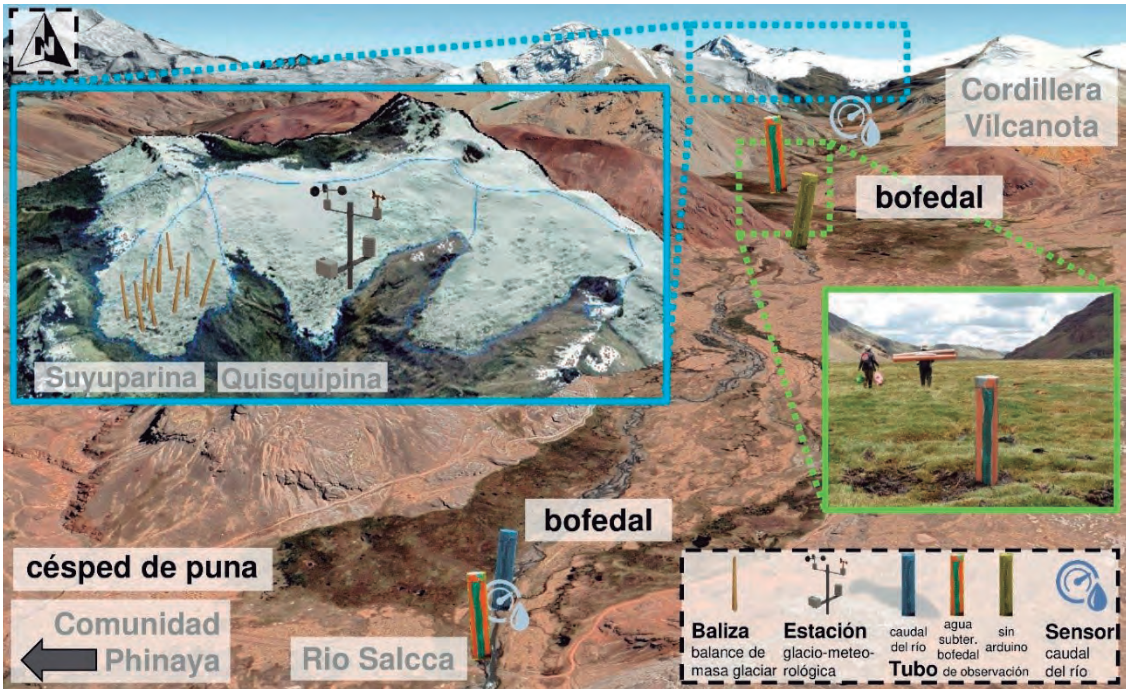
The idea is to begin intense medium to long-term monitoring using iMHEA methods with a network of sensors to acquire a better spatial-temporal understanding of glacial and non-glacial runoff, including high Andean peat bogs. The results will serve as input to design and calibrate a hydro-glaciological model of the RAHU project so as to be able to combine the results with a reliable analysis of potential scenarios of human vulnerability in the face of water scarcity in different key points of the basin. It will also provide support to local institutions for research and decision-making. The objective is to engage people connected to research or the local community by explicitly focusing on the implementation of innovative citizen science methods with low-cost sensors built at Imperial College London (Buytaert *et al*., 2016).

Furthermore, the analysis of the new data patterns, the glacio-hydrological modeling, and mapping of vulnerabilities will enable water security assessment at different points of the basin. Finally, the plan is to formulate different adaptation strategies, including implementing various basin interventions by focusing on natural infrastructure. To do so, it is crucial to rely on robust adaptation measures approaches based on risk assessment (Ludwig, van Slobbe, Cofino, 2014) with good performance in a context of high variability of potential climatic, socio-economic and, therefore, hydro-glaciological scenarios (*cf.* Wilby and Dessai, 2010; Ceola *et al*., 2016). These strategies will be defined in the context of the new Peruvian legislation and the potential opportunities arising from the creation of the Vilcanota-Urubamba Basin Water Resources Council (2018), its commitment to draft the Water Resources Management Plan and the new law on Compensation Mechanisms for Ecosystem Services (MRSE, 2014). This work will be carried out in close collaboration with the Natural Infrastructure for Water Security Project (INSH) in Peru, which, among others, is being executed by one of RAHU's partners, the Consortium for the Development of the Andean Ecoregion (CONDESAN). The Project is also working closely with the Regional Conservation Area of Ausangate (recently created, 12/Dec/2019) in the Upper Vilcanota to create significant impact on the new Master Plan. This includes the conservation of headwaters, peat bogs and possible green infrastructure interventions to sustain and increase the ecosystem services linked to water regulation.

## Preliminary results

During a first field campaign in the Salcca-Sibinacocha sub-basin (C1, Figures 1 + 4), a system of low-cost sensors (Arduinos) was installed to measure the water level (groundwater) in the peat bogs (type 2). Before this campaign, there was already a gauge in place, operated by the National University San Antonio Abad del Cusco (UNSAAC), to measure the river flow (type 1) at the mouth of the Quisoquipina (glacial altitude: 5,600 m a.s.l., glacier coverage: 3.3 $km^2$) and Suyuparina glaciers (5,452 m a.s.l., 1.1 $km^2$, Figure 4). In addition, there are two weather stations, one in the ablation zone of the Quisoquipina glacier (Figure 4) and one close to the Sibinacocha reservoir (average altitude: 4,917 m a.s.l.; ~28 $km^2$; ~0.11 $km^3$, Figure 1) in which there is also a flow measurement gauge. RAHU uses this data and continues to expand the monitoring system with different low-cost sensors manufactured in-house to measure river flow and install weather stations. While agricultural activities are limited and population density is low, the Salcca-Sibinacocha sub-basin deserves special attention because of its role in water regulation downstream, primarily through the Sibinacocha reservoir for the Machu Picchu and Santa Teresa hydropower plants at the outflow of the study basin.

Figure 4. Overview of the upper Salcca-Sibinacocha basin with glaciers, peat bogs, and river flow monitoring




Source: Own compilation based on information from Google Earth

The work in the Urubamba sub-basin (C2, Figure 1) will be carried out in two micro-basins: one dominated by glacial streamflow (type 1) and one with minimal glacial influence (type 3). A flow gauge, a weather station, and a rain gauge have already been installed in the central Urubamba basin (type 1). The Urubamba river flow is also monitored as part of the Early Warning System for glacial lake outburst floods.

The work within this sub-basin is carried out considering that water is mainly used for agriculture and supplying the population in many of the cities in the basin (Sacred Valley). The experiences in Salcca-Sibinacocha (C1) and Urubamba (C2) will later be used to upscale the lessons learned to other sub-basins in the Vilcanota-Urubamba and beyond. It is also expected to be implemented at the Aobamba-Santa Teresa sub-basin (C3, Figure 1) in 2021.

## Discussion and conclusions

The RAHU Project's innovation is that it combines the different components of glacio-hydrological measurement and modeling with further analysis of high Andean wetlands and water demand and adaptation issues. In this context, it is worth highlighting the citizen science methods with low equipment costs. The great advantage of using a dense network of low-cost sensors in this area is to obtain non-existent data on glacial, non-glacial, and peat bog "behavior" in high spatio-temporal resolution that wouldn´t traditionally exist for the Andean basins. In addition, by engaging the local communities and decision-makers, it is possible to build greater trust through the interaction of locals and foreigners, which will help ensure results and may promote closer collaborations on the long term.

One of the limitations in the use of citizen science methods is probably managing the workflow: the sensors built in the United Kingdom have to arrive in Peru on time to, with great effort and coordination, and be installed in a remote area above 4,700 m a.s.l under adverse environmental conditions. This work requires a lot of coordination and effort with and by the local partners. Besides, a frequency (minimum: biannual) of data collection would have to be guaranteed. It is therefore vital to have the support of trusted local people. This last aspect may even be a greater obstacle than the technical issues themselves. Different experiences in the tropical Andean region, Peru, and the Vilcanota-Urubamba basin show that the collaborative work with local communities and authorities is often underestimated. Still, it is essential to obtaining the social license for the Project. RAHU is currently working hard on an agreement with the Phinaya community (Alto Vilcanota, C1) to combine joint work with collaborative hydrological monitoring, participation in community meetings, training, workshops, and exchange between academic research and local knowledge.

It is hoped that this method will help improve the understanding of hydrological processes and, at the same time, inform the design and implementation of adequate strategies for adaptation to climate change and (natural) interventions in the basin to increase water security.

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# Harvesting rainwater to adapt to climate change

*Henry Abel Vergara*[1]

**Abstract:** Climate change is evident in the Cusco region, mainly in the high Andean areas, due to the effects on water availability for different uses such as agriculture and human consumption. The lack of water is aggravated by poor water use practices and inadequate agricultural technologies such as contour plowing for crops or intensive livestock grazing in natural grasslands. The Cusco-Region Special Project - Institute of Water Management and the Environment (PER IMA) implemented a project to address this problem called Adaptation to climate change: water harvesting in lake microbasins of the upper Vilcanota basin—ACAMCAV. It aims to reduce water scarcity in the intervention areas, including the Quillayoc microbasin in the Sangarara district, Acomayo-Cusco province. Its actions include stormwater retention by building a dam to take advantage of the Matarampampa wetland, recovery of water retention from soils with erosion problems, afforestation, reforestation of native species, and building infiltration trenches. Furthermore, training sessions in water management were held, and organizations that use water resources were strengthened. The project results include a dam that stores a maximum rainwater capacity of 500,000 $m^3$/year, the improvement of climate and ecosystem conditions, the recovery of vegetation cover in the upper basin, and soil erosion control.

**Keywords:** Keywords: water harvesting, climate change, wetland, dam.

## Introduction

Climate change poses what may be considered an unprecedented threat to human development. Much of this threat will be perceived in changes in hydrological cycles and the impact of higher surface temperature on water evaporation (UNDP, 2006). Several countries and communities worldwide are already experiencing considerable impacts related to climate change, including droughts, floods, more frequent and intense natural disasters, and sea-level rise. The poorest and most vulnerable sectors are the most affected (World Bank, 2019).

Climate change will impact society, the environment, and the economy in all respects. This entails the need to adjust people's behavior, livelihoods, infrastructure, laws, policies, and institutions to respond to climate events already taking place and expected in the future (Ministry of the Environment of Peru, 2010).

According to forecasts until 2030, in the Sierra del Peru regions, annual rainfall would show deficiencies between -10% and -20%; in the northern and central Amazon (high forest), the annual rainfall would decrease up to -10%, and in the north and south coast, rainfall would increase between +10% and +20% (iNDC Peru, 2016). There is a problem of water scarcity due to climate change in the Andean area of the Cusco region. As a result, the Cusco-Region Special Project - Institute of Water Management and the Environment (PER IMA)—created in 2008—prioritizes water harvesting projects, based on already existing socioeconomic and environmental diagnoses, and the Regional Economic Ecological Zoning (PER IMA, 2013).

The PER IMA runs water harvesting projects (PER IMA, 2009, 2011) that aim to develop territorial intervention strategies and identify high Andean areas as the most affected by water scarcity in the dry season. They also include agricultural lands with the greatest potential and which still have

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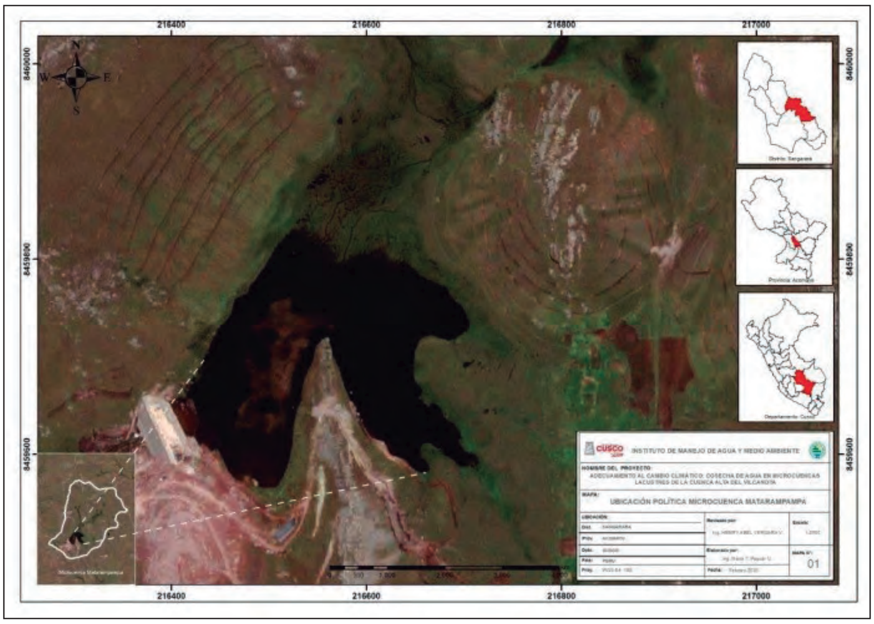
significant water deficits due to irregular rainfall and the presence of snowfalls, lakes, and peat bogs that are deteriorating.

## Materials and methods

The proposal implementation's starting point was to communicate and enter into agreements with the beneficiary population and the local authorities by participating in their community assemblies and working meetings with local government and political authorities. The following elements were addressed based on the existing water harvesting project in the district of Sangarara (Figure 1):

Figure 1. Political location map




Source: PER IMA.

When the dam's construction in the Matarampa-Sangarara wetland began, there was no access road to transport construction materials, construction personnel, and technicians. However, inter-institutional agreements and local authorities' involvement (Sangarara district municipality) have made it possible to build a dirt road leading to the dam works area stretching over approximately 3.5 km. The district municipality also made a financial contribution. The construction technology used in the Matarampampa dam was selected based on the materials already available in the area. In this way, the dam was built with loose material (local soils). The dam has the following technical characteristics:

- The Matarampampa dam has a homogeneous earthfill levee with a trapezoidal section. Its smaller base is 5 m wide, and the larger base, 52 m wide. The total dam length is 90 linear m.
- The total dam height is 7.30 m as measured from the minimum operating level to the crowning level.

- The effective water storage height is 6 m: the difference between the total height and the freeboard (1.30 m).
- The planned storage capacity is for a total volume of 500,000 $m^3$.
- The dam was waterproofed with different materials (geotextiles and geomembranes) placed on the upstream slope.
- The upstream and downstream slopes were secured with compacted rock fill. This was done on the upstream slope to protect the waterproofing material from the effects of solar radiation and waves. On the downstream slope, it was done to prevent the collapse of the loose material (soil) used to build the dam.
- The spillway channel is formed by a wide crest spillway made with stone masonry material, a single concrete canal, a water intake at the bottom, and a vent to the main ravine. It has an excess water evacuation capacity of 1.60 $m^3/s$.
- The dam water release system consists of a concrete intake, an 8” diameter PVC pipeline, a valve cabin, and a break pressure chamber.

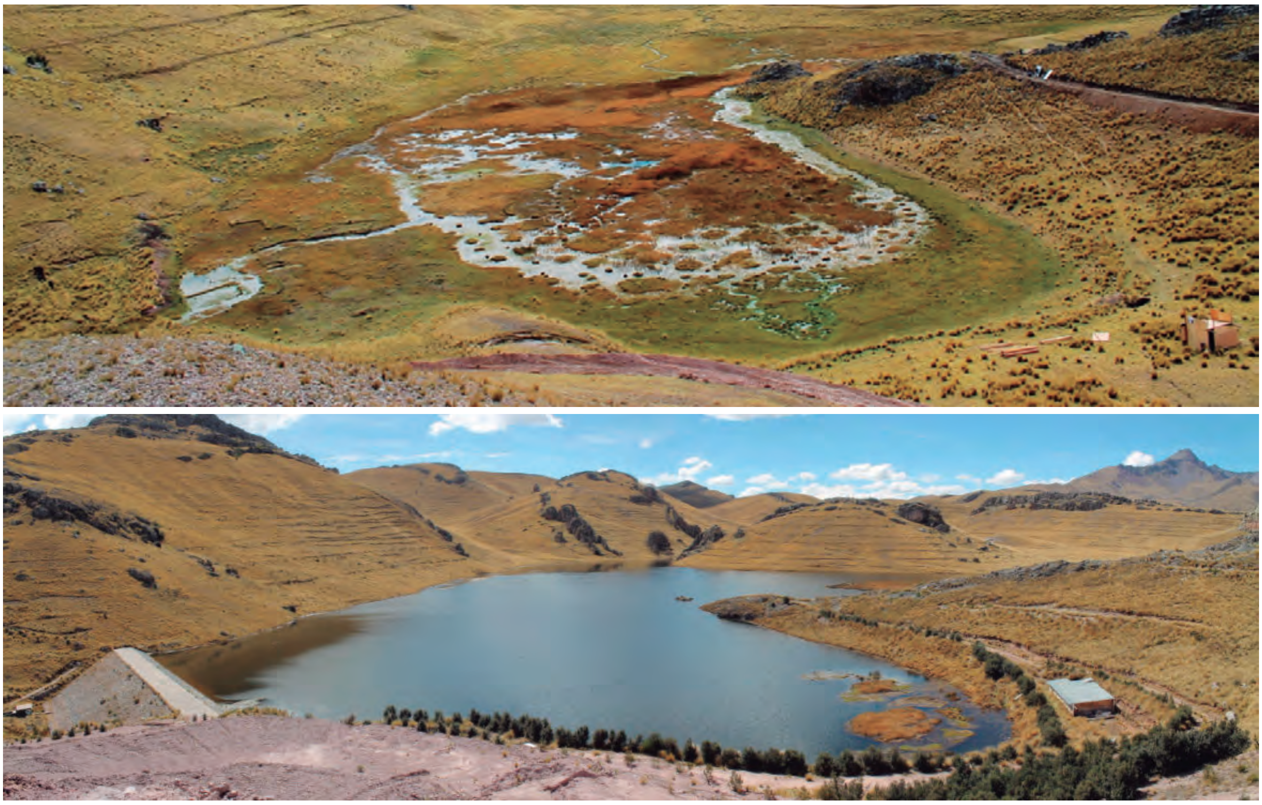
### *Forestry and soil conservation activities*

Interinstitutional cooperation agreements have been signed with the district municipality of Sangarara and the beneficiary community to implement **the forestry and soil conservation** components. This has made it possible to co-finance forestry actions such as seedling production and planting. Regarding soil conservation, community members contributed working hours to building infiltration trenches and control gullies, which amounted to 50% of the financial contribution needed.

**Forestry activities** are implemented in the water harvesting project **to** facilitate water infiltration into the soil, increase vegetation cover, and improve the area’s environmental conditions (Figure 2). To this end, a diagnostic assessment was conducted at the Quillayoc microbasin before the intervention to determine which areas had a loss of vegetation cover due to overgrazing in natural grasslands. Besides assessing the problem of loss of vegetation cover in the relevant microbasin, the forestry potential of the area was studied, as well as the connection of this potential with aquifer recharge areas.

Forest plantation has been implemented in priority areas to reverse the loss of vegetation cover, including native tree species such as Qolle (*Buddleja coriacea*), queuña (*Polylepis incana, Polylepis weberbaveri, Polylepis racemosa),* and chachacomo (*Escallonia resinosa*), which adapt to high Andean areas 4,000 m above the sea level. These tree species have the advantage of acting as a natural water reservoir, like a sponge. They retain water for longer, both in the aerial part and in the root system, thus contributing to the project’s objective.

Figure 2. Matarampampa before and after the intervention



Source: PER IMA's photographic record

It was suggested to build levee infiltration trenches and living barriers to control gullies to meet the soil conservation objectives. Infiltration trenches are small trapezoidal excavations built transversely to the slope to decrease water runoff on the slopes during rainy seasons. As these trenches are built upslope, they temporarily store surface water, contributing to aquifer recharge. Infiltration trenches also accumulate a percentage of moisture in the soil, which helps vegetation to recover in empty areas, especially natural grasses in each area.

The areas for soil conservation practices were also selected based on technical and social aspects, such as the site's hydrogeological characteristics, because it was essential to locate the areas in water recharge aquifers. Regarding social uses, practically all areas are used for grazing, protection, or rotational crops (laymes), with soils of acceptable conditions for building infiltration trenches.

The hydrological software Mauco was used to design the trenches. Its database was fed with the following information:

- Rainfall (maximum rainfall in 24 hours, frequency, intensity, and magnitude with a return period of 10 years).
- Soil (texture, infiltration, permeability, slope, runoff, depth).
- Vegetation cover.

According to the calculations made, the infiltration trenches were constructed with the following dimensions: width of the upper crest - 0.75 m; base width - 0.30 m; depth - between 0.30 m and 0.25 m; slope inclination - 1:1 upstream and 0.5:1 downstream. The distance between trenches ranges from 15 to 25 m; thus, the areas where the infiltration trenches are located have a slope that varies between 25% and 60%. Each trench—with the calculated dimensions—has a water storage capacity ranging from 0.61 to 0.79 $m^3$.

With all the information processed for the construction of the infiltration trenches, it was observed that 60 trenches can be built on average on one hectare (ha) of land (5 m long caissons, separated by 0.20 m partitions between trenches), distributed in approximately six rows per ha.

### *Training and strengthening of organizations*

The inhabitants in the intervention area mostly include peasant communities. They are traditional organizations of public interest that are legally recognized and have a legal status, including families who inhabit and control certain territories, united by ancestral, social, economic, and cultural ties expressed in the communal ownership of land, communal work, mutual assistance, democratic government and the development of cross-sectoral activities that seek to contribute to the full realization of their members, and therefore, of their town, region, and country.

A substantial weakening of the community organization was identified analyzing further population characteristics. This happened because the population grew and adopted new characteristics and ways of life where the uses and customs for adequate water management (gratitude rituals, offerings to Pachamama) and agriculture (terracing, natural fertilizers, camelid breeding) have decreased.

An additional variable detected in the social diagnostic assessment is that the populations directly involved in the project are **the most vulnerable** to climate change given the direct link between their economic activities involving the use of water and the other natural resources available in their environment.

Other cross-cutting activities have been implemented in addition to building dams in lakes, forestry, and soil conservation actions to achieve the project's objective of reducing water scarcity. These include activities to **strengthen organizations and provide training** to the beneficiary population to reverse the organizational and capacity problems that—added to the effects of climate change—accentuate the decrease in water supply from natural reservoirs (snowfall, springs, streams, lakes).

The actions taken have aimed to promote water resources management and environmental care through various training events, updating and developing management tools, such as regulations and plans for natural resource management, creating specialized committees, and electing community promoters as communication and skill-transfer links between the community and the project. Training has been expanded to primary and secondary school students from mixed-sex educational institutions, where training workshops were held on natural resource management and environmental care issues.

## Results

The construction of the Matarampampa-Sangarara dam is succeeding in storing rainwater and, therefore, the area has greater availability of water resources. There has been an additional improvement in the ecosystem conditions within that microbasin. This is evidenced by the establishment of some wild bird species that inhabit lake ecosystems, such as gulls (*Larus serranus*), wild ducks (*Spatula cyanoptera*), and huallatas (*Chloephaga melanoptera)*.

### *Quantitative results*

- The dam has made it possible to retain 500,000 $m^3$ of rainwater (Figure 2).
- The microbasin soils increased their water retention capacity by 4,200 $m^3$ after soil conservation and vegetation recovery actions.
- The ecosystem and landscape of the microbasin improved.
- The population of the rural community of Sangarara is now more aware of the care for and rational use of natural resources.
- The direct beneficiaries are 423 families and 2,157 people (51.11% women; 48.89% men) from the rural community of Sangarara. The population that benefits from the experience are poor people who mainly work in agriculture.

In the Quillayoc-Sangarara microbasin, 120 ha have been reforested (Figure 3) with seedlings of native forest species of queuña, qolle, and chachacomo, and 100 ha of infiltration ditches have been built, which currently promote water infiltration into the soil at a rate of 4,200 $m^3$ per year (Figure 4).

Figure 3. Forest planting with community participation

Source: PER IMA's photographic record.

The microbasin now has a more significant vegetation cover due to the afforestation and soil conservation actions taken. This vegetation increase controls soil erosion that occurred before the project and has also improved water retention. Therefore, there is greater water infiltration into the soil, which in the future will lead to increased flows in surface water bodies (springs and streams) of the middle and lower sections of the microbasin.

Figure 4. Construction of infiltration trenches

Source: PER IMA's photographic record.

The beneficiary population has improved their knowledge and attitudes regarding natural resource management, water management, and environmental care, thus influencing the rational and sustainable use of vegetation, soils, and water.

## Conclusions

The implementation of vegetation cover recovery activities has shown that forest plantation accompanying infiltration ditches has been successful (higher percentage of plant starting and development), reflecting the project's success. By the end of the project, 80% of the beneficiary population (51.11% women; 48.89% men) are expected to have improved their livelihoods by 50% including natural capital (availability of water, soil, and vegetation), human capital (human capacities), social capital (organizational and institutional capacities), physical capital (infrastructure availability) and financial capital (financial income).

With the project in place, the PER IMA shows that institutions can lead to specific regional and nationwide actions to address the effects of climate change, such as ensuring water availability as vital for populations and the environment, which are and will be affected by ongoing climate change impacts.

The involvement of the local government of Sangarara and the beneficiary peasant community has made it possible to agree on implementing the project components regarding financing and participation.

## Acknowledgments

The experience and its results would not have been possible without the participation of the following people and institutions, whom we would like to acknowledge for their valuable contributions:

- The professional, technical, and administrative staff of the PER IMA's project Adaptation to climate change: water harvesting in lake microbasins of the upper Vilcanota basin—ACAMCAV. Those who worked as a team and with great commitment to execute all the project components at the Quillayoc-Sangarara microbasin.
- The Sangarara District Municipality of the province of Acomayo - Cusco Region, for their valuable contributions and their empowerment with the proposal implemented.
- Board and members of the peasant community of Sangarara-Acomayo for always being present and contributing their labor force to implement the changes.

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# Mapping of amunas in the Santa Eulalia sub-basin, Peru

*Aldo Cárdenas[1] and Rene Pumayalli[2]*

**Abstract**

In recent years, The Nature Conservancy (TNC), AQUAFONDO, and other institutions have been focusing on the conservation and recovery of ancestral infiltration canals called amuneros or amunas in the communities of San Pedro de Casta and San Juan Iris, located in the Santa Eulalia sub-basin, which is part of the Rimac river basin. These projects were launched to recharge aquifers and increase groundwater production. First, TNC recovered the Saywapata and Huaycananpo amunas in San Pedro de Casta and San Juan de Iris in 2016 and 2017. Later on, AQUAFONDO recovered the Huitama amuna in 2017 in San Pedro de Casta, and thus continued other initiatives to restore more amunas. Local inhabitants have witnessed an increase in water supply and other benefits in just two years. Thus, TNC decided to evaluate the amunas and estimate their impact on the Santa Eulalia sub-basin. Visits to the amuna canals included local community members. In total, 25 amunas were identified, six of which have already been recovered. These infrastructures were assessed, and local people were interviewed to determine their current level of knowledge on conservation, recharging, and water seeding and harvesting within their communities. Implementing more amunas will help create jobs for local inhabitants, preserve water in communities, and prevent natural disasters in the lower river basin.

**Keywords:** amunas, pre-Inca, aquifer recharge, water conservation, natural infrastructure, disaster risk management, Andes.

## Introduction

We are all aware of the global warming our planet has been experiencing, with high temperatures causing extreme droughts and fires such as the recent events in Australia and the Brazilian Amazon. The recent fires in Australia are emblematic because the country has been experiencing a prolonged drought—the driest season in the last 120 years—aggravated by strong winds and extreme temperatures. It is estimated that over 6 million hectares were burned—twice the size of Belgium. In comparison, almost 2.5 million hectares turned to smoke in August 2019 in the Amazon.

Although Lima has not reached its "zero hour," the Peruvian capital has already faced massive water service restrictions due to weather patterns. The coastal El Niño caused the most recent event in March 2017: the heavy rains created huaicos (landslides) with large amounts of solid material that hindered water treatment at La Atarjea plant. Other serious problems affecting Lima's water supply include the deterioration of natural infrastructure –ecosystems such as forest, grasslands and wetlands, which, like grey or conventional infrastructure, contributes to water conservation or storage for baseflow during the dry season.

One way to prevent a potential water crisis in the Peruvian capital is to recover ancient infiltration canals known as amunas or amunero canals. Aquifers had already been identified in ancient times, possibly before the Inca, and their functioning dynamics were well known (Ochoa-Tocachi

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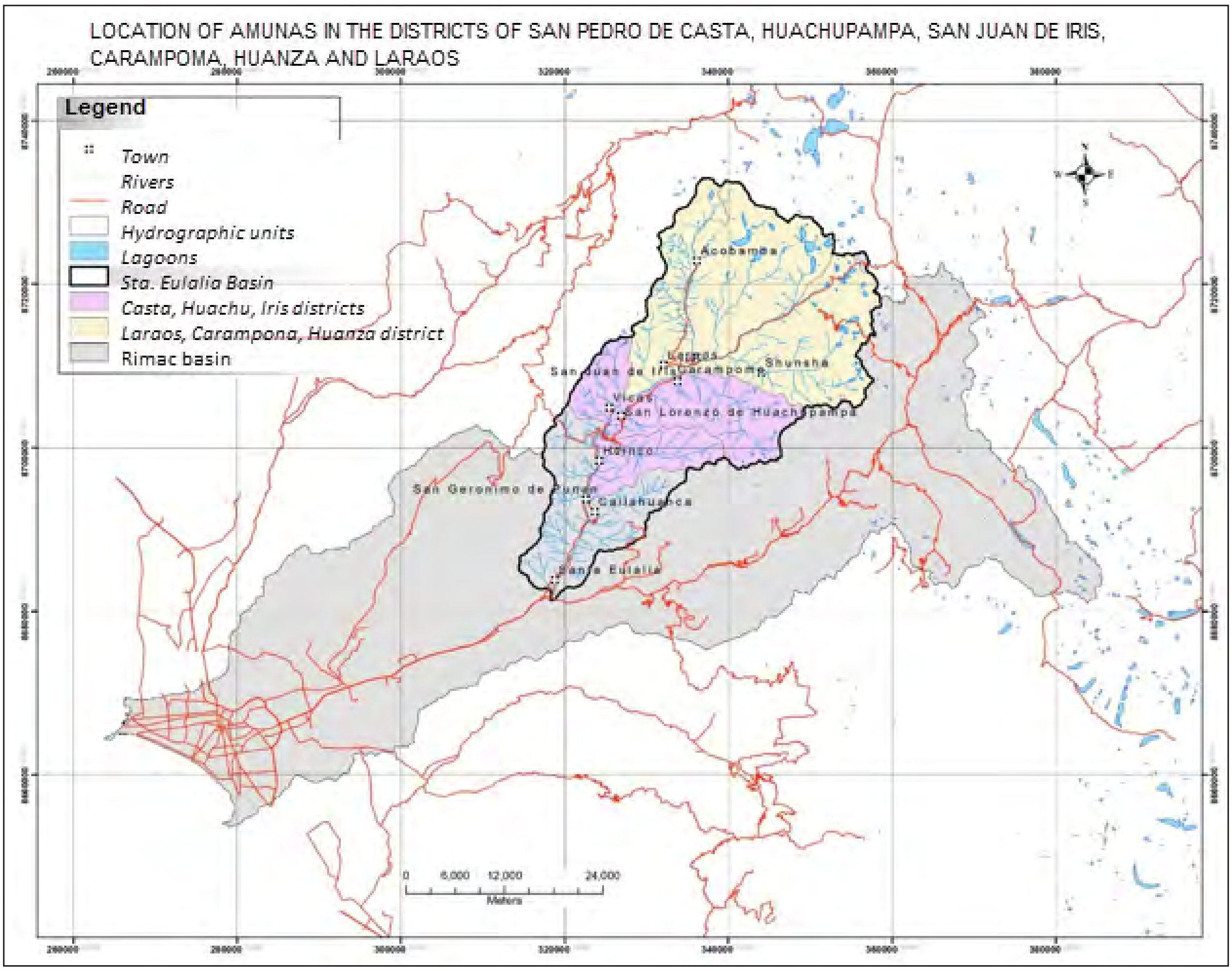
et al., 2019). This is how what we now call *amunera structures* were designed and built. Since then, these structures have been used to recharge aquifers artificially.

The area under study is located at the upper Santa Eulalia sub-basin. It is accessed from the city of Lima following the central road to Santa Eulalia over 49.1 km. The next stretch covers 18.8 km on an unimproved earthen road towards the town of Huinco. From that point, earthen roads lead to the various districts and annexes, as shown in Figure 1.

Figure 1. Location map of the study area




Sourc: Compiled by the authors.

This paper is based on information from a study conducted in 2019: Mapping report—identification and assessment—of Amunas located in the Santa Eulalia sub-basin made by the consultancy firm Unu Kamachiq between February and March 2019. The document aims to communicate the progress made in implementing amunas in the Santa Eulalia sub-basin and their impact on water gains. It also seeks to highlight the importance of conservation and restoration of these water canals to recharge aquifers and increase groundwater production.

## Materials and methods

The following information was used to map the amunas:

- Satellite image mapping using Google Earth and SASPlanet.
- Digital information taken from maps and bulletins of the Chosica (24j) Matucana (24k) quadrangles and developed by INGEMMET.
- Digital information from the report *Las amunas de Huarochirí - Recarga de los acuíferos en los Andes*, under the IICA - GSAAC agreement.
- Digital information from 2010 report *Evaluación de los Recursos Hídricos en la Cuenca Rímac* made by the National Water Authority.

Based on the information collected and the ArcGIS system, 25 amunero canals were identified using satellite images, geological maps, vegetation cover, and land use. Then, after coordination with the TNC technical team, specific canals were selected to collect detailed information in the field. The canals selected for field visits were:

1. Senega-Tambo (San Pedro de Casta)
2. Huacsay-Yanachiuchi (San Pedro de Casta)
3. Huaclacayo-Chinca (San Pedro de Casta)
4. Cayula alto (San Pedro de Casta)
5. Cayula bajo (San Pedro de Casta)
6. Cáscara Amarilla (San Pedro de Casta)
7. Huayapacha-Machiquimarca (San Juan de Iris)
8. Ancashi-Pariurco (San Juan de Iris)
9. San Juan de Iris Alto (San Juan de Iris)
10. Acobamba-Laraos (Carampoma-Laraos)

Once the field visits were completed, the information collected was analyzed, processed, and refined. Then surveys were summarized and processed, thematic maps were drawn, and the corresponding reports were made. Figure 2 shows the location of the main amunas visited.

Figure 2. Location of amunas in the districts of Carampoma, Huanza, Laraos, Huachunpampa, San Juan de Iris and San Pedro de Casta


Source: Developed by the authors.

Table 1 shows a summary of the water characteristics of the amunas found in the upper Santa Eulalia sub-basin. There are 69.5 km of amunas to be restored, which could infiltrate a volume of 2.78 MCM (million cubic meters) of water to the aquifer. The Senega-Tambo amuna stands out among the 25 amunas as it is over 8-km long and features a potential infiltration volume of 728,895 $m^3$. Six amunas have been restored in San Pedro de Casta and San Juan de Iris to date.

Table 1. Water characteristics of the amunas identified in the study area

| N.º | Location | Name | Operation | Length (m) | Average whith (m) | Infiltr. whith (m²) | Permeab. (m/day) | Av.Restored volume (l/s) | Inf. Vol. (m³) | Coordination with other water systems |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | S. P. de Casta | Saywapata | Temporary | 1.939 | 0,7 | 1.260,4 | 28,7 | 10,5 | 243.991,2 | Restored in 2016 |
| 2 | S. P. de Casta | Kayrachin (Huitama) | Temporary | 1.276 | 0,5 | 638,2 | 22,1 | 4,1 | 95.205,7 | Restored in 2018 |
| 3 | S. P. de Casta | Laguna Pestancia | Temporary | 1.418 | 0,6 | 850,7 | 28,7 | 7,1 | 164.679,7 | Restored in 2018 |
| 4 | S. P. de Casta | Senega-Tambo | Permanent | 8.367 | 0,5 | 3.765,2 | 28,7 | 31,2 | 728.895,4 | 1,5 km restored in 2019. It goes through several ravines from where it also recives water. |
| 5 | S. P. de Casta | Shucuni-Lag. Cercano | Temporary | 4.967 | 0,4 | 1.986,8 | 21,8 | 12,5 | 292.357,6 | 2 km restored. Aquifer recharge at headwaters |
| 6 | S. P. de Casta | Huacsay-Yanachiwchi | Permanent | 865 | 0,3 | 259,5 | 13,3 | 1,0 | 23.226,5 | Not detected |
| 7 | S. P. de Casta | Huaclayco-Chinca | Permanent | 191 | 0,3 | 57,3 | 13,3 | 0,2 | 5.128,6 | Not detected |
| 8 | S. P. de Casta | Punabanca-Cacala | Permanent | 3.045 | 0,5 | 1.522,5 | 13,3 | 5,8 | 136.271,4 | Aquifer recharge |
| 9 | S. P. de Casta | Huaclayco-Achin | Temporary | 2.022 | 0,3 | 606,6 | 28,7 | 5,0 | 117.431,7 | Aquifer recharge |
| 10 | S. P. de Casta | Cushpina-Cashanan | Temporary | 466 | 0,4 | 186,4 | 13,3 | 0,7 | 16.683,7 | Aquifer recharge |
| 11 | S. P. de Casta | Cushpina-Cashanan medio | Temporary | 440 | 0,4 | 176,0 | 13,3 | 0,7 | 15.752,9 | Aquifer recharge |
| 12 | S. P. de Casta | Cushpina-Cashanan bajo | Temporary | 324 | 0,4 | 129,6 | 13,3 | 0,5 | 11.599,8 | Aquifer recharge |
| 13 | S. P. de Casta | Cayula alto | Temporary | 567 | 0,3 | 170,1 | 13,3 | 0,7 | 15.224,8 | Aquifer recharge |
| 14 | S. P. de Casta | Cayula bajo | Temporary | 315 | 0,3 | 94,5 | 13,3 | 0,4 | 8.458,2 | Recarga de acuífero |
| 15 | S. P. de Casta | Cascara Amarilla | Temporary | 717 | 0,3 | 215,1 | 13,3 | 0,8 | 19.252,5 | Small springs at the lower section |
| 16 | S. J. de Iris | Pumacocha-Huaycanampo | Permanent | 2.089 | 0,3 | 626,7 | 13,3 | 2,4 | 56.092,8 | Restored in 2017 |
| 17 | S. J. de Iris | Huayapacha - Machiquimarca | Temporary | 548 | 0,6 | 328,8 | 11,9 | 1,1 | 26.299,9 | Aquifer recharge at headwaters |
| 18 | S. J. de Iris | Ancashi-Pariurco | Temporary | 1.593 | 0,9 | 1.433,7 | 21,9 | 9,1 | 211.743,2 | Aquifer recharge at headwaters |
| 19 | S. J. de Iris | San Juan de Iris alto | Temporary | 553 | 0,4 | 221,2 | 11,9 | 0,8 | 17.693,2 | Aquifer recharge |
| 20 | Carampoma | Antapampa | Temporary | 2.016 | 0,4 | 806,4 | 13,3 | 3,1 | 72.176,8 | Aquifer recharge at headwaters |
| 21 | Carampoma | Japani | Temporary | 3.012 | 0,4 | 1.054,2 | 21,8 | 6,6 | 155.125,5 | Small springs at the lower section |
| 22 | Acobamba, Carampoma, Laraos | Acobamba-Laraos | Permanent | 24.660 | 0,4 | 9.864,0 | 3,0 | 8,5 | 197.748,5 | Several springs underneath the canal |
| 23 | Acobamba | Empalme | Permanent | 5.477 | 0,5 | 2.738,5 | 3,0 | 2,4 | 54.900,1 | Canal feeding underneath the canal |
| 24 | Huachupampa | Chucuhuasi | Temporary | 1.186 | 0,4 | 474,4 | 13,3 | 1,8 | 42.461,2 | Unidentified |
| 25 | Huachupampa | Carhuachayo | Temporary | 1.473 | 0,4 | 589,2 | 13,3 | 2,3 | 52.736,3 | Unidentified |
| | TOTAL | | | 69.526 | | | | 119 | 2.781.137 | |

Source: Developed by the authors.

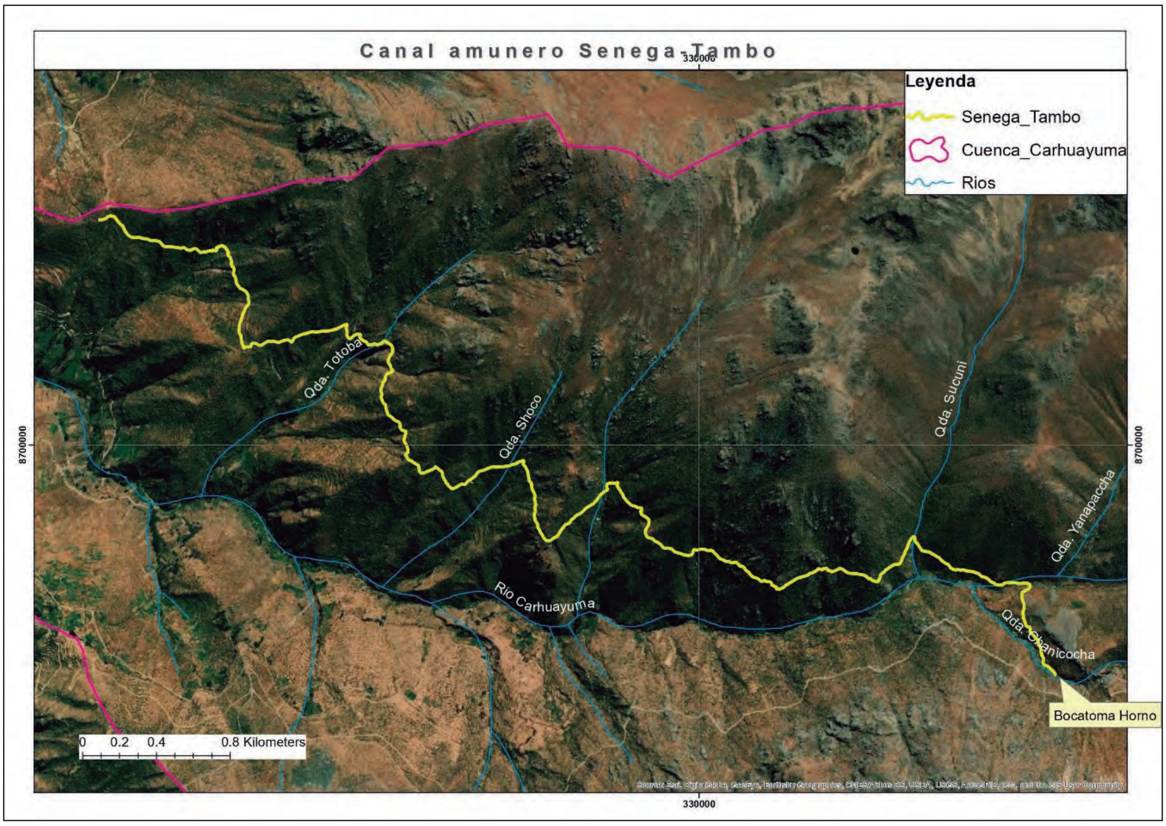
Based on the restoration of amunas in the area, an estimated USD 33.3 per longitudinal meter of canal has been set (exchange rate USD 1 = S/. 3.3). Therefore, restoring the 25 amunas would cost USD 2,317,533. This represents USD 0.83 per cubic meter recharged to the aquifer would be invested.

## Results

The main results are:

- The entire Santa Eulalia basin comprises geological formations that have undergone a series of tectonic events, which have fractured the rock base. These fractures enable stormwater to infiltrate and shape the groundwater stored in these large rock masses called *aquifer rocks* (Peña et al., 2015).
- All the amunas are located on highly permeable soils (aquifers). Many of them, such as the Senega-Tambo amuna, go through several aquifers along their path. There are also amunas such as those of the Achin ravine, in San Pedro de Casta, which are "staggered" or at different heights. Their infiltrated waters feed the same aquifer, as shown in Figure 3.

Figure 3. Location of the Senega-Tambo amunas in San Pedro de Casta




Source: Developed by the authors.

If two amunas were to be selected for restoration, they would be the Shucuni-Chinchaycocha amuna in San Pedro de Casta (part of Senega-Tambo) and the Ancashi Pariurco amuna in San Juan de Iris, considering aquifer recharge efficiency. The local population verified this. In 2019, 1500 meters of the Shucuni-Chinchaycocha amuna were restored, as shown in Figure 4.

Figure 4. Restored Shucuni-Chinchaycocha amunero canal

Source: Unu Kamachiq.

- Of the 67 people surveyed, 70% know the amunas. The population of San Pedro de Casta and San Juan de Iris have an in-depth knowledge of the management, maintenance, and operation of the structures that make up the amunas. They are also aware of their importance for recharging the hills and their benefits for springs. This is so because these communities have the largest number of amunas, and several institutions are currently working there.
- Furthermore, 99% of the people surveyed do not use concepts like aquifers, aquifer recharge, or other engineering terms, because they are highly technical and the institutions that organize water-related talks or training do not use this technical approach.
- Finally, 100% of respondents believe that climate change dramatically affects communities, as there have been changes in rain, increased solar radiation, and real feel temperature.

## Conclusions

- Amunas have shown their efficacy in recharging aquifers compared to other types of natural infrastructure such as reforestation, wetland reclamation, infiltration trenches, etc.
- Amuna restoration must be considered an artificial aquifer recharge structure and a disaster risk management structure for the lower basin. Thus, this can benefit from a financial investment tool for local communities, as local people work in the project.
- Both men and women participated in the reconstruction of the Saywapata and Huaycanampo amunas. Remuneration was the same regardless of age or sex, which was welcomed by

the population. In many cases, women participated with greater interest, dedication, and building notions.

- Furthermore, of the total budget allocated to restore an amuna, over 70% is dedicated for the remuneration of workers and technical directors, thus generating significant income for the local population. This is not the case with similar projects (with the use of concrete and machinery) where wage payments do not exceed 25% of the budget in many cases.
- Maintenance of the amunero canals is required, especially after rains and in the catchment and ravines that go across the canal.

## Recommendations

- It is essential to promote the restoration of all the water canals in the basin. It favors water storage in aquifers and contributes to disaster mitigation in the lower basin.
- The amunero canals must be rebuilt considering ancient knowledge (use of stones and compacted earth) and avoiding the use of foreign materials as far as possible.
- One of the leading causes of the Rimac river overflow during the 2017 coastal El Niño phenomenon was the large flow of surface runoff and the resulting dragging of solids. This can be prevented by retaining surface runoff water in the upper basin through sowing and water harvesting projects such as the amunas project.
- Finally, amunas should be complementary to grey infrastructure. For example, in the Santa Eulalia sub-basin, the Lima water company SEDAPAL has an investment plan to build the Autisha dam, upstream of the Callahuanca hydroelectric dam intake. All these amunas would help regulate surface flow, delivering more water during the dry season to the future reservoir.

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# Regional hydrology for water usage purposes in the Sungaroyacu river basin, Huanuco region

*Jhon Walter Gómez[1] and Victor Hugo Gallo[2]*

**Abstract**

The objective of this study was to carry out a hydrological assessment in a Peruvian Amazon basin—for which there is a lack of hydrometric information—through the regionalization technique and water balance to determine flows for water usage. The physical characteristics of the Sungaroyacu basin were described using remote sensing techniques and Geographic Information Systems (GIS). We quantified the hydrometeorological variables using a regional analysis to establish mathematical models for precipitation, temperature, evapotranspiration, and runoff (variables involved in the water balance quantification) to identify the average annual and monthly flows at different frequencies. The Sungaroyacu basin has a total area of 2.180,5 km² and a perimeter of 281 km. Its altitudinal range varies from 175 to 2.800 m above sea level, and its fifth-order drainage network forms an elongated and irregular shape. The regional analysis determined an average annual rainfall of 2.716,8 mm, an average annual temperature of 24,8 °C, and average annual evapotranspiration of 1.175,5 mm. The annual runoff of the basin was 1.592,6 mm, which is equivalent to 110,1 m³/s. The duration curve defines flow volumes for water usage: for irrigation, a flow with a 75% frequency of 50,8 m³/s, for hydropower use, 95% of 32,6 m³/s, and population use, a 99% frequency of 29,8 m³/s.

**Keywords:** Basin, water usage, regional hydrology, remote sensing, Geographic Information Systems.

## Introduction

With a drainage area of 6,200,000 km² and an average annual water flow of 6,300 km³ of water discharging into the Atlantic Ocean (Molinier, Guyot, Oliveira, Guimarañes, 1996; Marengo, 2006), the Amazon Basin is the largest on the planet. Emanuel and Escurra (2000) state that the Amazon River Basin encompasses almost 99% of the Peruvian territory's total water resources. A study carried out by UNESCO (2006) shows that the annual net water availability in this basin is 2,696 mm.

Water is one of the most crucial resources in any country's development as it is used for productive activities such as agriculture and hydropower, and population and industrial use. Water management needs to be a priority to adopt a sustainable perspective. As a resource, water in Peru has unique characteristics. These result from the physiographic settings and climate variability, which cause certain regions to experience water scarcity for a part of the year and others with an overabundance in a short period. Due to the lack of hydrometeorological information, it is impossible to know the exact water balance and water availability to determine whether there is water deficit, limiting the development of a given productive activity or water abundance to harness its use and store it effectively. Likewise, further efforts are needed to learn about the hydrology of the Amazon. Applied research is necessary to identify the water balance or water availability at

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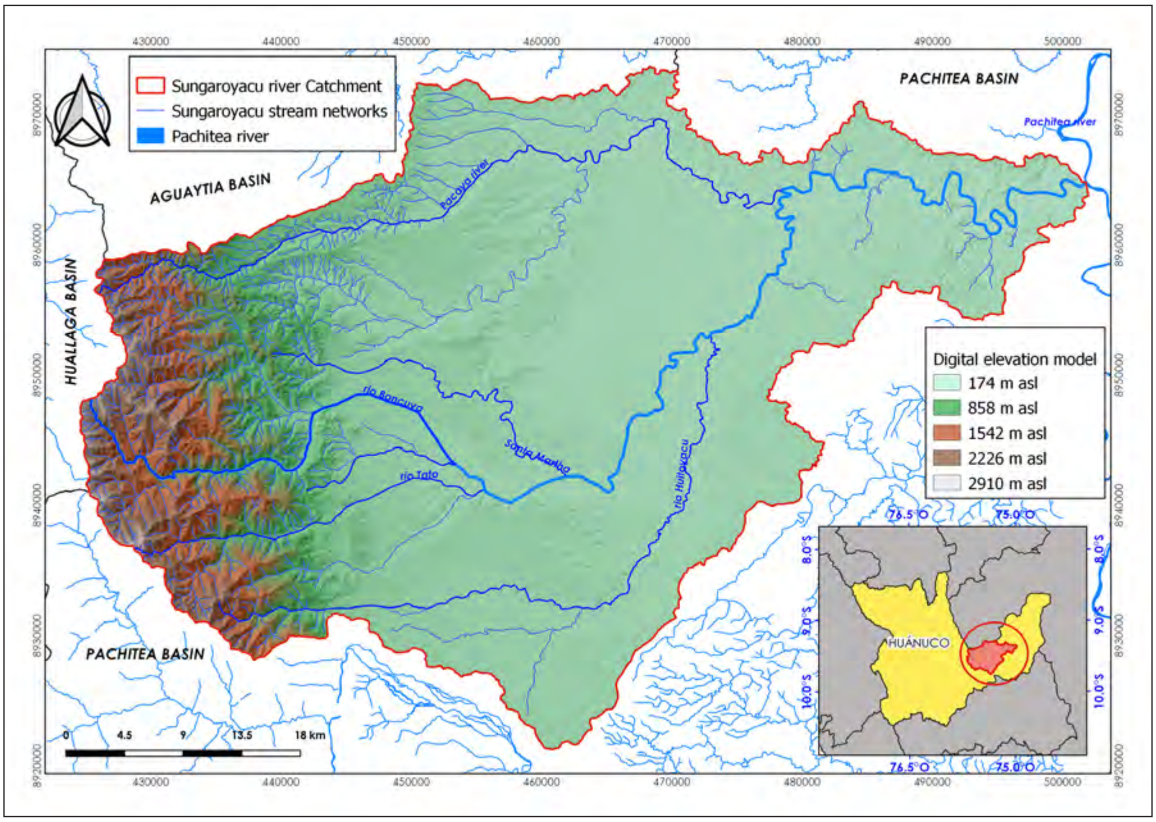
the basin or sub-basin level to manage this resource adequately. To our understanding, the first assessment of the potential of water resources at the Amazon basins—for which there's currently limited information—took place in 1986 under the SENAMHI/APODESA study.

Thus, as a way to contribute to solving this problem, we quantified the main hydrometeorological variables such as precipitation, temperature, evapotranspiration, and runoff. We calculated the contribution of these variables to water balance through a regionalization procedure to obtain annual and monthly average flow values for water planning purposes and define the persistence curve to calculate the water use flow available.

## Materials and methods

The Sungaroyacu River is a left-bank tributary of the Pachitea River, and it stretches across approximately 115 km. Its basin is located in the department of Huanuco, in the provinces of Puerto Inca and Padre Abad, across the districts of Codo del Pozuzo, Puerto Inca, Daniel Alomias Robles, and Irazola, between the geographic latitude 9°20'00'' and 9°50'00'' South (S) and longitude 74°20'00'' and 75°40'00'' West (W).

Figure 1. Location of the study area




Source: Compiled by the authors.

## *Materials*

### *a. Cartographic information*

We used national maps (Table 1) on a 1: 100000 scale, developed by the National Geographic Institute (IGN).

Table 1. Cartographic information

| Código | Name |
|---|---|
| 19 - l | Aguaytía |
| 19 - m | Río Nova |
| 20 - l | Panao |
| 20 - m | Codo del Pozuzo |

Source: IGN.

### *b. Satellite information*

The ALOS satellite Digital Elevation Model (DEM) with a spatial resolution of 12.5 meters (Table 2) was used to supplement the cartographic information.

Table 2. Satellite images

| Path / Frame | Date |
|---|---|
| 108 / 6990 | 15/Jul/2010 |
| 107 / 6990 | 13/Aug/2010 |

Source: Granule Information UAF Portal.

### *c. Meteorological information*

The meteorological information used for the regional assessment (Table 3) was provided by the National Weather and Water Service (SENAMHI)

Table 3. Weather stations

| Station | Coordinates | | Altitude (m s.n.m.) | Variable | Time scale | Period considered (yrs) |
|---|---|---|---|---|---|---|
| | Latitude | Longitude | | | | |
| Tingo María | 9° 18'30,6''S | 76° 0'1,59''W | 660 | Total precipitation and mean tem-perature | Monthly | 1987 - 2015 |
| Tulumayo | 9° 8',49,4''S | 76° 0'34''W | 611 | | | 1987 - 2015 |
| Puerto Inca | 9° 22'53''S | 74° 57'39''W | 211 | | | 1987 - 2015 |
| El Maronal | 8° 26'60''S | 75° 5'48''W | 175 | | | 1987 - 2015 |

Source: SENAMHI.

## *Methods*

The methodology proposed in this research aims to quantify water availability in a Peruvian Amazon basin, for which there is no hydrometric information, to contribute to sustained and efficient water resource planning that can, at the same time, be replicated in other areas because:

- Regional models are developed to quantify water balance by calculating annual and monthly flows to determine water availability.
- This allows for adequate water planning at the basin for water use purposes.
- The resulting information is useful to gain further knowledge of hydrology in Peruvian Amazon basins.
- The proposed method will be validated with on-site measurements through gauging and water quality measurements, thus contributing to efficient water use and increasing availability.

### *a. Design and morphometry*

The topographical delimitation of the water divide was done using the information in Table 1 and 2. QGIS and SAGA tools were used, allowing for a more thorough analysis (Table 4).

Table 4. Description of the software

| Software | Purpose |
|---|---|
| SAGA GIS | Visualize and process the basin's drainage network. |
| QGIS 3.2 | Generate and integrate databases, together with the design of the Sungaroyacu basin. |

Source: Developed by the authors.

The morphometry was described by calculating the physiographic parameters, which allows us to determine the basin's physical attributes through the study of its surface, relief, and drainage network. This makes it possible to understand its hydrological functioning and to make comparisons between basins.

### *b. Hydrometeorological variables*

Regionalization made it possible to quantify the following variables:

- **Rainfall**

  The equations were determined as a function of altitude, isohyets were drawn, and mean rainfall was calculated using the partial areas, contour lines, altitude ranges, and regional model methods. In addition, a monthly record was also developed using the dimensionless model.

- **Temperature**

  The regional equations defined temperature behavior based on altitude. The mean annual temperature was calculated using isotherms and the regional model. The Tulumayo records were considered representative given their physical similarity to the basin.

- **Evapotranspiration**

  Monthly values were determined using the Thorntwaite method, based on the equations cited in Gómez Lora (1987). The evapotranspiration is estimated as a function of temperature and latitude, and it implicitly introduces the theoretical duration of sunshine.

$$ET_{m\,c} = ET_{m\frac{s}{c}} x\ \frac{N}{12}\, x\, \frac{d}{30}$$ *…Equation No. 1 - Evapotranspiration*

ETmc : corrected monthly evapotranspiration.

ETm s/c: uncorrected monthly evapotranspiration.

N: maximum number of hours of sunshine, depending on month and latitude

d: days of the month

The annual evapotranspiration is determined by adding the evapotranspiration values of each month.

### *c. Water balance*

By quantifying the hydrometeorological variables, we can determine the water balance.

$$P - Ev = E$$ *…Equation N. 2 - Water balance*

Q: annual runoff (mm)

P: annual rainfall (mm)

Ev: annual evapotranspiration (mm)

Flow (Q) is then converted to $m^3/s$ by a simple mathematical conversion.

The monthly flows to determine the duration curve were calculated using (1) the rational method basic equation using the annual runoff coefficient and (2) Lutz Scholz's deterministic-stochastic model (Plan Meriss, 1980) adapted for the Sungaroyacu basin. This model estimates the effective precipitation in the basin and flows for an average year, considering its output and retention. Afterward, using a multiple regression using the monthly mean effective precipitation values (US method) and average flows, we determined the coefficients used in equation 3 to identify the extended period's flows based on the effective monthly precipitation. For more details of the equations, see Plan Meriss, 1980: 6-35.

$$CMt = B1 + B2\ x\ CMt - 1 + B3\ x\ PEm + z\ x\ S\ x\ (1 + r2)^{1/2}$$ *...Equation No. 3 - Flow rate - Extended periods*

CMt: monthly flow (mm/month)

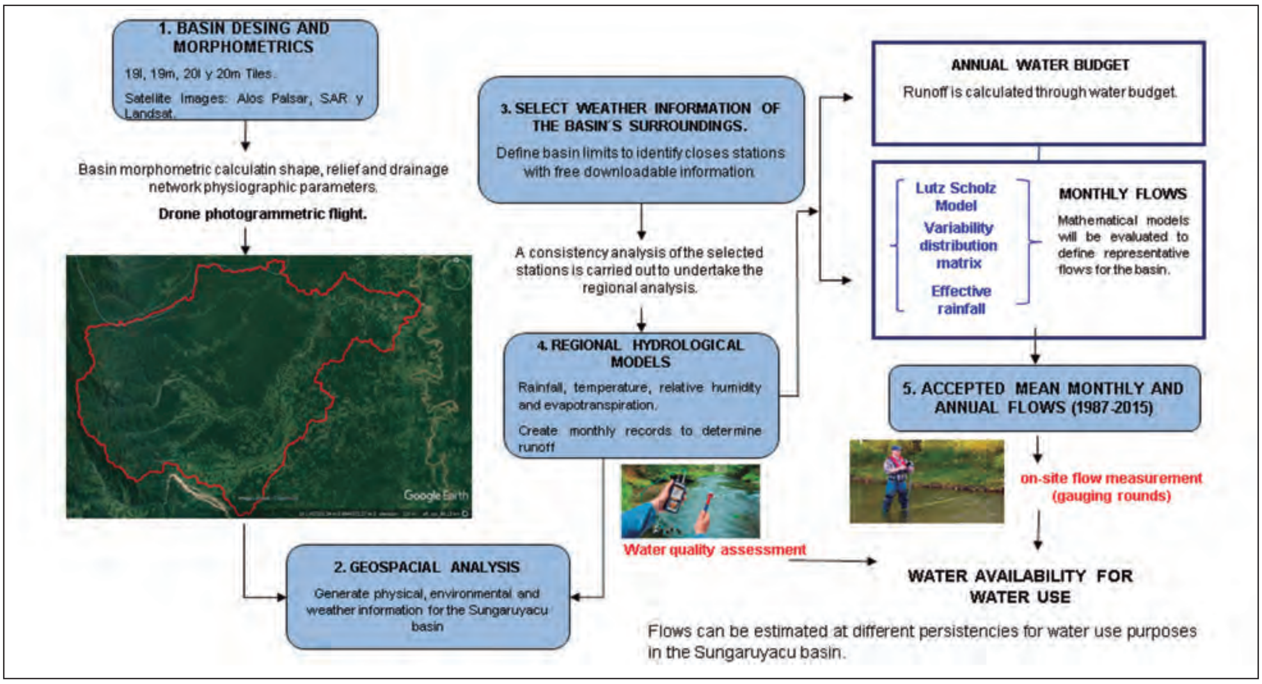
CMt-1: flow rate of the previous month (mm/month).

PEm: effective monthly precipitation (mm).

B1: constant factor of multiple regression.
B2: coefficient of the CMt-1 value.
B3: coefficient of the PEm value.
R2: coefficient for multiple regression determination.
S: standard error of the multiple regression.
z: random number with normal distribution with mean 0 and standard deviation 1.
r: correlation coefficient

Figure 2 shows the procedure to follow in the study.

Figure 2. Procedures followed in the study




Note: The borders, names, and the designations used on these maps do not imply any official endorsement or acceptance by the United Nations.
Source: Compiled by the authors.

## Results and discussion

### *Results*

#### *(1) Basin Morphometry*

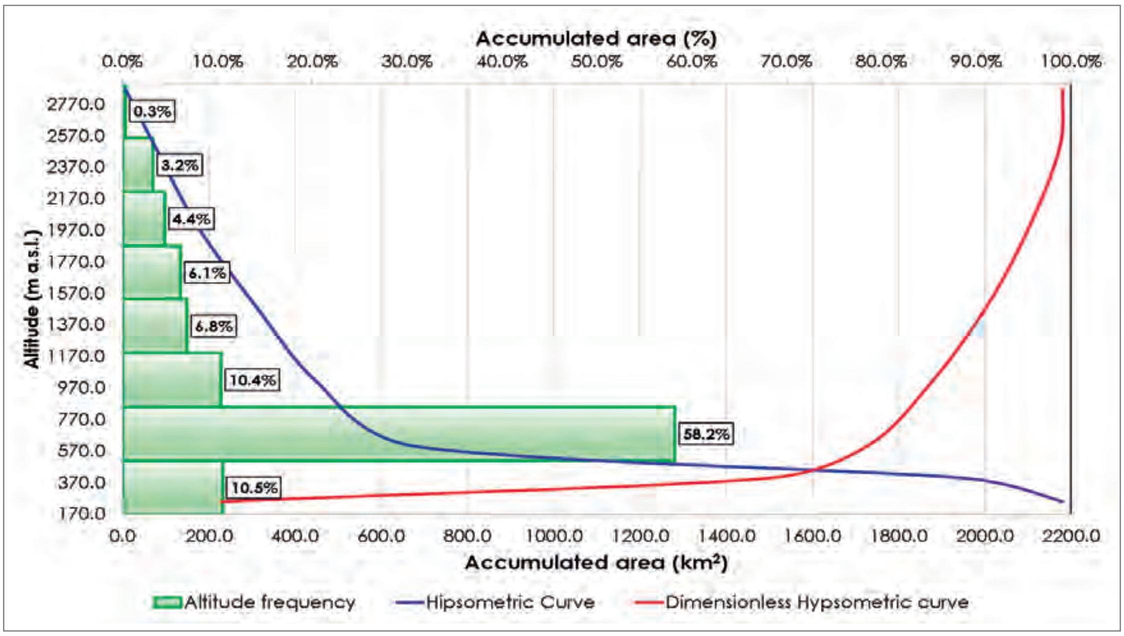
Table 5 shows the morphometric characteristics of the Sungaroyacu basin using GIS and spatial remote sensing techniques, and Figure 2 shows the shape of the basin's hypsometric curve.

Table 5. Morphometric characteristics of the Sungaroyacu basin

| Feature | Physiographic Parameter | Unit | Result |
|---|---|---|---|
| Surface | Area | $km^2$ | 2,180.5 |
| | Perimeter | km | 281 |
| Shape | Compactness coefficient | Dimensionless | 1.7 |
| | Shape factor | Dimensionless | 0.16 |
| | Longest side of the equivalent rectangle | km | 122.7 |
| | Shortest side of the equivalent rectangle | km | 17.8 |
| Relief | Mean slope of the basin | % | 15.6 |
| | Mean slope of the main channel | % | 26 |
| | Mean altitude of the basin | m above sea level | 552.6 |
| | Slope index | % | 10.6 |
| Red de Drainage network | Branching | Dimensionless | 5.00 |
| | Drainage density | $km/km^2$ | 0.60 |
| | Frequency of rivers | $rivers/km^2$ | 0.60 |
| | Mean distance of surface runoff | km | 0.61 |
| | Coefficient of torrentiality | $rivers/km^2$ | 0.4 |

Source: Compiled by the authors.

Figure 3. Hypsometric curve and frequency of altitudes




Source: Compiled by the authors.

### *(2) Regional Assessment and water balance*

The regional assessment made it possible to establish equations of the hydrometeorological variables involved in water balance. These are useful to estimate flows in areas that have no hydrometric information accurately. These estimates are later validated with on-site measurements (Table 6).

Table 6. Hydrometeorological variables

| Variable | Regional equation | Correlation coefficient (R) | Components of the equation |
|---|---|---|---|
| Rainfall | $PP = 500{,}93 \text{ x } (H)^{0{,}2761}$ | R = 0,92 | PP: Rainfall (mm)<br>H: Altitude (m asl) |
| Temperature | $T = 34.723 \text{ x } (H)^{-0{,}053}$ | R = 0,97 | T: Temperature (°C).<br>H: Altitude (m asl) |
| Evapotranspiration | $EVTP = 856{,}7 \text{ x } (H)^{0{,}0501}$ | R = 0,95 | EVTP: Evapotranspiration (mm)<br>H: Altitude (m asl) |
| Runoff deficit | $D = 0{,}0008 \text{ x } (P)^{1{,}8017}$ | R = 0,92 | D: Runoff deficit (mm).<br>H: Altitude (m asl) |

Source: Compiled by the authors.

### *Rainfall*

The following (Table 7) was calculated for mean precipitation. The average among the values obtained by partial areas and contour lines was considered the representative value: 2,716.8 mm.

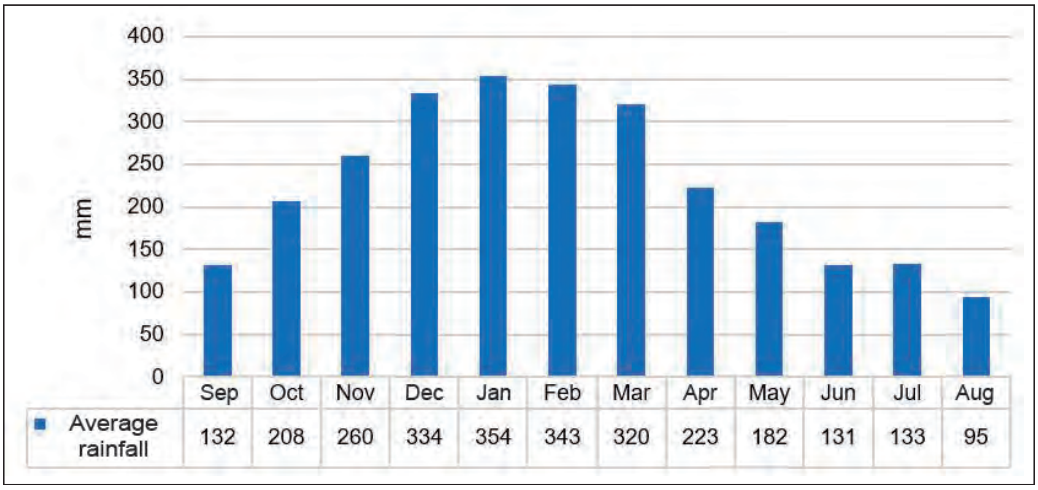
Table 7. Methods to calculate mean precipitation

| Partial areas | Contour lines | Regional model |
|---|---|---|
| 2.714,2 mm | 2.719,5 mm | 2.863,9 mm |

Source: Compiled by the authors.

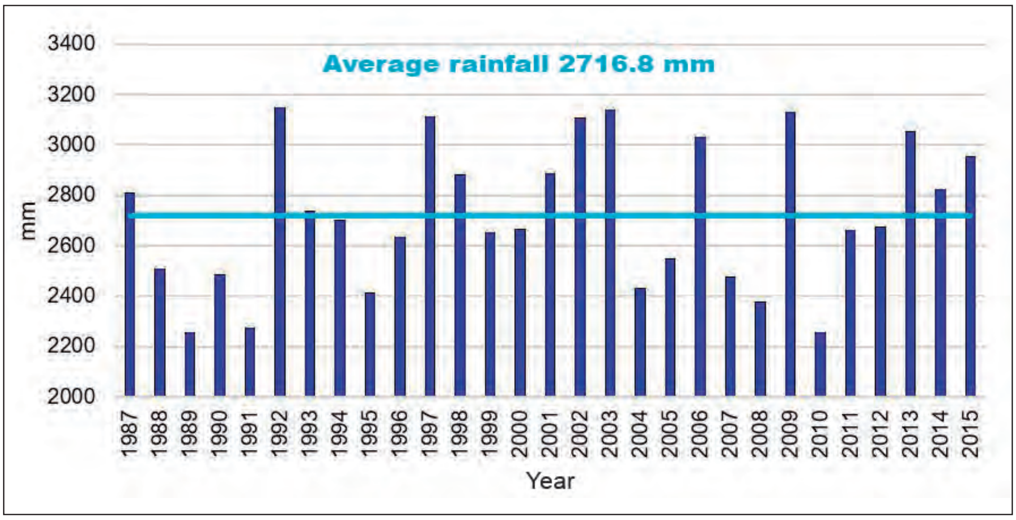
Monthly rainfall information was generated, adopting the Tulumayo station's values because the average annual rainfall and the altitude are similar. Figure 4 shows the average values, and Figure 5 shows the annual values.

Figure 4. Average histogram (water year 1987-2015)




Source: Compiled by the authors.

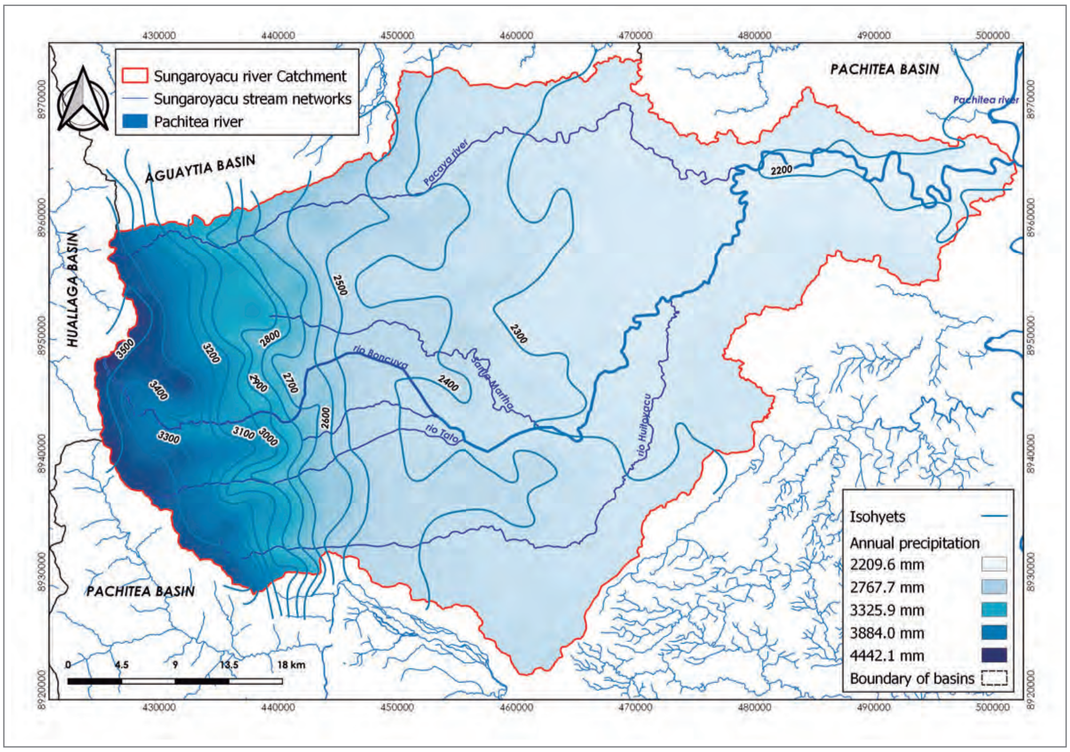
Figure 5. Annual rainfall at the Sungaroyacu basin




Source: Compiled by the authors.

Figure 6 shows the isohyets identified through regionalization and geospatial hydrological modeling using **GIS**.

Figure 6. Mean multiannual isohyets (1987-2015) of the Sungaroyacu basin




Source: Compiled by the authors.

### *Temperature*

Its spatial distribution was analyzed, and the average temperature was calculated, yielding a mean temperature of 25.2 ºC per partial areas and 24.8 ºC per regional model.

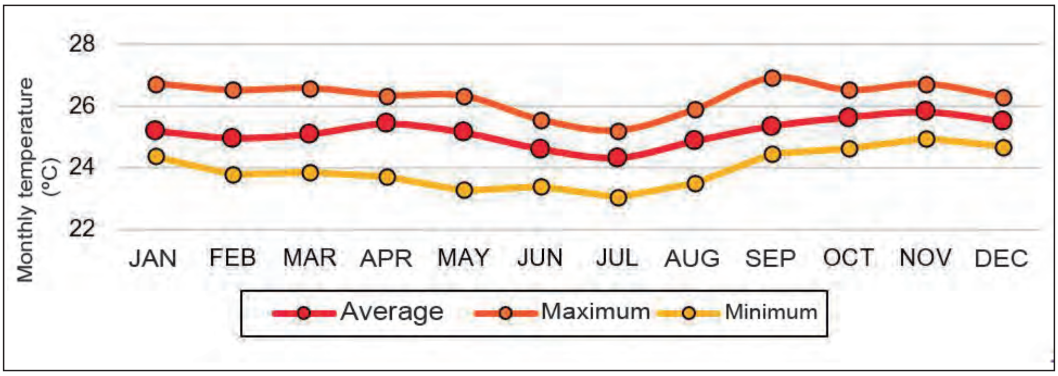
Moreover, since the Tulumayo station and the basin share similar physical characteristics, the station's monthly values were considered representative (Table 8 and Figure 7).

Table 8. Average temperature at the Tulumayo station

| Temperature (ºC) | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 25.2 | 25.0 | 25.1 | 25.4 | 25.1 | 24.6 | 24.3 | 24.9 | 25.3 | 25.6 | 25.8 | 25.5 |
| Max. | 26.7 | 26.5 | 26.6 | 26.3 | 26.3 | 25.5 | 25.2 | 25.9 | 26.9 | 26.5 | 26.7 | 26.3 |
| Min. | 24.4 | 23.8 | 23.9 | 23.7 | 23.3 | 23.4 | 23.0 | 23.5 | 24.4 | 24.6 | 24.9 | 24.7 |

Source: Compiled by the authors.

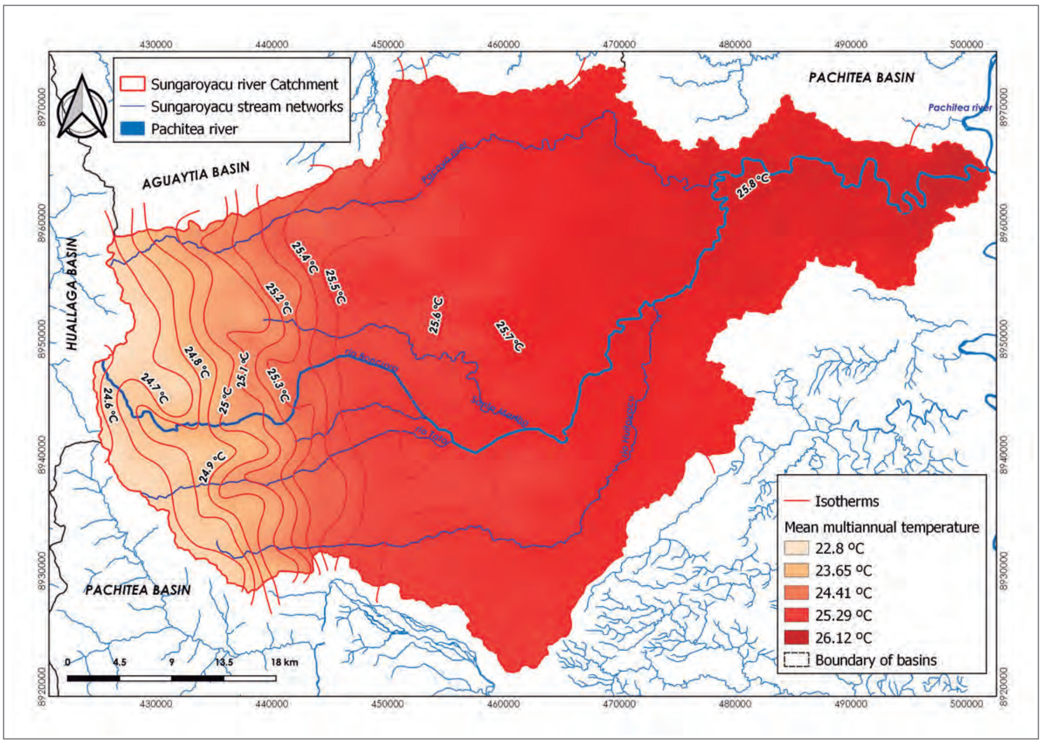
Figure 7. Temperature variation at Tulumayo station




Source: Compiled by the authors.

The isotherms were drawn using GIS (see Figure 8).

Figure 8. Mean multiannual average isotherms (1987-2015) of the Sungaroyacu basin




Source: Compiled by the authors.

## *Evapotranspiration*

It was determined for each station (Table 9) using the temperature data. It was associated with altitude to determine its behavior and to define the equation in Table 6.

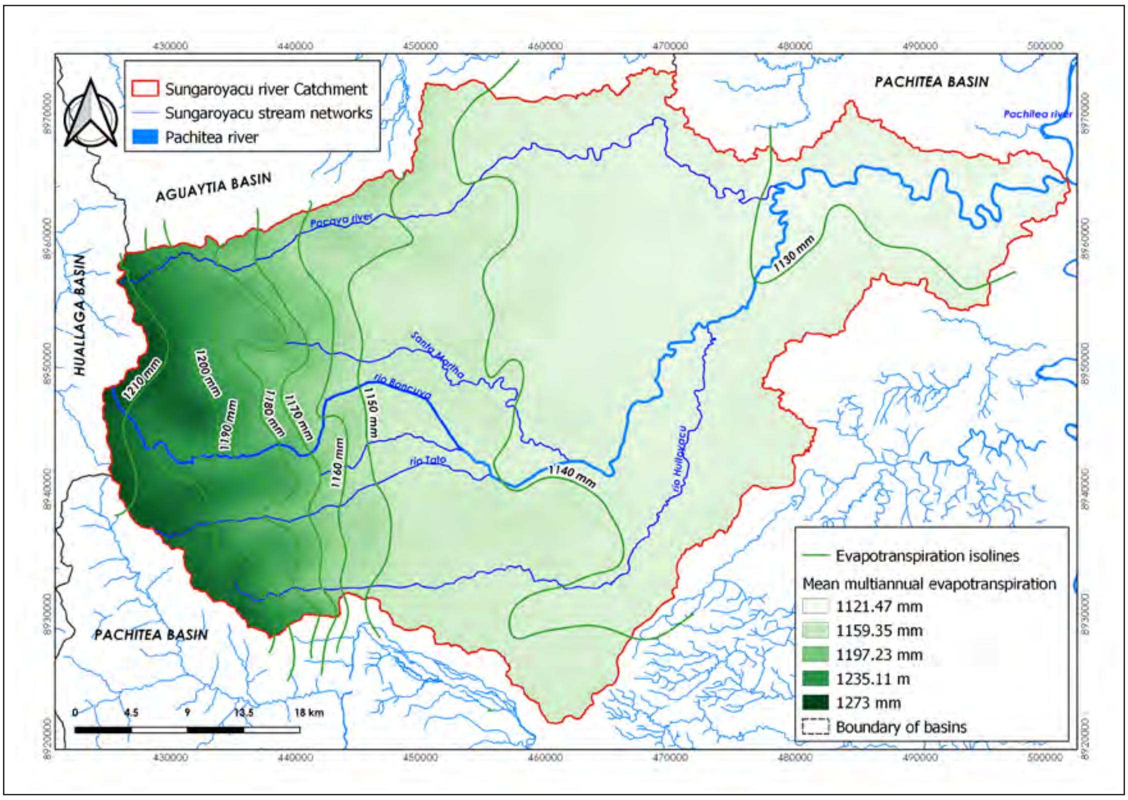
Table 9. Average evapotranspiration (mm) (1987-2015)

| Station | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tingo María | 107.2 | 93.4 | 104.0 | 102.1 | 98.7 | 90.2 | 90.2 | 92.1 | 99.6 | 109.5 | 106.7 | 107.7 | 1201.4 |
| Tulumayo | 103.2 | 89.8 | 99.0 | 97.2 | 95.1 | 85.5 | 86.1 | 93.3 | 99.3 | 105.6 | 107.2 | 107.8 | 1169.1 |
| Agencia Agraria Puerto Inca | 96.4 | 86.0 | 95.1 | 91.2 | 90.2 | 82.9 | 83.0 | 92.1 | 97.4 | 103.7 | 97.5 | 99.6 | 1115.2 |
| El Maronal | 101.8 | 88.6 | 96.4 | 91.0 | 88.5 | 82.0 | 81.4 | 89.6 | 96.7 | 102.8 | 97.6 | 101.0 | 1117.1 |

Source: Compiled by the authors.

The average evapotranspiration was estimated using Table 10 methods using evapotranspiration isolines drawn with GIS (Figure 9). Figure 10 shows annual values.

Figure 9. Mean multiannual evapotranspiration isolines of the Sungaroyacu basin



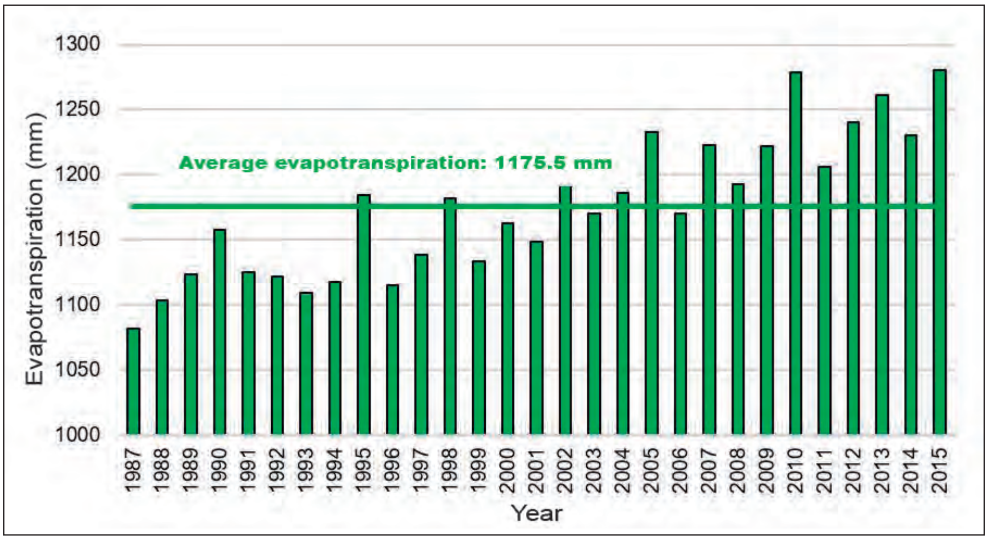

Source: Compiled by the authors

Table 10. Mean evapotranspiration calculated using the partial areas method and regional model

| Partial areas | Regional model |
| --- | --- |
| 1,149.3 mm | 1,175.5 mm |

Source: Compiled by the authors.

Figure 10. Annual evapotranspiration at the Sungaroyacu basin




Source: Compiled by the authors.

Table 11 Annual runoff and flows

| YEAR | R (mm) | Q ($m^3/s$) | YEAR | R (mm) | Q ($m^3/s$) |
| --- | --- | --- | --- | --- | --- |
| 1987 | 1,749.2 | 120.9 | 2002 | 1,960.4 | 135.5 |
| 1988 | 1,465.5 | 101.3 | 2003 | 1,978.2 | 136.8 |
| 1989 | 1,178.2 | 81.5 | 2004 | 1,252.1 | 86.6 |
| 1990 | 1,390.3 | 96.1 | 2005 | 1,447.4 | 100.1 |
| 1991 | 1,262.9 | 87.3 | 2006 | 1,868.2 | 129.2 |
| 1992 | 2,046.8 | 141.5 | 2007 | 1,381.0 | 95.5 |
| 1993 | 1,656.8 | 114.6 | 2008 | 1,216.2 | 84.1 |
| 1994 | 1,656.0 | 114.5 | 2009 | 1,906.4 | 131.8 |
| 1995 | 1,314.6 | 90.9 | 2010 | 1,176.8 | 81.4 |
| 1996 | 1,601.9 | 110.8 | 2011 | 1,524.5 | 105.4 |
| 1997 | 2,014.0 | 139.3 | 2012 | 1,534.1 | 106.1 |
| 1998 | 1,750.6 | 121.0 | 2013 | 1,764.6 | 122.0 |
| 1999 | 1,588.2 | 109.8 | 2014 | 1,577.5 | 109.1 |
| 2000 | 1,552.8 | 107.4 | 2015 | 1,614.0 | 111.6 |
| 2001 | 1,756.4 | 121.4 | Average | 1592.6 | 110.1 |

Source: Compiled by the authors.

### *Monthly flows*

Effective precipitation (Tables 12 and 13) was calculated using two methods:

(1) The annual runoff coefficient and the deficit equation (Table 12).

Table 12. Average monthly effective precipitation (Pe) using the annual runoff coefficient and the deficit equation (1)

| Year | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average (mm) | 190,9 | 179,4 | 164,1 | 124,2 | 96,8 | 69,6 | 70,4 | 54,6 | 68,7 | 112,8 | 138,0 | 175,9 | 1.445,4 |

Source: Compiled by the authors.

(2) Using the annual precipitation (Table 13) and runoff (Table 11) data.

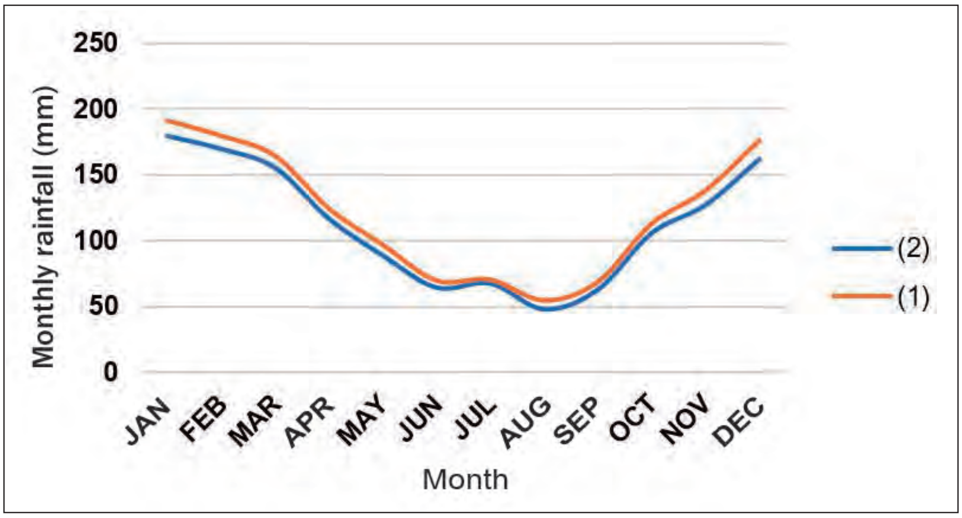
Table 13. Average monthly effective precipitation (Pe) using annual rainfall and runoff data (2)

| Year | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average (mm) | 179,6 | 169,7 | 155,3 | 116,4 | 88,6 | 64,1 | 67,3 | 47,6 | 62,6 | 105,7 | 127,0 | 161,9 | 1.345,8 |

Source: Compiled by the authors.

Due to the similarity in the results, the average value was considered the representative value for the Sungaroyacu basin (Figure 11).

Figure 11. Effective precipitation methods (1) and (2)




Source: Compiled by the authors.

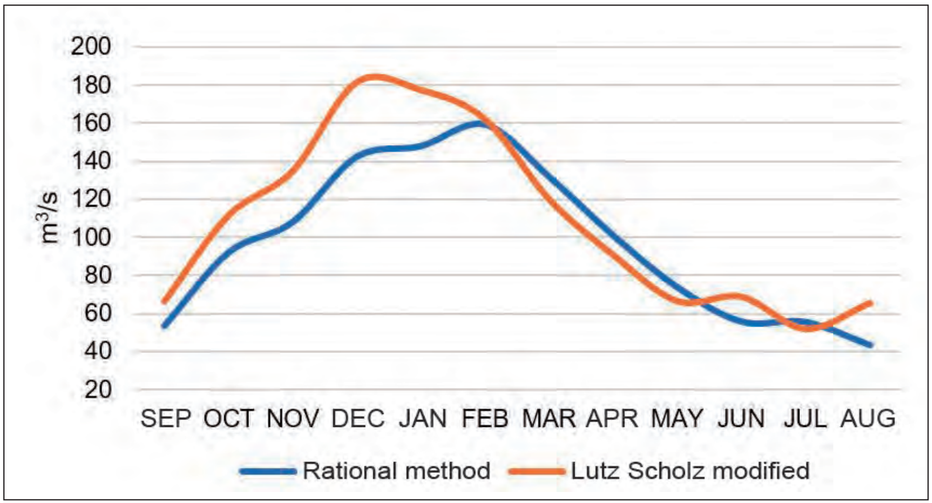
We calculated the mean monthly flows using equation 11. The results obtained using the **modified Lutz Scholz** method (Table 14) are also reported.

Table 14. Mean monthly flows (m3/s) in the Sungaroyacu basin

| Hydrological year (1987/1988 - 2014/2015) | Sep. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Apr. | May. | Jun. | Jul. | Aug. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rational method | 53.5 | 91.9 | 107.9 | 142.1 | 147.7 | 159.0 | 131.6 | 100.8 | 73.7 | 55.7 | 55.5 | 43.4 |
| Lutz Scholz modified | 66.2 | 111.3 | 134.6 | 181.3 | 177.2 | 161.8 | 119.8 | 90.5 | 66.3 | 68.6 | 51.7 | 65.3 |

Source: Compiled by the authors.

Figure 12. Flow comparison for the Sungaroyacu basin



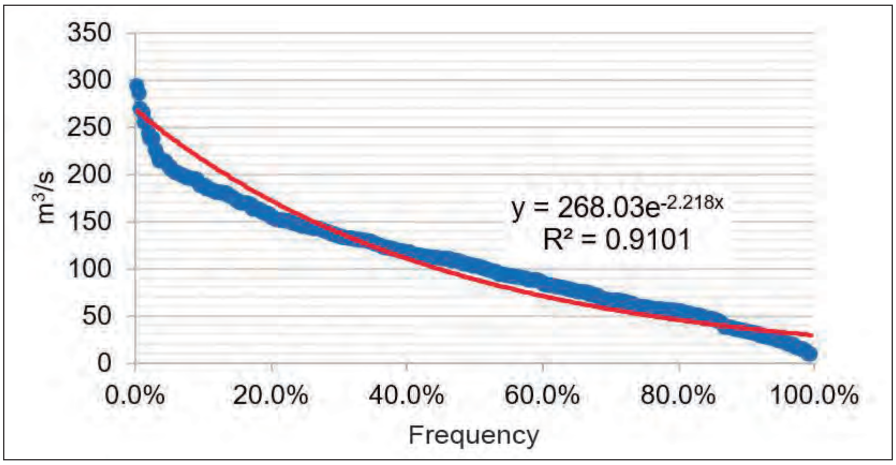

Source: Compiled by the authors.

Finally, due to the similarity in the initial results (Figure 12), we considered the average values of the estimated flows as admissible for the Sungaroyacu basin, and these will be validated through gauging processes.

### *Flow persistence curve*

The flows were ordered (Y), and their frequency was determined (X), the plot was created on a Cartesian plane, and an exponential type equation was established.

Figure 13. Flow persistence curve - Sungaroyacu basin




Source: complied by the authors

Table 15. Flow persistence

| Frequency | 5% | 10% | 20% | 50% | 75% | 80% | 85% | 90% | 95% | 99% |
|---|---|---|---|---|---|---|---|---|---|---|
| Flow ($m^3/s$) | 239,9 | 214,7 | 172,0 | 88,4 | 50,8 | 45,5 | 40,7 | 36,4 | 32,6 | 29,8 |

Source: complied by the authors

## Discussion

The research consisted of carrying out a hydrological assessment through the regionalization technique and water balance to determine the flow for water usage purposes. As input data, we had the monthly and annual rainfall and temperature data from stations located close to the Sungaroyacu basin, a tributary of the Pachitea River.

### *Rainfall*

Arteaga (1986: 40) shows the altitude - precipitation relation for the Pachitea River. In the curves' discretization, Area I—with 2,128.7 mm—corresponds to the Sungaroyacu basin. Such value is 500 mm smaller than the one determined by this investigation.

The Volume I - Rainfall and SENAMHI (1999:60) IILA-SENAMHI-UNI Technical Cooperation Agreement (1982) identified a rainfall behavior zone (zone 2 and subzone 22), M = 3090 - 0.660 (Y), Y is the altitude, and M is the annual rainfall module, for which 2,725.4 mm were identified. Considering there is little meteorological data for the Amazon and that the result is 0.3% higher than the findings in our study, we accept our results as representative for the Sungaroyacu basin.

### *Temperature*

Temperature is another of the most influential meteorological parameters in hydrological processes. Monthly and annual temperature correlations were defined for this research, developing potential regional models.

Arteaga (1986: 48 to 54) determined monthly and annual linear regional models for Pachitea. The annual model is T (°C) = 27,187 - 0.005 x H. This yields an average temperature of 24.4 °C for the

Sungaroyacu basin. The mean temperature value found in this study was 24.8 °C. Both values are close and consistent with the physical behavior of the basin.

### *Evapotranspiration*

For Sánchez San Román (2010: 1), evapotranspiration focuses on quantifying water resources in a basin.

In that sense, although actual and potential evapotranspiration equations already exist, we chose to use Thorntwaite's potential evapotranspiration equation.

Gómez Lora (1987: 65) stated that the purpose of explaining evapotranspiration formulas is strictly for water balance studies.

After conducting a regional analysis between the evapotranspiration calculated for each station and their altitude, the regional equation and evapotranspiration isolines yielded 1,175.5 mm 1,149.3 mm, respectively. As the values are similar, the former is accepted as representative for the basin.

Monthly evapotranspiration was calculated using the temperature data of the Tulumayo station. These values were then estimated as dimensionless to calculate the monthly values. We have not found any studies providing actual or potential monthly evapotranspiration data for basins that are hydrologically similar to Sungaroyacu.

### *The model used*

This study focused on identifying mean, annual values at different persistency levels for water use purposes at the Sungaroyacu basin. Cartographic and hydrometeorological data is available. Thus, the most appropriate methodology is one that combines hydrometeorological and morphometric parameters.

It was deemed convenient to use a procedure to determine accurate enough flows to estimate the dimension order of the hydrographic system of the Sungaroyacu River and to be able to provide data to a future project on the use of the water resources. As a result, the following was decided.

#### *Water balance equation*

Calculated for a long period (1987-2015), for the 29 years under study and according to Custodio and Lamas (1996, quoted in Besteiro, 2015: 13), when the time unit is large, storage variations are negligible and eliminated from this equation, and inputs and outputs are practically the same. Rainfall is considered the basin's input and evapotranspiration as the output, and the annual runoff values were calculated and converted to flow.

#### *Runoff deficit*

Sánchez San Román (2010:1) states that in a hydrologically closed basin, where balance is estimated based on a series longer than 20 years, the runoff deficit can only result from evapotranspiration. Thus, the rainfall and evapotranspiration values were used to calculate annual runoff coefficients and determine monthly and annual flows for the 1987-2015 period.

The Lutz Scholz model was used—and was adapted to the Sungaroyacu basin—to determine monthly flows based on effective precipitation.

Finally, the mean flows are calculated as the average of Table 14, and due to the regionalization, errors up to 30% can be accepted.

## Conclusions

The Sungaroyacu river basin, with an area of 2.180,5 km$^2$ and a perimeter of 281 km, is elongated and irregular and very unlikely to be covered by a storm since floods are evacuated through the riverbeds. The altitude ranges from 200 to 2,868 m above sea level, and the mean altitude is 552.5 m above sea level. The basin's surface distribution shows that 70% is located between 200 and 770 m above sea level. The shape of the hypsometric curve shows that it is in the maturity phase. Thus, since the erosion potential is variable, it will depend on maximum intensities. Its slope is 15.6%, with rough terrain. The fifth-order drainage network has 775 first-order rivers, which are streams found in the upper and more rugged parts of the drainage basin.

The regional hydrological analysis shows a mean annual precipitation of 2,716.9 mm, an average annual temperature of 24.8 °C, and annual evapotranspiration of 1,175.5 mm. Runoff is 1,541.4 mm, equivalent to 110.1 m3/s. The maximum runoff is 2,046.8 mm, equal to 141.5 m3/s, and the minimum runoff is 1,178.2 mm, equal to 81.5 m3/s.

The persistence curve that defines the flows at different frequency levels for water use in the basin is exponential. For irrigation, the flow at 75% persistence is 50.8 m3/s. In terms of hydropower use, at 80%, 85%, and 95%, the flows vary from 45.5 to 32.6 m3/s. Finally, for population use, at 99% persistence, the flow is 29.8 m3/s.

## Recommendations

The regional models can estimate rainfall, temperature, and evapotranspiration values in known altitude locations in the Sungaroyacu basin or hydrologically similar regions. To monitor it, it is necessary to install hydrometeorological instruments in the Sungaroyacu basin, increase the network of stations, and gather measurable information to create robust models.

## Acknowledgments

After being awarded first place in the I Contest of technological development research projects (RDR 2019 Funds) of the National University Federico Villarreal, the research funding was achieved.

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# A century of droughts: Why water policies have not been developed in the semi-arid regions of Brazil

*Humberto Alves Barbosa[1] and Catarina de Oliveira Buriti[2]*

**Abstract**

The Brazilian semi-arid region is affected by long droughts. During the 2010-2017 period, the Brazilian semi-arid region faced a "drought of the century," the worst drought recorded in the history of the country. This paper aims to provide a historical evaluation of the different stages of the public policies implemented in the region to help cope with the drought. Based on the historical documentary research and satellite monitoring of the impacts of the drought, it was concluded that government actions contributed to providing greater water availability in this semi-arid region of Brazil by focusing on assessing water management effectiveness and the impacts of social technologies. The research findings showed that the policies implemented throughout history, under a centralized model, were not effective in developing the region. Access to decentralized social water technologies in rural areas—despite of positive results—is not yet equally available for the entire population. Therefore, policies remain insufficient to cope with the impacts of droughts. The study yields important historical lessons for water management today.

**Keywords:** Drought, water policy, history, satellite monitoring.

## Introduction

Droughts affect all regions of the planet and have the potential to impact millions of people's lives. The consequences of drought include food insecurity, increased poverty, and the risk of internal conflicts over access to essential natural resources such as water and productive land. In Brazil, almost 28 million people live in the semi-arid region, 13% of the country's population (IBGE, 2010). The Brazilian semi-arid region stretches across approximately 1 million km$^2$ (MI, 2017) and is often affected by long droughts. In some areas of the region, droughts usually last up to 11 months, under historically normal conditions (Ab'saber, 1977). In the 2010-2017 period, the Brazilian semi-arid region faced the "drought of the century," considered the worst drought ever recorded in the history of the country. This climatic event had an unprecedented magnitude, reach and span, which had devastating consequences for the population (Buriti and Barbosa, 2018). When the water in rivers and reservoirs reached a critical level, the region was affected by an acute water crisis during this great drought. Large cities ran the risk of a collapse of the entire supply system (Barbosa and Kumar, 2016; Stanke et al., 2013). In the book *A Century of Droughts* (Buriti and Barbosa, 2018), the authors researched history to find lessons for sustainable management of droughts in the Brazilian semi-arid region. This challenge persists, despite so many scientific and technological advances in environmental monitoring. Among the questions addressed by the authors are: Why have the water access policies implemented in the Brazilian semi-arid region over more than a century been unable to transform the social reality of the region? Why do droughts continue to take on the proportions of natural disasters, causing widespread damage to the economy?

Historically, policies to cope with droughts have focused on implementing different water storage technologies, such as dams, irrigation, well drilling, or basin integration projects, among others.

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Despite a century of investing public resources to solve water scarcity in the Brazilian semi-arid region, these policies have still not been sufficient to change the region's socioeconomic scenario (Buriti and Barbosa, 2018).

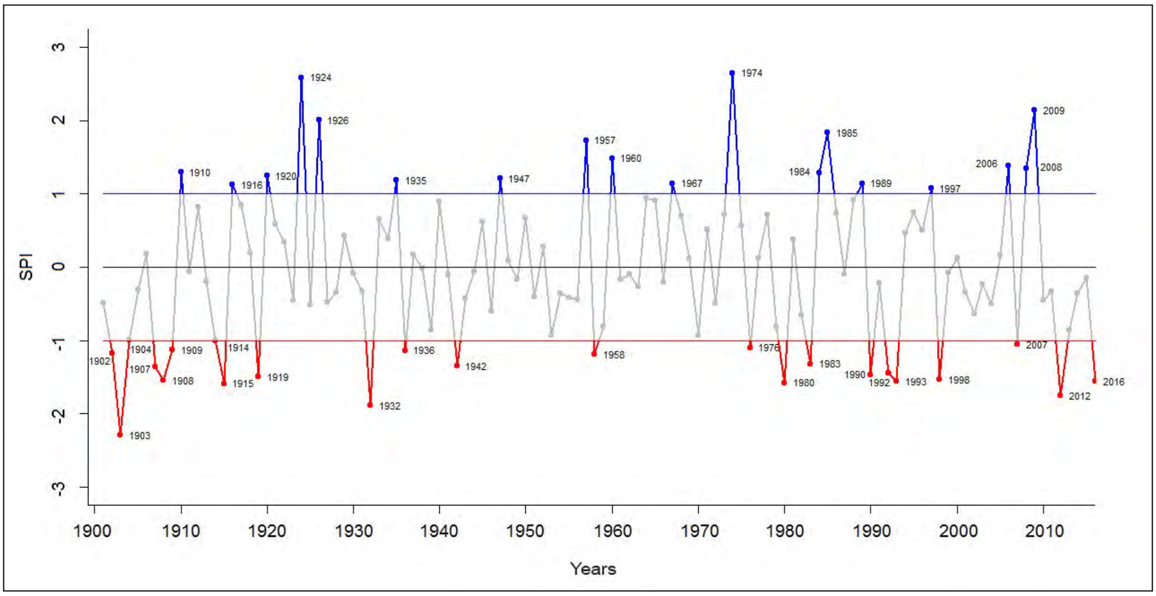
The authors (Buriti and Barbosa, 2018) described the droughts that occurred during this period (1901-2016) after conducting an extensive desk study based on weather, meteorological, historical, and satellite images. At the same time, they analyzed both the policies implemented during each of these drought events and the governmental response capacity in the aftermath for the socially vulnerable population.

This historical assessment of water policies resulted in the current study of how these actions contributed to increased water availability in the Brazilian semi-arid region, focusing on the effectiveness of management practices and technologies for rainwater storage. Based on a long-term historical approach to water policies in the semi-arid region of Brazil, this research is important because it draws lessons for more successful water policies around the world.

## Water policies in the Brazilian semi-arid region: lessons after one hundred years

The classification of the meteorological drought intensity in the Brazilian semi-arid region for the 1901-2016 period was processed by the Laboratory for Satellite Image Analysis and Processing (LAPIS), based on the Standardized Precipitation Index (SPI). This method makes it possible to monitor the precipitation deficit, in a standardized way, at different temporal and spatial scales, in monthly historical precipitation series. Figure 1 shows the results of this analysis. Figure 1 shows the drought severity classification based on the SPI calculation, as shown in Table 1.

Figure 1. Standardized monthly precipitation index, processed annually between February and May (1901-2016)




Source: LAPIS, 2016.

Table 1. Classification of droughts according to the Standardized Precipitation Index (SPI).

| Category | Potential impacts | SPI |
|---|---|---|
| Normal drought condition | Normal precipitation condition. | 0 to -0,5 |
| Normal drought condition | Onset of drought, short period when crops, plantations, and pastures slowly dry out, fire hazards and water shortages begin, fields and crops are not fully recovered. | -0,5 to -0,8 |
| Moderate drought | Some damage to crops and pastures, a high fire risk. Streams, dams, wells with low water levels, and water scarcity are imminent, resulting in a request for water conservation. | -0,8 to -1,3 |
| Severe drought | Potential crop and pasture losses, fire risks, water shortages are widespread, water use restrictions. | -1,3 to -1,6 |
| Extreme drought | Greater crop/pasture loss, extreme risk of fires, severe water use restrictions. | -1,6 to -2,0 |
| Exceptional drought | Exceptional and extended crop/pasture loss, imminent fire danger, water scarcity in dams, streams, and wells, state of emergency declared. | -2,0 and below |

Source: National Drought Mitigation Center (2006).

Drought policies in the Brazilian semi-arid region were structured in three distinct historical phases, according to each period's political and technological solutions. Each of these phases will be analyzed as follows.

### *1) Water solution (1909-1940)*

The institutionalization of the first water policies took place during this period. The Brazilian Government implemented these to mitigate the impacts of droughts. This was done through the Inspection of Works Against Drought (IOCS), the current National Department of Works Against Drought (DNOCS). At this stage, water policies focused on constructing large reservoirs to store rainwater by building large dams and drilling underground wells.

It is a fact that these works helped establish a water storage infrastructure that was, until then, non-existent in the region. However, these actions were not enough to change the way the population coped with droughts. The waterworks were concentrated in large rural farmers' properties, favored by the region's political elites. Consequently, most of the population remained vulnerable and dependent on government aid to face drought, a weather event that normally have devastating effects (Furtado, 1998; Silva, 2006).

### *2) Economic development policies (1950-1980)*

The influence of the Brazilian economist Celso Furtado—from the Superintendence of Development for the Northeast (SUDENE)—in implementing a political development project in the Brazilian semi-arid region was particularly important during this phase.

He proposed an industrialization project for the region with democratic access to water and land in a socially equitable manner. However, the period was marked by many contradictions and obstacles to this transformation project, which certainly did not appeal to the political and economic power groups in the region (Furtado, 1959).

### *3) Sustainable development policies (1990-2016)*

The National Water Resources Policy (Law No. 9,433 / 97) provided the legal framework for this phase. It is considered one of the most democratic water laws globally to support a sustainable, shared, decentralized, and participatory water management model.

The previous phases of National Water Policy were centralized, concentrated, and vertical, from governmental planning to implementation. It was only in the 1990s that there was a successful attempt to decentralize water policies, engaging civil society.

**This issue will be discussed later.**

### *Water crisis or lack of governance?*

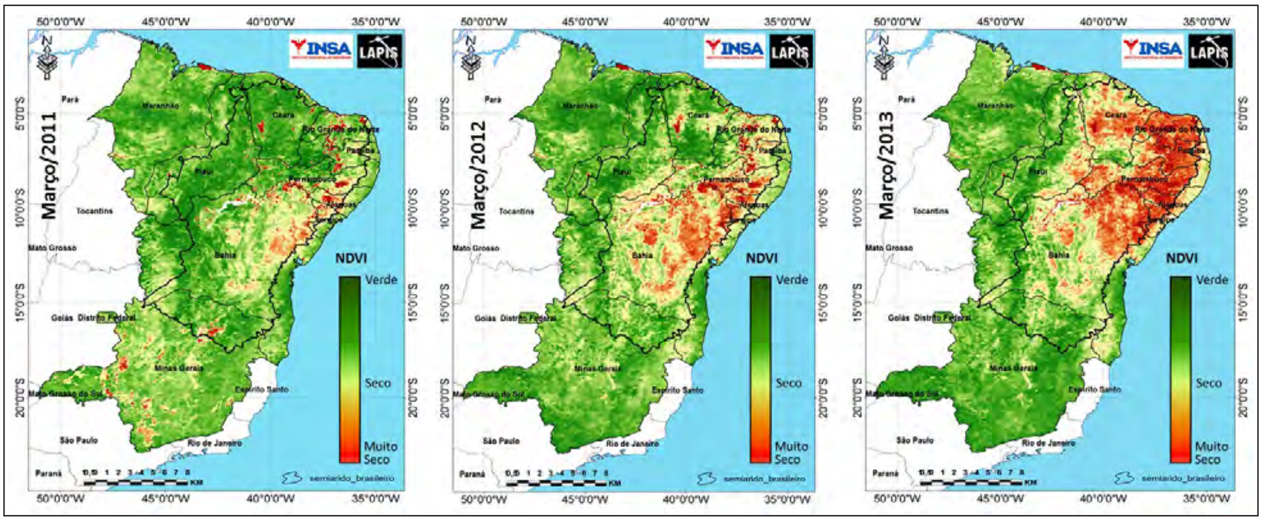
In 2012, about 5 million people were directly affected by drought in the semi-arid region. Almost all of the 1,135 municipalities, which were then part of the region, declared a state of emergency due to the climate disaster. Some of these municipalities declared this condition more than once (MI, 2016).

The “drought of the century” directly affected the national economy. It especially affected city dwellers, as there was a shortage of goods and increased food prices (Stanke et al., 2013).

This region has limited water resources, making it impossible to meet the agricultural sector’s water needs, the main driver of the regional economy (Azevedo et al., 2018). This scenario makes the Brazilian semi-arid region highly vulnerable to climate variability, especially droughts (Marengo and Bernasconi, 2015).

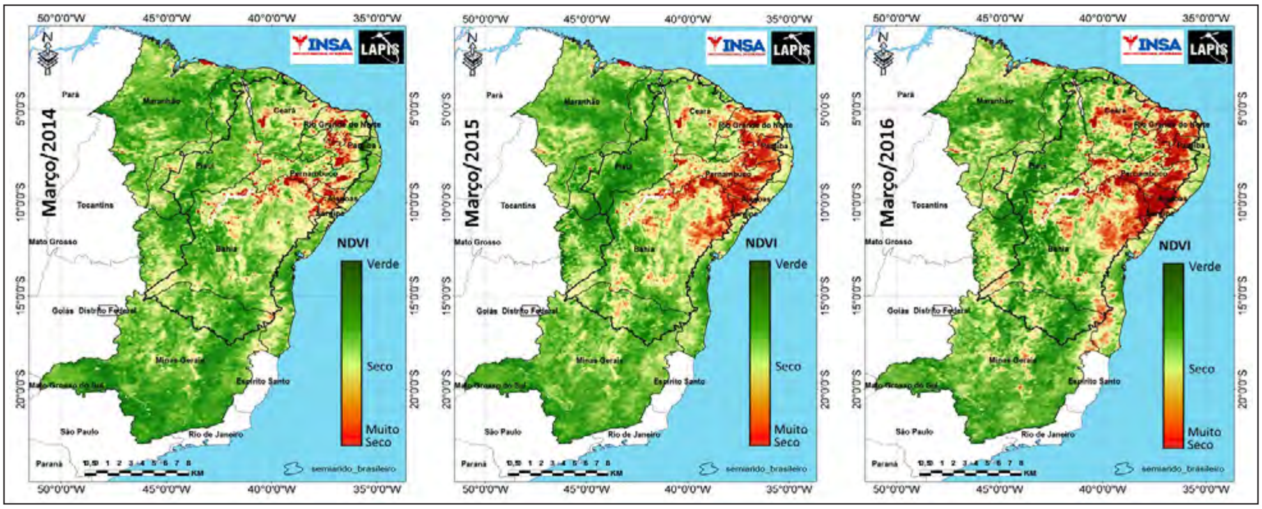
Satellite images of the Brazilian semi-arid vegetation cover show the impacts of the droughts in the region for each year between 2011 and 2016 (Figures 2 and 3).

Figure 2. Satellite monitoring of the Brazilian semi-arid vegetation cover (2011-2013)




Source: Buriti and Barbosa (2018).

Figure 3. Satellite monitoring of the Brazilian semi-arid vegetation cover (2014-2016)




Source: Buriti and Barbosa (2018).

Little was done about public policies to address this recent water crisis in the region to change the population's unreasonable and wasteful use of water through environmental education. There was also a lack of consistent actions to promote water recycling and desalination, the expansion of the region's water infrastructure, and institutional strengthening of the operations (Letras Ambientais, 2018).

According to the book *A Century of Droughts* (Buriti and Barbosa, 2018), the water crisis could be attributed to poor governance and not necessarily to scarcity. Brazilian water management institutions are still not adequately prepared to implement the instruments provided for in the legislation. Efficient water resources management can lead to positive impacts on the water security of the population and the productive sector.

River basin committees are still ruled by political, economic, and knowledge power inequalities. Civil society is not adequately qualified to take part in the water policy decision-making process. Also, governments seem unwilling to relinquish their centralized control (Abers et al., 2009).

This is not only a reality in Brazil. If we look at each region's particularities, efficient water management is a complex and challenging concept for many other countries as well.

## Civil society engagement in the democratization of access to water

Starting in the 1990s, civil society began to actively participate in the formulation of policies that are suitable for the Brazilian semi-arid region to cope with droughts. The federal government programs "One million cisterns" and "One land and two waters" were especially noteworthy. These consisted of implementing social water technologies for water storage to meet the demands of the scattered rural population (Gomes, Heller, 2016).

In the country's current water legislation, social engagement in the governance process was considered essential to advance efficient and democratic water use (Watanabe et al., 2014). Shared management allows different users to work preventively in planning measures to adapt to droughts.

The book *A Century of Droughts* (Buriti and Barbosa, 2018) reports how the specific social groups in Paraíba Cariris, the driest micro-regions of Brazil, exercised their right to participate in basin committees to promote democratic water governance.

It is important to highlight the progress achieved through civil society engagement in decentralizing these water access policies (Baqueiro, 2016; Butler, Adamowski, 2015). These social water technologies, implemented with the support of social organizations in the Brazilian semi-arid region, have had important breakthroughs in terms of water access in the region. However, there are still many challenges to achieve universal access to these social water technologies, especially in rural areas, to better adapt the population to droughts. Researchers learned that not all of the families in Cariris, Paraíba state, received social technologies for water storage (Buriti and Barbosa, 2018). This means that many families still face the daily burden of carrying water over long distances (Gomes et al., 2012).

The water access programs based on social technologies implemented in the Brazilian semi-arid region have had a significant impact on rural women's lives. Historically, women have been primarily responsible for carrying the burden of procuring water from distant sources to support the family. Before P1MC, women spent in total over 36 days a year just carrying water from reservoirs that were too far from their homes (Gomes and Heller, 2016).

With the implementation of social water technologies close to their homes, women's total time carrying water has been reduced to 12 days a year (Gomes and Heller, 2016).

The increased water availability in rural areas due to the implementation of social water technologies has brought tangible benefits for women. They were able to reduce this workload and devote their time to productive activities, contributing to their households' livelihood and increased welfare (Buriti and Barbosa, 2018).

Social water technologies have had an important impact on the ability to cope with droughts in Paraíba Cariris. However, in the Cariri Oriental da Paraíba micro-region, 62% of the rural population had access to the P1MC social technology, while only 13% were given access to the second social technology, through P1 + 2. In the Cariri Oriental da Paraíba micro-region, 32% of the population had access to the P1MC social technology, while only 0.17% had access to P1 + 2.

This study on the distribution of social water technologies in Cariris da Paraíba shows how access to social technology policies for rainwater storage is not yet equally distributed across rural communities.

Therefore, the main challenge faced nowadays is achieving universal access to social water technologies in rural areas, aiming to provide better means for the population to cope with droughts. Social technologies also require improvements in terms of quantity and quality of stored water.

## Conclusions

Historical experience is critical for the design of sustainable development strategies in Brazil's semi-arid region, especially in the face of complex challenges such as sustainable drought management and identifying the most appropriate methods to increase water availability.

By studying the past water policies, the authors of the book "A Century of Drought" (Buriti and Barbosa, 2018) have shed light on the current planning efforts of coordinated and systematic responses to drought adaptation to increase the population's resilience to its impacts. The "drought of the century" left important lessons for today's water policymakers in the Brazilian semi-arid region. One of them is the need to design programs that help the population build greater resilience.

Some of the issues that require further investments in the Brazilian semi-arid region are environmental education, sustainable drought management, a more informed civil society to participate in water governance, water reuse and desalination infrastructure, and urban water abstraction. In addition to focusing on water and energy efficiency strategies, the conservation of natural resources, water pollution reduction, preventing losses and waste, charging for the use of water resources, and drought-adapted technologies are equally relevant issues.

The lessons learned from the water access policies in place in the Brazilian semi-arid region for over a century stress the need for decentralization in water policies planning and implementation; the need to prioritize social water technologies that contribute to democratic access to water, especially by the most vulnerable population; and the need for equitative access to social water technologies and the improvement of these technologies to minimize the impacts of drought on water supply and the food security of the population.

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# Water balance prediction for a venezuelan andean paramo catchment

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Abstract

It is expected that environmental change in páramos (tropical alpine grasslands) will have a substantial impact on their hydrological behavior. For this, a solid understanding and prediction of the hydrology of the Venezuelan páramo are necessary to support decision making on nearfuture water resource management. Until now, the focus has been on the hydrological modelling of the Venezuelan Andean páramos, but it is time to use the generated knowledge to provide tools that support water resource planning, *conservation* and use. This study aims to predict monthly and annual water balances for a microcatchment located in the main valley of Venezuelan páramo applying a variant of the TOPMODEL hydrological model. The model outputs were compared to runoff measurements, and evapotranspiration estimates to evaluate the predictions. In addition, the predictions were evaluated for both calendar and hydrological years. In the case of dry years, it is necessary to evaluate the basic assumptions on which TOPMODEL is based. In general, the model performs best when using hydrological years. However, the model's performance decreased dramatically with one-year executions, so the calibration process should also be reviewed. This research provides elements that must be evaluated to improve the prediction of the water balance components and the water production and regulation capacity of Venezuelan páramo. It also invites us to continue studying and promoting actions aimed at preserving storage units since actions to increase water-use efficiency must include actions that ensure sustainability so that the stored water remains within the natural systems.

**Keywords:** Venezuelan paramo, Andes, hydrological model, TOPMODEL, water balance, water production, water regulation.

## Introduction

Environmental change in páramos (tropical alpine grasslands)—from land-use change to global climate change—will have a substantial impact on their hydrological behavior (Buytaert and Beven, 2011). This results from the strong connection between the water cycle and ecosystem biophysics, mainly vegetation, soil, and climate. Most hydrological studies of the páramo have been conducted in Colombia and Ecuador. Such páramos are significantly different from Venezuelan páramos in their biophysical components. The climate in the Venezuelan páramos has a clear dry season lasting several months, with little to no rainfall. In contrast, the climate of Ecuadorian and Colombian páramos is predominantly humid and has sustained precipitation levels throughout the year (Buytaert *et al*., 2006). In addition, Venezuelan páramo soils are mostly young (entisoles and inceptisols) (Malagon, 1982), whereas páramo soils in Ecuador and Colombia are mainly volcanic or andosol soils (Buytaert and Beven, 2011; Gil and Tobón, 2016). Therefore, the hydrological behavior of Venezuelan páramos is distinct than that of its peers.

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It is essential to fully understand the hydrology of the Venezuelan páramo and its hydrological predictions to support important watermanagement decision making. Simulation models are useful to test hypotheses about a hydrological system, to improve our understanding of hydrological systems, and to make predictions (Buytaert and Beven, 2011). Here, TOPMODEL has been implemented to model the main valley of a Venezuelan páramo microcatchment (Yeguez *et al.*, 2018). TOPMODEL is a physically-based hydrological model used in Ecuadorian and Colombian páramo that shows a reliable performance. In addition, a TOPMODEL variant aiming at representing the hydrological behavior of the rocky outcrops in the study area, was implemented (Yeguez *et al.*, 2019).

Until now, the use of models to understand the hydrology of the Venezuelan Andean páramos has been a main research focus, but it is time to use the generated knowledge to provide tools that support water resources planning, including its *conservation* and use. Therefore, this study aims to predict monthly and annual water balances for the study area by applying a TOPMODEL hydrological model variant. Consequently, it will be possible to quantify the primary environmental services attributed to the páramo: water production and regulation capacity (Buytaert *et al.*, 2006). Water production and regulation capacity are quantified by predicting runoff and water storage variation.

## Materials and methods

The following is a brief description of the study area, the hydrological model used, and the data available to predict and assess water balances. Finally, we describe the water balance equation and present the definition of hydrological year applied.

### *Study area*

The study area is in the main valley of a microcatchment of the Miguaguo ravine (Mixteque sector in Mérida, Venezuela). It has an area of 3.62 $km^2$ and is located at 3,600 m above sea level. The site has a unimodal precipitation regime, with marked seasonality of two to three dry months. The average annual precipitation is 1,170 ± 125 mm. Rainfall events record 7 mm on average (Rodríguez *et al.*, 2014) and are characterized by low magnitude, low intensity, and high frequency (Rodríguez, 2010). Furthermore, solar radiation reaches up to 1,200 Wm-2, especially during the dry season (Córdova, 2014).

The prevailing types of relief are the following: till on hillsides, a unit covering 53% of the area, followed by rocky outcrops (18%), till on the valley floor (17%), and lagoons and wetlands on over-excavation closed basins (8%). The rest of the area has recessional moraines and rockfalls (Rodríguez *et al.*, 2014). Furthermore, slopes range from 0 to over 60%: those between 15% and 30% cover 34.4% of the total area (Córdova, 2014). Soils in this catchment mainly have a high skeletal or coarse fraction. Sand predominates in the fine fraction, resulting in thick textures (sandy loam and loamy sand). Also, soil surface horizon features a high organic matter content ranging from 8% to 28%, and is closely linked to slopes. Slopes under 5% have the highest organic matter values (histosols, inceptisol mineral soils, and some have surface histic features). As the slopes increase, organic matter content (young mineral soils, entisoles, and inceptisols) decreases (Córdova, 2014).

The study area is covered by natural vegetation composed of low shrublands-shrub roses, high shrublands, wetlands, and high Andean forests. The dominant vegetation type is the low shrublands-shrub roses, which are evenly distributed over the entire area. The remaining vegetation formations are arranged in patches, immersed within the other vegetation. At the same time, wetlands are dominated by grasses and swamps (Rodríguez, 2010), forming a rosary system with occurring lagoons (Rodríguez *et al.*, 2014)

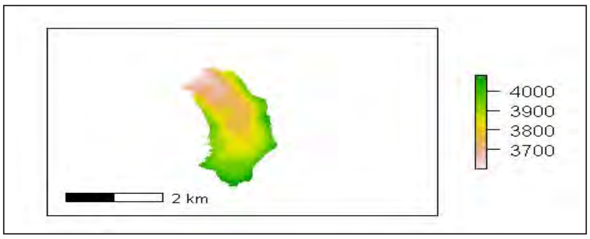
### *Modified TOPMODEL*

An R-implementation of TOPMODEL was used, which was modified and calibrated to represent the hydrological behavior of the rocky outcrops in the study area. Data series from 01/Sep/2011 to 31/Mar/2012 were used to calibrate the model. The Nash-Sutcliffe Efficiency (NSE) obtained was 0.75 when assessing the simulated runoff adjustment with the observed runoff (Yeguez *et al.*, 2019).

### *Data availability*

The following elements were available from a monitoring system implemented in the study area in 2008: a digital elevation model and data on precipitation, runoff, and evapotranspiration. The digital elevation model has a 5-m resolution (Figure 1). Precipitation measurements were taken by an automated weather station in the valley floor. Runoff data were recorded from measurements made at a triangular weir (90°) located at the watershed outlet (Rodríguez *et al.*, 2014).

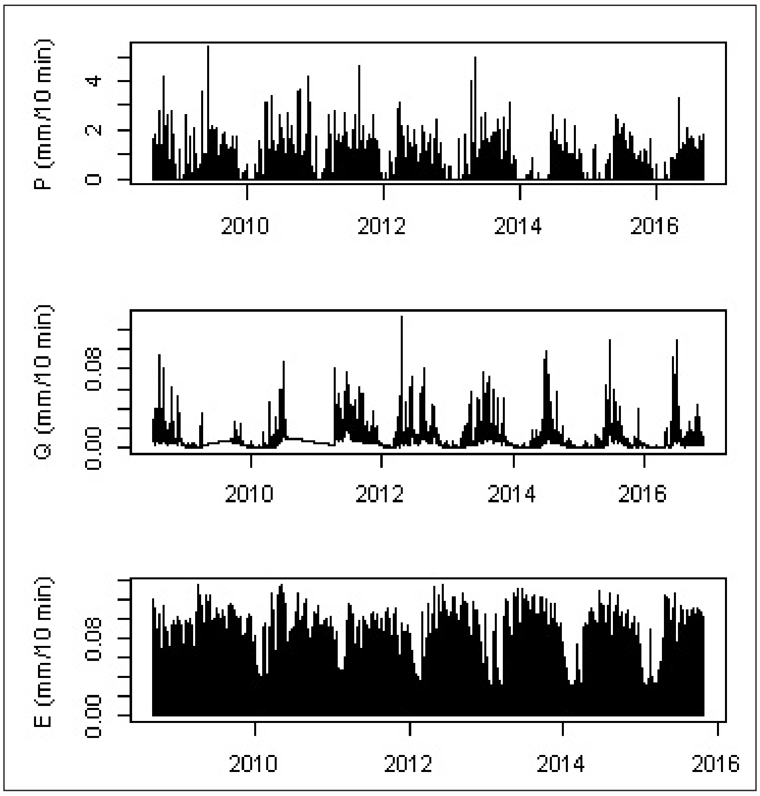
Figure 1. Digital elevation model in the study area




Source: Developed by the authors.

Precipitation and runoff data were stored at a 10-minute temporal resolution. As data series must be equidistant and have the same length, missing data were identified. Daily vegetation evapotranspiration estimates were adjusted to water stress conditions (FAO method). This measurement was selected over reference evapotranspiration, which greatly overestimates the water losses, mainly during the dry season (Rodríguez, 2010). Each daily estimate was distributed into 144 values—one every 10 minutes—using a normal distribution, mimicking *the approx.pe.ts function* of the R DYNATOPMODEL package (Metcalfe *et al.*, 2016). Figure 2 shows precipitation (P), runoff (Q), and evapotranspiration (E) data series up to mid-September 2016. Some precipitation data gaps exist between 04/Mar/2015 and 25/Mar/2015. Two large discontinuities were detected in the runoff rate. Therefore, the series before April 2011 were not used. Other smaller discontinuities were found and linearly interpolated to fill data gaps.

Figure 2. Precipitation (P), runoff (Q), and evapotranspiration (E) data series available




Source: Developed by the authors.

### *Water balance equation*

This equation is a mathematical description of hydrological processes taking place within a given time frame and includes principles of continuity of mass and energy. In this way, the hydrological cycle is defined as a closed system, so there is no mass or energy created or lost within the system. In this case, the mass of interest is water. The balance equation (Equation 1) evaluates water runoff to and from the surface, with the inclusion of a storage term, precipitation (P), evapotranspiration (E), runoff (Q), and storage change (ΔS). The storage term can be positive or negative, as water can be released from storage (negative) or absorbed by storage (positive) (Davie, 2008).

$$P - E - Q - \Delta S = 0 \tag{1}$$

In the study area, storage occurs mainly in soils, lagoons, and wetlands, which hinders storage measurements or estimates. Therefore, in this research, changes in storage were determined for each month of the year by considering the difference between precipitation data and the model outputs (evapotranspiration and simulated runoff). The model outputs were compared to evapotranspiration estimates and runoff measurements to validate the obtained values.

#### *Hydrological year*

Various studies have used the concept of hydrological year to estimate water balances, especially in regions with very marked dry seasons, such as the case of this study area. Therefore, the water balance equation was used for both calendar years and hydrological years. According to the

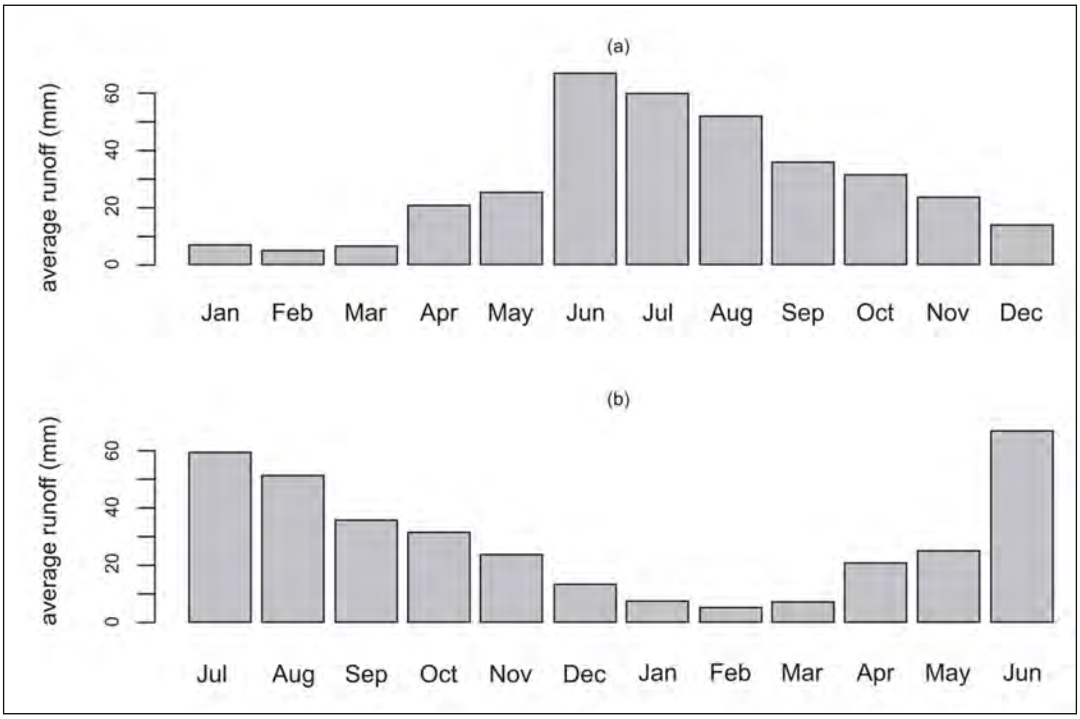
World Meteorological Organization (WMO), the hydrological year starts in a season in which runoff is probably high so that it is unlikely that low annual runoff periods are divided between different years.

## Results and discussion

The seasonality diagram starting in January and using all the runoff data available shows that the low flow period is interrupted (Figure 3a). This is not the case if the seasonality diagram starts in July (Figure 3b), when the hydrological year begins in the southern hemisphere (American Meteorological Society, 2019). Therefore, July is suggested as the starting month of the hydrological year for the study area because the month's average runoff is relatively high, the low flows are not interrupted, and Venezuela is just above the equator.

To estimate water balances, we only considered the calendar and hydrological years that did not have large gaps in the flow records and were not used to calibrate the model. The model was then run for the 2013 calendar year, obtaining an NSE of 0.5, while for the hydrological year 2013 (corresponding to July 2012 - June 2013), the NSE was 0.6. The NSE values obtained here are lower than the calibration values possibly because the model was run for a period larger than the seven months used for calibration.

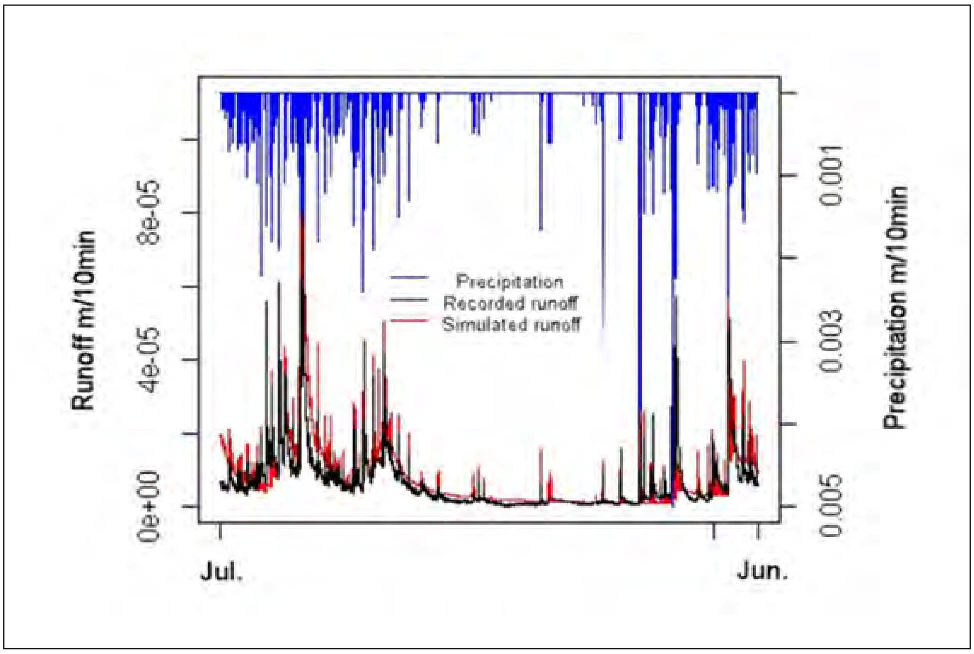
Figure 3. Seasonality diagram (a) starting in January, (b) starting in July




Source: Developed by the authors.

Figure 4 shows the recorded precipitation, runoff, and simulated runoff for the hydrological year 2013. Although the simulated runoff does not fully match the recorded runoff rate, seasonality and dynamics are appropriately represented. Table 1 presents the monthly predictions of the water balance components for that year (model outputs), and Table 2 summarizes the monthly predictions leading to the annual balance.

Figure 4. Recorded precipitation, recorded runoff, and simulated runoff for the hydrological year 2013




Source: Developed by the authors.

Table 1. Monthly predictions for water balance components for the hydrological year 2013

| Month | Recorded precipitation (mm) | Simulated evapotranspiration (mm) | Simulated runoff (mm) | Storage variation by difference (mm) |
|---|---|---|---|---|
| July 2012 | 97.00 | 51.09 | 40.81 | 5.11 |
| August 2012 | 224.20 | 60.99 | 110.22 | 52.99 |
| September 2012 | 79.51 | 62.15 | 49.27 | -31.91 |
| October 2012 | 127.70 | 55.73 | 65.00 | 6.97 |
| November 2012 | 14.60 | 53.55 | 24.62 | -63.57 |
| December 2012 | 17.00 | 33.68 | 12.57 | -29.25 |
| January 2013 | 0.00 | 16.74 | 7.71 | -24.46 |
| February 2013 | 21.40 | 21.93 | 6.33 | -6.86 |
| March 2013 | 20.40 | 15.35 | 5.70 | -0.65 |
| April 2013 | 91.60 | 34.23 | 8.34 | 49.03 |
| May 2013 | 131.60 | 60.60 | 21.54 | 49.46 |
| June 2013 | 136.16 | 56.95 | 49.17 | 30.04 |

Source: Developed by the authors.

Table 2. Prediction of water balance components for the hydrological year 2013

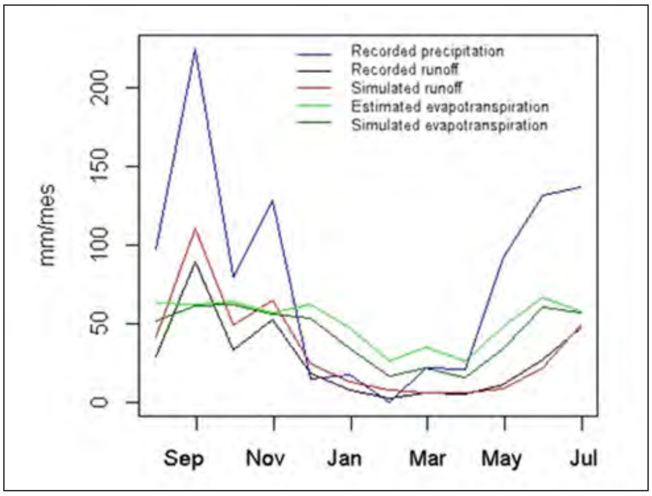
| Recorded precipitation (mm) | Simulated evapotranspiration (mm) | Simulated runoff (mm) | Storage variation by difference (mm) |
|---|---|---|---|
| 961.18 | 523 | 401.29 | 36.89 |

Source: Developed by the authors.

Simulated evapotranspiration exceeds simulated runoff for most months. Only during August and October—when the highest precipitation level is recorded—simulated runoffs are larger. Additionally, consecutive months of storage recharge are observed, as well as consecutive months of discharge and, to a lesser extent, consecutive months with alternating months of recharge and discharge, which corresponded to very rainy and less rainy months. According to the simulated annual balance for that hydrological year, approximately 54.4% of the precipitation is lost as evapotranspiration, 41.7% comes out of the system as runoff, and 3.8% is stored. According to these results, water production reaches 401.29 mm: approximately 41% of precipitation volumes. This is mainly because of high evapotranspiration, while storage variation in that year ranged approximately between -64 mm and 53 mm. This indicates that the study area can store over 50 mm of precipitation per month. However, high runoff rates in August and October evidenced limited regulation capacity.

Figure 5 shows monthly discharge predictions along with runoff measurements and evapotranspiration estimates. The model overestimates the runoff rate for slightly more than the first half of the year. Then it achieves a reasonable adjustment for a brief period, but then it slightly underestimates it until the end of the year. Evapotranspiration is underestimated by the model throughout the year, with more significant differences in magnitude compared to the estimates during the dry season and slightly later. In both cases, although the simulated magnitudes do not match the observed data, the model does replicate the seasonal dynamics. First, the results suggest that TOPMODEL's assumptions regarding the evapotranspiration process need to be revised because it accounts for the largest output, despite its apparent underestimation.

Figure 5. Monthly output flow predictions along with runoff measurements and evapotranspiration estimates




Source: Developed by the authors.

We replicated the analysis for the calendar year 2015 and for the hydrological year 2016 (July 2015 to June 2016), but the NSE values obtained by the model were unsatisfactory: 0.31 and 0.44, respectively. Years 2015–2016 are drier and have lower precipitation inputs than 2013 (both calendar and hydrological). Therefore, the lower model performance is attributed to these differences. This entails evaluating the basic assumptions on which TOPMODEL is based (Beven, 2012). However, the model does achieve better NSE values when working with hydrological years than with chronological years.

## Conclusions

The modified version of TOPMODEL allows us to predict water balance components for a hydrological year. It aims to represent the hydrological behavior of the rocky outcrops in the study area. Although the estimates seem consistent, recorded runoff rates and estimated evapotranspiration points can be compared to assess some assumptions in the model. This aims at improving the predictions of the water balance components and the estimations of water production and regulation capacity of the Venezuelan páramo.

Predicting water balances to support water resources planning and help foster water *conservation* and exploitation made it necessary to use a month other than January as the starting month of the year. In fact, the model performed at its best when working with hydrological years (July to June) than with chronological years (January to December). However, model performance decreased dramatically with one-year executions, so the calibration process must also be reviewed.

To improve water balance calculations, we must continue studying their components, particularly water storage elements (soils, wetlands, and lagoons). In addition, actions promoting the conservation of these elements should be fostered, as has been done in the past, for example, by fencing wetlands. Efforts to increase water-use efficiency must be accompanied by actions to ensure their sustainability so that the saved water remains within natural systems.

This article presents the results of a study that seeks to support water resources planning in the Venezuelan páramo and was conducted by a research group mostly composed of women. However, any person of any gender will benefit from the study’s contributions.

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# A proposed methodology for managing drought-related risks in water concessions: the Tempisque River pilot case

*Milton Gerardo Pérez Matamoros*[1]

**Abstract**

The Tempisque River is the primary water source for agricultural and industrial supply in Costa Rica's North Pacific Coast. The river faces serious problems related to the variation in minimum flows during drought events. Therefore, a methodology was developed to balance the concession flows and preserve the environmental flow of the Tempisque River. It is necessary to have a water-conservation method at the source, considering that El Niño events in Central America result in a decrease in rainfall and, therefore, in streamflows. Therefore, three scenarios are designed, considering the severity of the event (moderate, strong, and very strong), and they are related to the flow records of the Guardia hydrometric station. Three scenarios are created in the Tempisque River, starting from a design flow for neutral events and the environmental flow. These scenarios include the moderate to strong effects of El Niño during its warm phase.

**Keywords:** water concession, risk management, ENSO, Tempisque River, MINAE.

## Introduction

The impact of the El Niño Southern Oscillation (ENSO) phenomenon has increased in magnitude and frequency in the last twenty years, with stronger and more frequent El Niño events than in previous decades. One of the most severe El Niño events in history occurred between 2015 and 2016 when significant environmental and material consequences became apparent in the Guanacaste area in Costa Rica's North Pacific Coast.

Wateruse concessions are granted with minimum flows in neutral periods (no extreme scenarios). There are events in which the sources' streamflow is affected by an excess in rainfall or dry spells, as declared by the National Meteorological Institute of Costa Rica (IMN). This could affect the available and environmental flows of water sources under concession agreements.

The flow decreases during the warm phase of ENSO (El Niño phase). Therefore, it is necessary to find a mechanism to reduce the flow granted under concession agreements when there is a drought and thus ensure the source's well-being within the relevant environmental risk management program.

Various studies are conducted to analyze the availability of water flow and its variability during drought events. These studies are technical but also have a social and economic impact on the water source area. When managing the risks entailed by water concessions, it is essential to know or calculate the source's environmental flow to preserve ecological well-being. Therefore, it is vital to discuss these methodologies with the people involved in the process.

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## Materials and methods

The methodology was developed from a series of water flow measurements made at the source to be analyzed. The flows were then compared to the Oceanic Niño Index[2] (NOAA, 2019) (ONI) to consider scenarios describing the flow percentage decrease in each El Niño phase. It is also necessary to determine the scenarios to analyze (weak, moderate, strong, very strong). This includes distinguishing the impact periods with the data published by the National Oceanic and Atmospheric Administration (NOAA), a scientific agency of the United States Department of Commerce. These are mapped to the flow data provided by the hydrometric stations to determine flow variation in each scenario.

Daily flow data or monthly averages for a minimum series of 20 years was used as primary input to develop the methodology. The years analyzed had ENSO phases or drought periods that are to be studied. These data may be obtained from one or more hydrometric stations. It is necessary to identify an institution or organization that provides climate projections to ensure effective management. Ideally, the institution should be from the country where the methodology is executed, or NOAA alerts should be taken as reference (NOAA, 2019). The limitation of this methodology is the need for longterm flow data. However, to take parallel action, it is necessary to model the basin with variables that determine drought events such as precipitation decrease and temperature increase, focusing the analysis on years with the relevant event.

The Hydro-BID software was used to complement the methodology and to work on modeling. This software creates scenarios with variations in temperature and rainfall to analyze drought events and classify different degrees of impact. This provides data on the flow variations for each scenario.

## Results and discussion

### *Determining flows in drought events: a pilot case*

A period from 1950 to 2010 was analyzed for the Tempisque River pilot case considering the flows provided by the Guardia hydrometric station and the ONI data. In addition, the results focus on the months between January and May because they have the lowest flow rates in the dry season. This creates three scenarios regarding the degree of impact of the El Niño phenomenon (moderate, strong, and very strong), as presented in Table 1 and Figure 1.

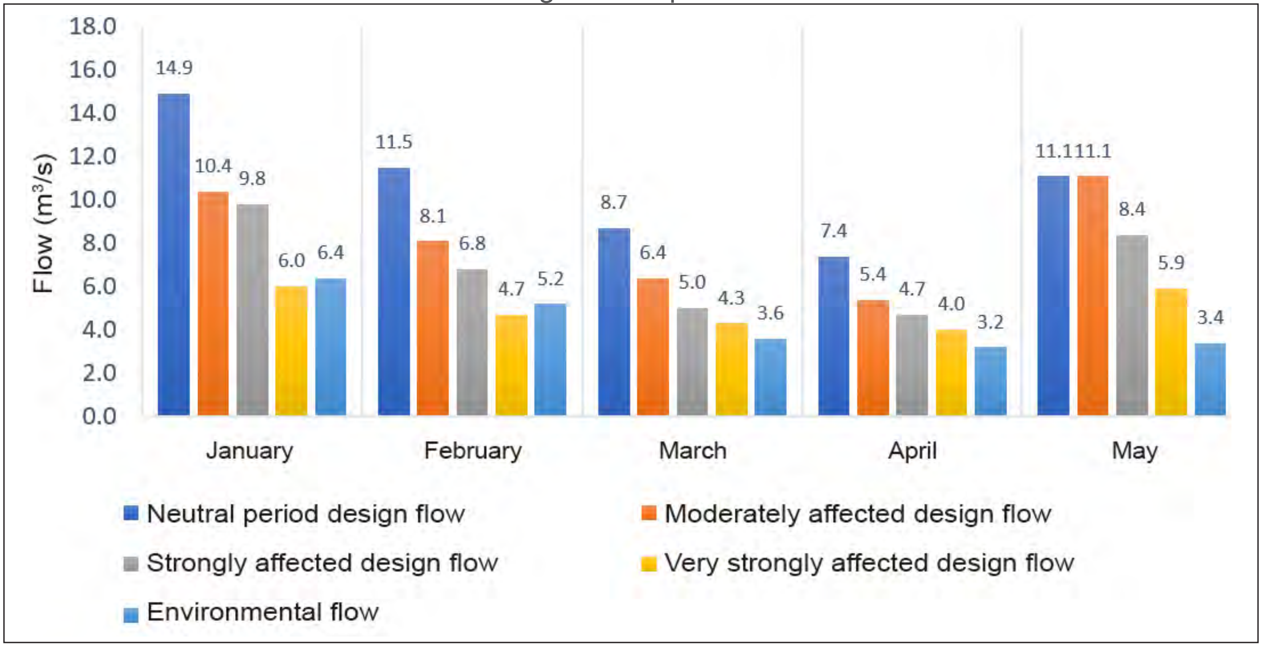
2 ONI: Oceanic Niño Index: the mean of three consecutive months of sea surface temperature anomalies in the Pacific Ocean.

Table 1. Proposed design flow regarding the impact of El Niño

| Scenarios | January | | February | | March | | April | | May | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Flow ($m^3/s$) | Reduc. (%) | Flow ($m^3/s$) | Reduc. (%) | Flow ($m^3/s$) | Reduc. (%) | Flow ($m^3/s$) | Reduc. (%) | Flow ($m^3/s$) | Reduc. (%) |
| Design flow in neutral period | 14.9 | | 11.5 | | 8.7 | | 7.4 | | 11.1 | |
| Environmental flow | 6.4 | | 5.2 | | 3.6 | | 3.2 | | 3.4 | |
| Moderately affected design flow | 10.4 | 30.2 | 8.1 | 29.6 | 6.4 | 26.4 | 5.4 | 27.0 | 11.1 | 0.0 |
| Strongly affected design flow | 9.8 | 34.2 | 6.8 | 40.9 | 5.0 | 42.5 | 4.7 | 36.5 | 8.4 | 24.3 |
| Very strongly affected design flow | 6.0 | 59.7 | 4.7 | 59.1 | 4.3 | 50.6 | 4.0 | 45.9 | 5.9 | 46.8 |

Source: Water Directorate Office DA-UHTPNOB-0394-2017 (Pérez, 2017).

Figure 1. Analysis of flows of the Tempisque River classified into the degree of impact of El Niño




Source: Developed by the authors

Once the flow has been determined for the various scenarios, the source's environmental flow can be set aside, and the available flow redistributed to all the concessionaires. Water concessions in Costa Rica are usually granted for ten years at a fixed flow rate. This methodology allows us to adapt the flow rate to the available flow in extraordinary drought events, thus safeguarding the environmental flow rate.

### *Implementing the reduction of granted flows during events of drought*

It is necessary to identify the institution that provides weather forecasts to implement the reduction of concession flows, in this case, the IMN: a specialized entity that manages local predictions on the impact of the ENSO phenomenon or weather events causing temporary droughts. Typically, potential drought threats are forecast six months in advance. At this point, it is essential to share the information with the water concessionaires so they can take measures to mitigate potential flow decreases considering the data presented in Table 1.

Once the alert protocol is initiated, source flows are monitored for variations. When the observed flow falls below the neutral period design flow, reductions are applied to all concessionaires through official notifications.

On-site monitoring and controlling the situation is essential to verify compliance with the guidelines and with flow reductions. At the same time, hydrometric stations should monitor the problem or take specific measurements on an ongoing basis to determine how long the reduction will be in place.

This methodology is applied to address the need for specialized records that would make it possible to modify the granted flow. This flow has been managed as rigid data for an established period, affecting the sources that are naturally dynamic and prone to varying flow rates due to weather events. This pilot case is in its implementation stage, which began in 2018 and aimed to be validated.

### *The most recent severe drought event*

The 2015-2016 period recorded one of the strongest El Niño events in Costa Rica. According to the bulletin No. 86 of the National Meteorological Institute, the balance for the last quarter of 2015 shows that the North Pacific had a 79% rainfall deficit and that the area's annual balance was 40% (IMN, 2019).

Officials from the Water Directorate of the Ministry of Environment and Energy (MINAE) measured flow rates for the 2016 dry season because of the extreme flow decrease in the Tempisque River. They found a minimum flow of 0.165 $m^3/s$ in one of the sections on 20/Apr/2016. This was 19.39 times lower than the minimum flow rate recommended for this month compared to the April environmental flow rate shown in Table 1.

In 2016 there was still no methodology to manage the environmental risk that could affect the biodiversity and natural dynamics of the Tempisque River. Efforts were made to maintain the environmental flow and prevent the decrease in water use under temporary concession agreements. However, they failed to maintain the recommended minimum river flow.

The Tempisque River water users have helped during the drought events by reducing water use and scheduling water extraction when there were minimum flows. However, the government administration cannot place this responsibility on the shoulders of temporary agreements; therefore, the application of this methodology is under study, with the necessary technical support to achieve environmental safety for the river.

Various reactions to these drought events and minimal flows have been reported. For instance, environmental groups have promoted social movements fighting for the wellbeing of the river and its ecosystems, making the issue more complicated and revealing the need for a more holistic analysis. This analysis shows the significant number of women benefiting from water concessions: currently, out of 30 concessions, 9 are led by a woman (30%). However, the men-women ratio of the average annual flow granted is 3.35% when considering the flow granted to these nine concessionaires from the total flow. It would be interesting to study this situation from a holistic perspective.

## Conclusions

Given the environmental and social problems in the Tempisque River, this methodology was developed to change the fixed flow rate granted to a lower flow rate. This is done with technical support drought events occur, to ensure efficient risk management in the environmental sector. The methodology is being tested as a pilot case on the Tempisque River, and needs to be replicated in the primary water sources of Costa Rica that are at risk of compromising the environmental flow available for concession. The methodology aims to help users improve water-use efficiency in irrigation systems given the flow adjustments and irregular periodic events of the El Niño phenomenon.

It is recommended that hydrological modeling is performed with HydroBID or other similar software to create scenarios for drought events and different degrees of impact.

## Acknowledgments

Flow data provided by Station 741901 known as Guardia, and by the Costa Rican Electricity Institute (ICE) were taken as the basis to execute this risk management methodology to control water concessions. It would have been impossible to conduct the technical analysis without this information and that taken from the ONI data series, as presented on the NOAA website (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

The Water Directorate should be recognized as the leading agency on Costa Rica's water resources so that human resources can be allocated to conduct this type of analysis, despite the limited number of officials.

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# Inter-basin transfer feasibility study: transfer of water from the Dry Harbour Mountains hydrological basin to augment water supply in the Rio Cobre and Kingston hydrological basins, Jamaica

*Natalee Hutchings[1]*

**Abstract:** Water resources within the Rio Cobre and Kingston Hydrologic Basins, which supply the Portmore Municipal Area (PMA) and the Kingston Metropolitan Area (KMA), respectively, are severely stressed by current and projected drinking water demands. Based on projected population growth, the demand will only continue to increase with further development and urban sprawl. This will exacerbate the problem of water shortages, assuming that public water supply and irrigation efficiencies are not significantly improved. To resolve this issue, inter-basin transfer of water from a hydrologic basin with surplus of freshwater resources is considered as a solution. The Dry Harbor Mountains Hydrologic Basin is the most suitable choice for inter-basin transfer to the Rio Cobre and Kingston Basins due to its location, bordering proximity and the abundance of freshwater resources. The Rio Bueno, Laughlands Great River and White River are three of the main rivers in the Dry Harbor Mountains Hydrologic Basin with significant perennial flows and long-term records of stream-flow data. These rivers were evaluated to determine whether any surplus water is available from each river and the available quantity. Evaluation of the selected water sources revealed that surplus water is available to make the inter-basin transfer of fresh water from the selected sources within the Dry Harbor Mountains Hydrologic Basin a feasible option to augment water supply in the Rio Cobre and Kingston Hydrologic Basins. Stream flow data from January 1st, 1951 to December 31st, 2017 for the mentioned rivers were evaluated and analyzed using HYDATA (Hydrological Database and Analysis System). Analysis of the data indicated that surplus surface water from Rio Bueno is 107,781.1 $m^3$/day (39 $Mm^3$/year), Laughlands Great River is 18,748.8 $m^3$/day (6 $Mm^3$/year), and White River is 140,551.1 $m^3$/day (51 $Mm^3$/year).

**Keywords**: Inter-basin Transfer, surplus, water resources assessment.

## Introduction

Global water demand has been rising at an annual rate of 1% throughout the last decades, where population growth, economic development and changing consumption patterns are the main drivers for this increase (WWAP, 2019). By the year 2030, there is an expected 40% global water scarcity attributable to the current climate situation (WWAP, 2015). Growing water stress indicates an increasing use of the water resources, with greater impacts on resource sustainability, and a rising potential for conflicts among users. Water availability depends upon the quantity of water physically available, and how it is stored, managed and allocated to various users. Net growth in population is taking place in cities and the world is becoming gradually urbanized, producing new challenges for urban water management; causing sustainable development challenges to be increasingly acute in cities, particularly in the developing countries where population growth and the pace of urbanization are greatest (WWAP, 2019).

In Jamaica, from 2014 to 2017, water demand moved from 2 billion to 2.5 billion $m^3$/year, reflecting a 25% increase for the period (Chambers & Hutchings, 2019). Two of the major urban centers in Jamaica, Kingston Metropolitan Area (KMA) and Portmore Municipal Area (PMA), have population

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(projected up to 2017) of approximately 670,000 and 220,000, respectively (STATIN, 2012). With positive projections of population growth (0.26% per year) (PIOJ, 2005), increase in demand is likely to exacerbate the problem of water shortages/challenges if public water supply efficiencies are not significantly improved and managed (WRA, 2005). With increased water consumption rates, risk of exhausting available water resources and threat to freshwater production (due to saline intrusion and nitrate pollution within the Rio Cobre and Kingston Hydrological Basins respectively), it is anticipated that potable water shortages will rise. Subsequently, mitigating against a deficit in supply is essential. As the negative effects of climate change (adversely affecting Jamaica since 2010) (CGSM, 2017), unpredictable rainfall patterns and the risk of extended drought conditions continue, water availability and supply in these vulnerable cities is expected to be severely affected. Water resources for the Rio Cobre and the Kingston Hydrological Basins (where the PMA and KMA are located, respectively) are projected to decrease by approximately 53.3 $Mm^3$/year in 2025 (based on 94.6 $Mm^3$/year in 2015 and 74.8 $Mm^3$/year in 2020) and deficits of approximately -2.3 $Mm^3$/year by 2025 respectively (WRA, 2005).

Currently, of Jamaica's ten hydrological basins (sub-divided into 26 Watershed Management Units), the Rio Cobre and the Kingston Hydrological Basins have the lowest calculated exploitable[2] water resources, having values at 80.68 $Mm^3$ and -2.21 $Mm^3$ respectively (WRA, 2010). Projected water demand (excluding irrigation) for the Rio Cobre and Kingston Hydrological Basins have been calculated at 160 $Mm^3$/year and 96.7 $Mm^3$/year by 2025 respectively (WRA, 2005). Ongoing efforts to curtail water supply deficits (as well as over-exploitation) and demands include the longstanding Moratorium on the Rio Cobre Hydrological Basin (St. Catherine 'Critical Area' Order, 1969), which prohibits any new abstraction, in an effort to militate against saline intrusion whilst protecting the available fresh water resources (Underground Water Control Law, 1959). Additionally, there is transmission of water from both St. Thomas (Yallahs Pipeline Project, 1986) and St. Catherine (ESL & NKC, n.d.; GOJ & NWC, 2009) to augment water supply in the Kingston Hydrological Basin. Inter-basin water transfer involves moving water from one watershed/hydrological basin to another (Minard, 2015) from groundwater and/or surface water sources and includes transport via pipeline/main and/or canal/tunnel. Based on the projections for water resources availability and demand, swift forward planning for implementing an alternative sustainable supply of freshwater to the most vulnerable/stressed areas is needed.

## Aims

This study examines the hydrological resource feasibility of inter-basin transfer of surface water from the Dry Harbor Mountains Hydrological Basin to the Rio Cobre and Kingston Hydrological Basins in order to augment water supply. This study aims:

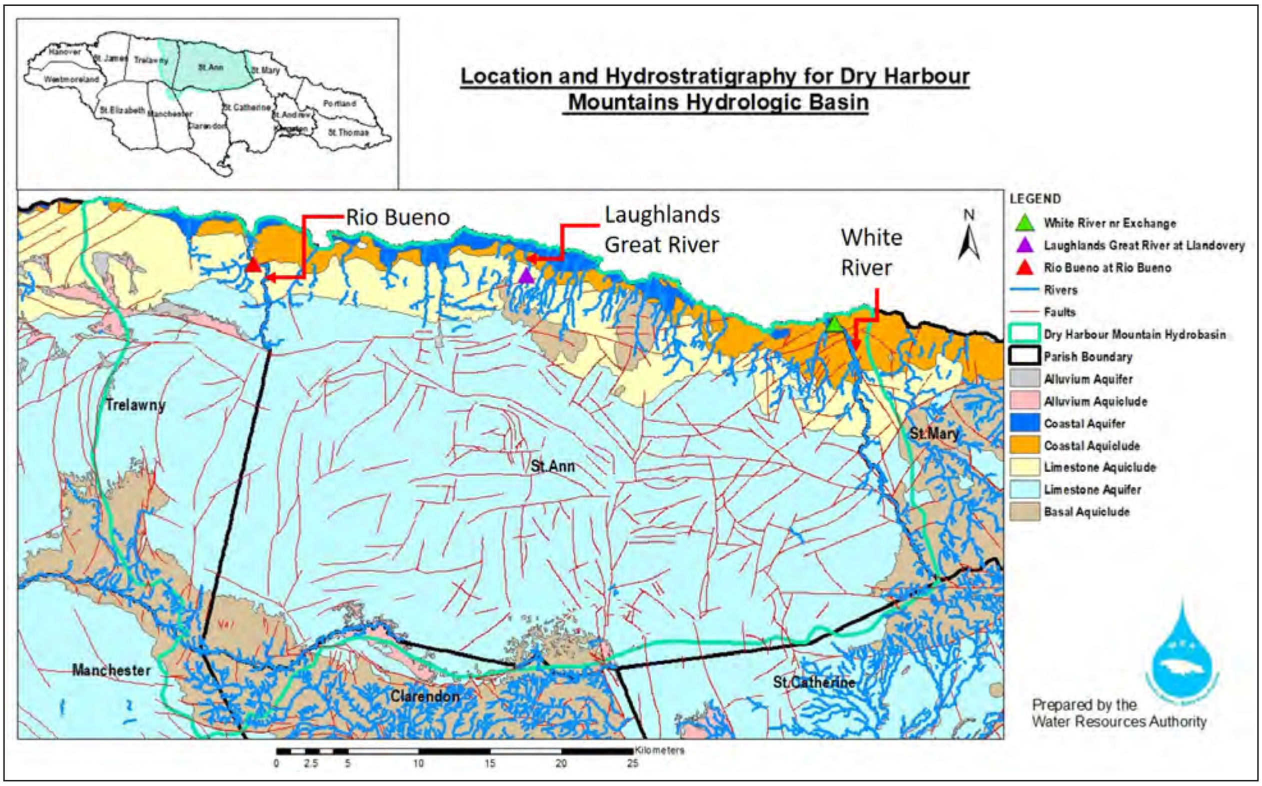
1. To locate and assess suitable surface water sources with surplus water within the Dry Harbor Mountains Hydrological Basin.
2. To conduct hydrological analysis and assessment on selected surface water sources to determine the amount of water available as surplus.
3. To determine, if inter-basin transfer of water is feasible to meet/augment projected demands in Rio Cobre and Kingston Hydrological Basins.

2 Exploitable Water Resources refer to the calculated Total Reliable Resources, less the Total Allocated Volumes/Abstractions. This was calculated for each hydrological basin, and relates to the Total Available Volumes of water resource from groundwater and surface water that is expected to remain in the basin after the Total Allocated Volumes/Abstractions have been accounted for, and is readily available for Use.

## Materials and methods

Located north of the Rio Cobre Hydrological Basin and northwest of the Kingston Hydrological Basin, the Dry Harbor Mountains Hydrological Basin stretches over the parish of St. Ann crossing the boundaries into Trelawny to the west, St. Mary to the east and Manchester/Clarendon in the southwest. This basin is comprised of one Watershed Management Unit (WMU): Dry Harbor Mountains, and two Sub-WMUs: Rio Bueno and White River. This Hydrological Basin is dominated by limestone aquifer and is bound to the north by a belt of limestone aquiclude, and a narrow belt of coastal aquiclude forming the seaward boundary of the basin (Figure 1).

Figure 1. Location and Hydrostratigraphy Map for the Dry Harbor Mountains Hydorologic Basin




Source: Water Resources Authority

Compilation of data and information from various references, desk study, source assessments and hydrological analyses were done to determine the most suitable sources to consider as the potential supplying one(s). Three options have been selected for hydrological assessments: 1) Rio Bueno, 2) Laughlands Great River and 3) White River.

Hydrological data was assessed and analyzed from stream gauge stations on each river for the study period 1st January 1951 to 31st December 2017 using the Hydrological Database and Analysis System (HYDATA 4.2 Software Application). HYDATA is a hydrological database and analysis system designed to analyze data most typically used in hydrological studies; with capabilities for producing rating curves, for storing, editing and graphing data, and for obtaining data in the form of specialized “yearbook” tabulations or exported to text files (IH & CEH, 2001).

The results were interpreted and then used to calculate the amount of surface water available from each source as surplus. Suitability as a supplying source was determined based on which source had the most available surface water resource and whether it was feasible to meet the projected demands of the receiving hydrological basins individually or collectively. Analysis conducted on each selected source include:

- Mean Daily Flow and Reliable Yield
- Flow Frequency or Exceedance Probability
- 7-Day Minimum Mean Flows
- Environmental Flow and Environmental Water Demand
- Base Flow and Base Flow Index
- Available Water Resource (Surplus)

The **mean daily flow** is the average flow from a stream/river within a 24-hour period calculated by dividing the total flow by the number of seconds in that day; *i.e.* 86,400 seconds (Lehre, n.d.). This is used to determine the **reliable yield** which is the maximum supply rate of a given water source that is expected to be available on demand for a certain percentage (for example the 90$^{th}$ percent) of a given time period (WRA, 2011). It is the time series of mean daily flows and not a single value that is used to determine the reliable yield. On the other hand, the reliable **surface flow yield** is the exploitable surface water represented as the daily water flow that is exceeded 90% of the time (*i.e.* the Q90). This level of reliability is sufficient for irrigation, however domestic and industrial water supplies usually need a higher level of reliability (WRA, 2018a); therefore, the 95$^{th}$ percentile (*i.e.* the Q95) is used to determine the reliable surface yield.

The **flow duration or exceedance frequency/probability** is the percentage of time that the given daily mean flow is equaled or exceeded and can be represented graphically with a Flow Duration Curve (Lehre, n.d.). This is useful in water supply studies as it indicates how much water is available on average for a given time period from a source.

The **7-day minimum mean flows** are the low flow indices used in the low flow frequency analysis and is carried out when 7-day consecutive periods of minimum daily flows over many years of data are averaged, ranked and plotted against exceedance probabilities and can be used to determine the minimum stream-flow return period (as expected low flow). This can also be used to estimate the **environmental flow** of a stream which is the flow of water required by rivers to maintain their functions and in-stream ecosystems (WRA, 2011) and is determined by the 7-day minimum mean flow with a 10-year return period (*i.e.* the 7Q10).

The **Environmental Water Demand** is the amount of water needed in a stream to sustain a healthy ecosystem (Lacroix & Xiu, 2013). This is assumed to be 60% of the environmental flow (*i.e.* 0.6*7Q10), and also accounts for the water that is not available for use, allocation or transfer.

That portion of the streamflow which is derived from the stored sources/aquifers is referred to as **base flow**. It is necessary to separate the direct and base flow of a stream in order to understand water reliability during low flow and drought periods (Woyessa & Welderufeael, 2010). The **Base Flow Index** (BFI) is a measure as a rank of base flow of the source over a set time period. A high BFI indicates a long base flow sustainable period and the low BFI indicates a short base flow sustainable period. In this case, a high BFI (typically ranging from 0.7 to >0.9) suggests a high permeability of the rocks and indicates a high base flow supply. A low BFI (typically ranging from <0.15 to 0.35) suggests a low permeability of the rocks and a low base flow supply (Gustard, Bullock, & Dixon, 1992).

The **Total Allocated Resource** includes the sum of all current licensed abstraction volumes and is also considered as the water that is not available for use, re-allocation or even transfer from a river/stream (Table 1). Note that the Total Allocated Volumes include total volumes abstracted from downstream of the gauge stations and do not account for the abstractions occurring upstream since the reliable surface yield (*i.e.* the Q95) would already have accounted for water that have been abstracted (or is not present) from upstream the source.

Table 1. Total Allocated Resource from each Potential Supply Source

| Source Name | Total Allocated Volumes (Downstream of Gauge Station) |
|---|---|
| Rio Bueno | 33,120 $m^3$/day |
| Laughlands Great River | 0 $m^3$/day |
| White River | 350 $m^3$/day |

Source: WRA, 2017.

The **Available Surplus Resource** is the reliable surface yield of the source which is expected for a given time period after accounting for the environmental water demand and the total allocated resource. This is achieved by determining the reliable surface yield from the flow frequency duration (the Q95), then subtracting the environmental water demand, and then subtracting the total allocated resource (Equation 1).

Equation 1: Available Surplus Resource = (Reliable Surface Yield – Environmental Water Demand) – Total Allocated Resource

## Results and discussion

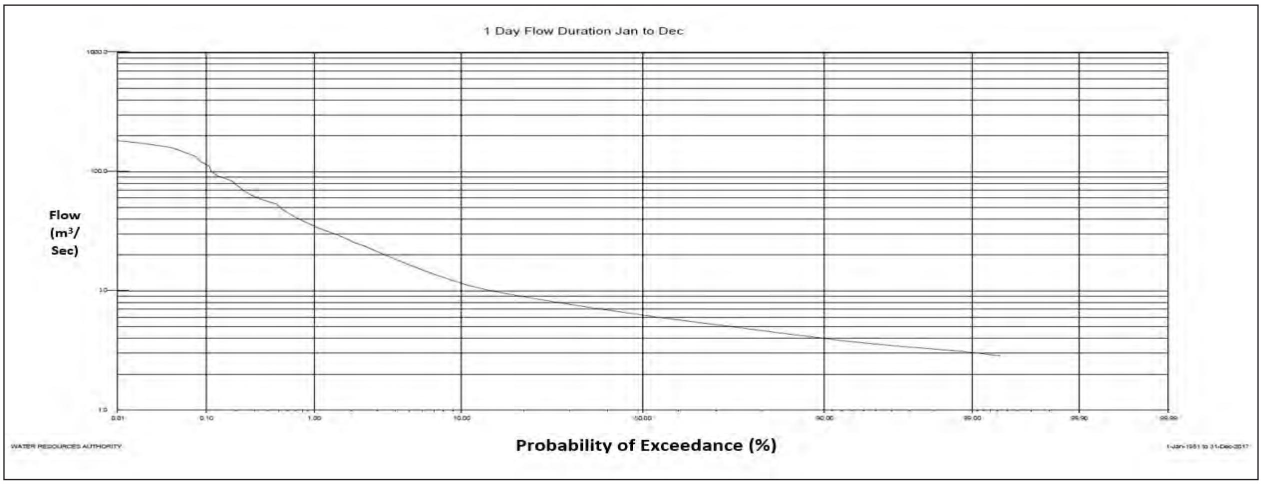
The analysis and assessment were done on the selected sources and are outlined below.

### *Rio Bueno Flow Analysis and Resource Assessment*

*Mean Daily Flow and Flow Duration/ Exceedance Frequency for Rio Bueno*

The mean daily flow for the Rio Bueno at Rio Bueno station is 676,425.6 $m^3$/day (247 $Mm^3$/year) during the study period. The flow of 306,633.6 $m^3$/day (112 $Mm^3$/year) was exceeded 95% of the time (*i.e.* the Q95) for the study period (Figure 2). This is a significant low flow indicator and is used to determine the reliable surface yield of the flow.

Figure 2. Flow Duration Curve of Mean Daily Stream Flow Exceedance Frequency from Rio Bueno at Rio Bueno station for January 1st, 1951 to December 31st, 2017




Source: WRA, 2018b.

### *Low Flow Frequency Analysis from 7-day Minimum Mean Flows for Rio Bueno*

A 7-day minimum mean flow analysis for the Rio Bueno was conducted for the study period. This was used to determine the 3-year, 10-year, 25-Year and 100-year low flow return periods (Table 2).

Table 2. Low Flow Return Periods for Rio Bueno.

| Low Flow Return Period | 3-year | 10-year | 25-year | 100-year |
|---|---|---|---|---|
| 7-day Minimum Mean Flow ($m^3$/day) | 320,889.6 | 276,220.8 | 244,857.6 | 232,416 |
| Exceedance Probability | 67% | 90% | 96% | 99% |

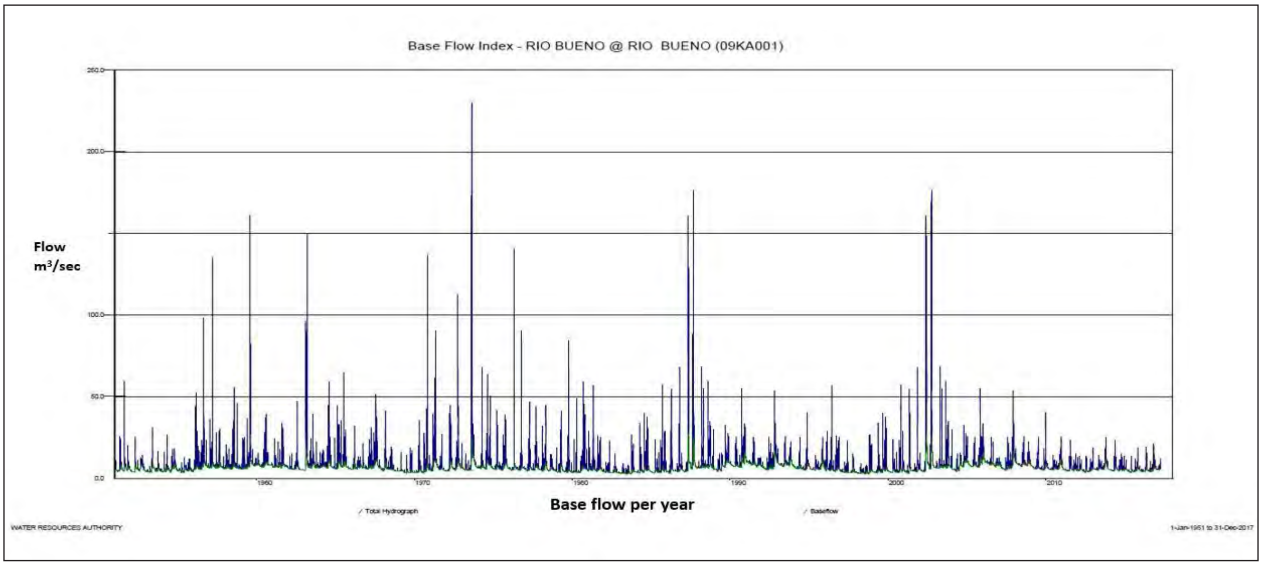
Source: WRA, 2018b.

The low flow return period indicates that on average, once every 3-year period, stream flow is 320,889.6 $m^3$/day and this flow magnitude has 67% chance of being exceeded in any given year. For the 10-year (*i.e.* 7Q10) and 25-year return periods, low flows of 276,220.8 $m^3$/day and 244,857.6 $m^3$/day, respectively, will occur with exceedance probability in any given year of 90% and 96% respectively. The flow of 232,416 $m^3$/day has a 100-year return period and an exceedance probability of 99%.

### *Base Flow and Base Flow Index for Rio Bueno*

The base flow recorded for Rio Bueno during the study period is 5,262.58 mm/year. For each hydrological year (January to December in this case), the annual BFI was calculated (Figure 3). The BFI for Rio Bueno at Rio Bueno Community is 0.777 and indicates a relatively high base flow and that this river has a high potential for flow sustainability during periods of low rainfall/drought.

Figure 3. Graph of Base Flow Separation for Rio Bueno at Rio Bueno Station with separated base flow indicated by the green line




Source: WRA, 2018b.

### *Environmental Water Demand for Rio Bueno*

The following equation is used to determine the EWD for Rio Bueno:

Equation 2: Environmental Water Demand = 60% * Environmental Flow

Therefore, EWD for the Rio Bueno can be calculated as:

EWD = 60% * 7Q10

= 60% * 276,220.8 $m^3$/day

= 0.6 * 276,220.8 $m^3$/day

= 165,732.5 $m^3$/day

The calculated EWD for Rio Bueno is 165,732.5$m^3$/day and represents the minimum flow that is needed by the source in order to sustain its natural ecosystem.

### *Amount of Surface Water Available as Surplus from Rio Bueno*

Surplus resource is determined by Equation 1 below:

*Equation 1: Amount of Surface Water Available as Surplus = (Q95 – 60% of 7Q10) - Current Total Licensed Abstraction*

Available Surface Water = (Q95 - EWD) - Total Allocated Volume

= (306,633.6 $m^3$/day - 165,732.5 $m^3$/day) - 33,120 $m^3$/day

= 140,901.1 $m^3$/day - 33,120 $m^3$/day

= 107,781.1 $m^3$/day

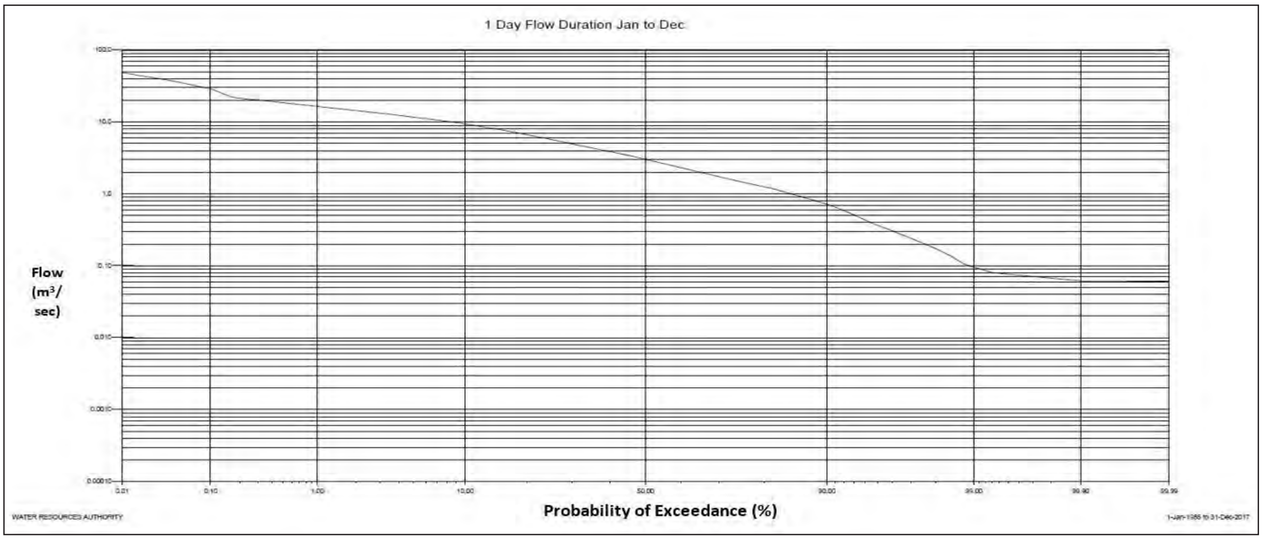
The calculated volume of water that is considered as available surface water resource or surplus from the Rio Bueno is 107,781.1 $m^3$/day.

### *The Laughlands Great River Flow Analysis and Resource Assessment*

*Mean Daily Flow and Flow Duration / Exceedance Frequency for Laughlands Great River*

The mean daily flow for Laughlands Great River at Llandovery is 358,992 $m^3$/day (131 $Mm^3$/year) for the study period. An average flow of 31,449.6 $m^3$/day (11 $Mm^3$/year) was exceeded 95% of the time (*i.e.* the Q95) for the study period (Figure 4). This is a significant low flow indicator and is used to calculate the reliable surface yield of the flow from the Laughlands Great River.

Figure 4. Flow Duration Curve of Mean Daily Stream Flow Exceedance Frequency from the Laughlands Great River at Llandovery from January 1st, 1951 to December 31st, 2017




Source: WRA, 2018b.

*Low Flow Frequency Analysis from 7-day minimum mean flows for Laughlands Great River*

A 7-day minimum mean flow analysis for the Laughlands Great River was conducted. This was used to determine the 3-year, 10-year, and 50-year low flow return periods (Table 3).

Table 3. Low Flow Return Periods for Laughlands Great River.

| Low Flow Return Period | 3-year | 10-year | 50-year |
|---|---|---|---|
| 7-day Minimum Mean Flow ($m^3$/day) | 66,700.8 | 21,168 | 13,910.4 |
| Exceedance Probability | 69% | 89% | 98% |

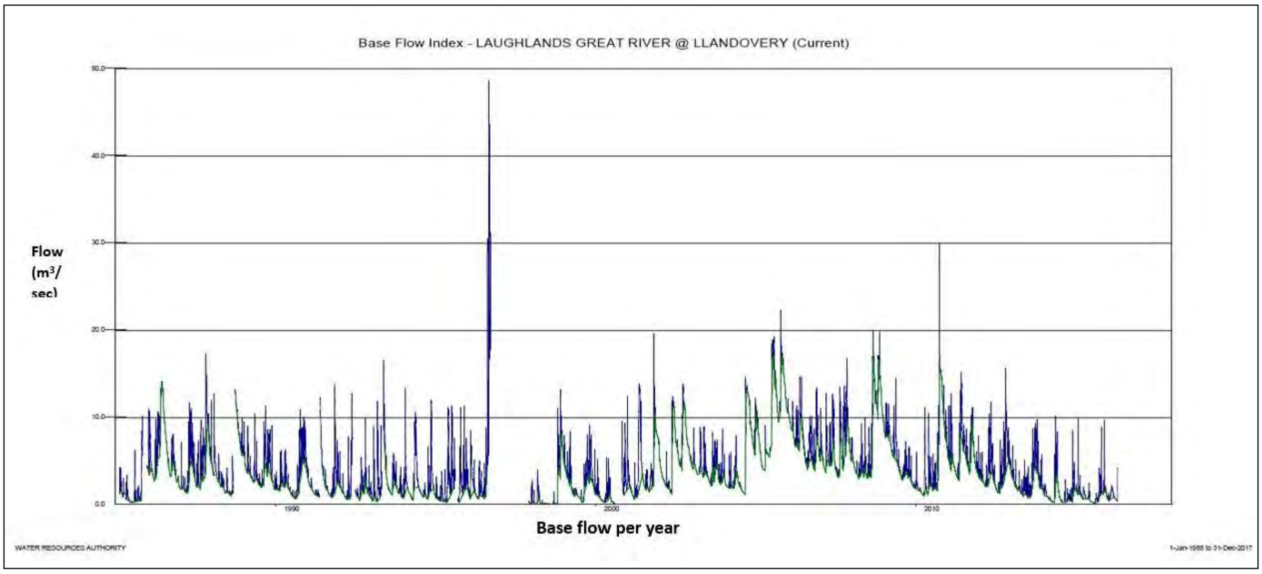
Source: WRA, 2018b

The low flow return period indicates that on average, once every 3-year period, stream flow is 66,700.8 m$^3$/day and this flow magnitude has 69% chance of being exceeded in any given year. For the 10-year return period (*i.e.* 7Q10), low flows of 21,168 m$^3$/day will occur with an exceedance probability in any given year of 89%. The flow of 13,910.4 m$^3$/day has a 50-year return period and an exceedance probability of 98%.

### *Base Flow and Base Flow Index for Laughlands Great River*

The base flow recorded for Laughlands Great River during the study period is 1,080.18 mm/year. For each hydrological year (January to December in this case), the annual BFI was calculated (Figure 5). The BFI calculated for the Laughlands Great River is 0.796 and indicates a relatively high base flow and that this river has a high potential for flow sustainability during periods of low rainfall/drought.

Figure 5. Graph of Base Flow Index for the Laughlands Great River at Llandovery with separated base flow indicated by the green line




Source: WRA, 2018b.

### *Environmental Water Demand for the Laughlands Great River*

Equation 2 is used to determine the EWD for the Laughlands Great River. Therefore, Environmental Water Demand can be interpreted as:

$$
\begin{aligned}
\text{EWD} &= 60\% * 7Q10 \\
&= 60\% * 21{,}168 \text{ m}^3/\text{day} \\
&= 0.6 * 21{,}168 \text{ m}^3/\text{day} \\
&= 12{,}700.8 \text{ m}^3/\text{day}
\end{aligned}
$$

The calculated EWD for the Laughlands Great River is 12,700.8 m$^3$/day. This is the minimum flow that is needed by the source in order to sustain its natural ecosystem.

### *Amount of Surface Water Available as Surplus from the Laughlands Great River*

The amount of surface water available as surplus resource is determined by equation 1.

Available Surface Water = (Q95 - EWD) - Total Allocated Volume

= (31,449.6 $m^3$/day - 12,700.8 $m^3$/day) - 0 $m^3$/day

= 18,748.8 $m^3$/day - 0 $m^3$/day

= 18,748.8 $m^3$/day

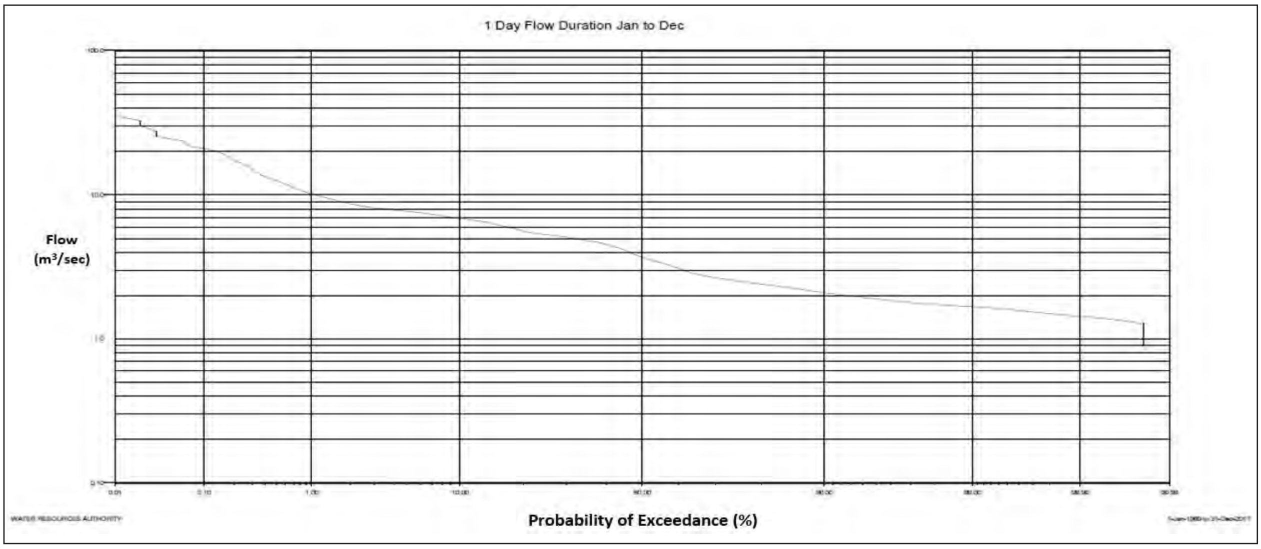
The calculated volume of water that is considered as surplus available flow from the Laughlands Great River is 18,748.8 $m^3$/day.

## ***The White River Flow Analysis and Resource Assessment***

### *Mean Daily Flow and Flow Duration/ Exceedance Frequency for White River*

The mean daily flow for White River at Exchange is 361,411.2 $m^3$/day (132 $Mm^3$/year) for the study period. An average flow of 163,209.6 $m^3$/day (60 $Mm^3$/year) was exceeded 95% (Q95) of the time for the study period (Figure 6). This is a significant low flow indicator and is used to determine the reliable surface yield of the flow from the White River.

Figure 6. Flow Duration Curve of Mean Daily Stream Flow Exceedance Frequency from the White River at Exchange from January 1st, 1951 to December 31st, 2017




Source: WRA, 2018b.

### *Low Flow Frequency Analysis from 7-day minimum mean flows for White River*

A 7-day minimum mean flow analysis for the White River was conducted for the study period. This was used to determine the 3-year, 10-year, and 50-year low flow return periods (Table 4).

Table 4. Low Flow Return Periods for White River

| Low Flow Return Period | 3-year | 10-year | 50-year |
|---|---|---|---|
| 7-day Minimum Mean Flow ($m^3$/day) | 187,920 | 140,400 | 119,145.6 |
| Exceedance Probability | 68% | 90% | 98% |

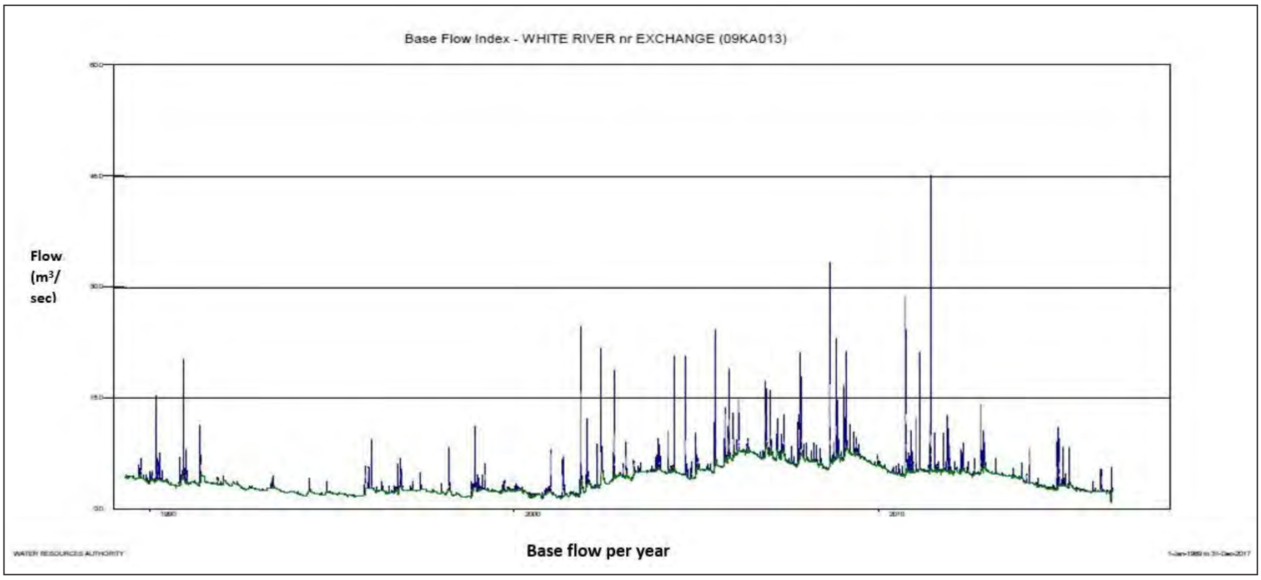
Source: WRA, 2018b.

The low flow return period indicates that on average, once every 3-year period, stream flow is 187,920 $m^3$/day and this flow magnitude has 68% chance of being exceeded in any given year. For the 10-year return period (7Q10), low flow of 140,400 $m^3$/day will occur with an exceedance probability in any given year of 90%. The flow of 119,145.6 $m^3$/day has a 50-year return period and an exceedance probability of 98%.

### *Base Flow and Base Flow Index for White River*

The average annual base flow recorded for White River during the study period is 1,340.78 mm/year. For each hydrological year (January to December in this case), the annual BFI was calculated (Figure 7). The Base Flow Index calculated for White River at Exchange is 0.941 and indicates a significantly high base flow and that this river has a very high potential for flow sustainability during periods of low rainfall/drought.

Figure 7. Graph of Base Flow Index for White River at Exchange with separated base flow indicated by the green line




Source: WRA, 2018b.

*Environmental Water Demand for the White River*

Equation 2 is used to determine the environmental water demand (EWD) for the White River. Therefore, Environmental Water Demand for the White River can be interpreted as:

$$
\begin{aligned}
EWD &= 60\% * 7Q10 \\
&= 60\% * 140{,}400\ m^3/day \\
&= 0.6 * 140{,}400\ m^3/day \\
&= 84{,}240\ m^3/day
\end{aligned}
$$

The calculated EWD for the White River is 84,240 $m^3$/day is the minimum flow that is needed by the source in order to sustain its natural ecosystem.

*Amount of Surface Water Available as Surplus from the White River*

The amount of surface water available as surplus resource from the White River is determined by Equation 1.

$$
\begin{aligned}
\text{Available Surface Water} &= (Q95 - EWD) - \text{Total Allocated Volume} \\
&= (306{,}633.6\ m^3/day - 165{,}732.5\ m^3/day) - 350\ m^3/day \\
&= 140{,}901.1\ m^3/day - 350\ m^3/day \\
&= 140{,}551.1\ m^3/day
\end{aligned}
$$

The calculated volume of water that is considered as surplus available flow from the White River is 140,551.1 $m^3$/day.

### *Why the Dry Harbor Mountains Hydrological Basin?*

This study focuses on hydrological resource availability from of one hydrological basin (from a total of ten) with the potential to supply excess resources. In comparing the water demand versus water allocated and water quality problems of each basin, the Dry Harbor Mountains Hydrological Basin was the most suitable basin to consider for transfer of water. This Basin has the second lowest total allocated volume of 29.5 $Mm^3$/year with no significant water quality problems (Table 5).

In terms of water demand, this Basin has the third highest demand of 220.8 $Mm^3$/year, following Rio Cobre Hydrological Basin with the highest demand of 328 $Mm^3$/year and Rio Minho Hydrological Basin with the second highest demand of 314.6 $Mm^3$/year (WRA, 2011). Other hydrological basins with relatively low water demand either have water quality problems or were located at significantly farther distances. The Kingston Hydrological Basin for example, has a relatively lower water allocated volume of 30.1 $Mm^3$/year and has water quality issues including sewage and saline groundwater contamination. Also, the Martha Brae River Hydrological Basin has the lowest allocated volume of 28.6 $Mm^3$/year but has contamination by dunder in groundwater. The Cabarita Hydrological Basin which also has a relatively low allocated volume of 35 $Mm^3$/year and has no significant water quality problems but is inconveniently located at a relatively far distance (approximately 72 km farther than Dry Harbor Mountains Hydrological Basin). The Blue Mountain North Hydrological Basin has high demands and highly allocated volumes.

Table 5. Water Demand, Allocated Volume and Water Quality Problems for Each Hydrological Basin

| Hydrologic Basin | Water Demand ($Mm^3$/year) | Water Allocated ($Mm^3$/year) | Water quality problems |
|---|---|---|---|
| Dry Harbour Mountain | 220.8 | 29.5 | No significant problems |
| Blue Mountain North | 131 | 192 | No significant problems |
| Martha Brae River | 111.6 | 28.6 | Dunder in Groundwater at Queen of Spain Valley |
| Great River | 65 | 78.3 | No significant problems |
| Cabarita | 179 | 35 | No significant problems |
| Black River | 190 | 85 | Caustic Effluent in groundwater |
| Rio Minho | 314.6 | 42.1 | Saline/Brackish surface water and groundwater |
| Rio Cobre | 328 | 328 | Caustic Effluent in surface and groundwater, saline and / or brackish groundwater |
| Kingston | 89.3 | 30.1 | Sewage contamination in groundwater, saline /brackish groundwater |
| Blue Mountain South | 85.3 | 32.8 | No significant problems |

Source: WRA, 2011.

The Dry Harbor Mountains Hydrological Basin currently has 457.05 $Mm^3$/year of water resources available and has an exploitable total of approximately 394.20 $Mm^3$/year (WRA, 2010); this increases the potential as the supplying source basin. The exploitable water resource within this Basin is deemed to be high even after meeting its 2025 projected demand (WRA, 2012; Clarke, 2018).

### *Surface Water versus Groundwater as Potential Supply Sources*

Within the Dry Harbor Mountains Hydrobasin, the available/exploitable surface water resource is 273 $Mm^3$/year and the available groundwater resource is 369 $Mm^3$/year (WRA, 2005). Although the amount of groundwater resources surpasses that of the surface water resources, the surface water resources were selected for assessment due to their perennial nature. This means that the surface water resources are recharged by both rainfall/surface runoff and stored water/groundwater from the aquifer. This is an important factor when considering the sustainable potential of a source over long periods of time and during low flow or drought periods, as was positively indicated by the base flow and BFI. It is acknowledged that groundwater is also a safe bet in that regard; however, development of groundwater resources for the purposes of water transfer has been proven more complex and costly when compared to the development of surface water resources. Another advantage to the development of surface water resource over groundwater is that surface water development has easier accessibility and will need less maintaining after implementation; which in short is more cost effective and less time-consuming. Thus, surface water resources were preferably considered for hydrological assessments in this study over that of groundwater resources.

### *Selection of the Assessed Surface Water Sources*

The major perennial rivers were considered and only three were selected for the hydrological assessment to determine the surplus. The major perennial rivers in the Dry Harbor Mountains Hydrobasin are White River, Mason River, Cave River, Quashie River, St. Ann's Great River, Rio Bueno, Laughlands Great River, Roaring River, Dunns River, Rio Hoe River, Pear Tree Bottom River, Turtle River, and Blue River (WRA, 2011). The three selected rivers (Rio Bueno, Laughlands Great River, and White River) were chosen based on length and least allocated water resources. The Rio Bueno and the White River are the longest rivers in the hydrological basin; approximately 11.5 km and 28.5 km respectively, and total allocated volumes of 911,612.1 $m^3$/day (333 $Mm^3$/year) and 915,316.12 $m^3$/day (334 $Mm^3$/year) respectively. The Laughlands Great River with a length of approximately 6 km currently has no allocations, thus is considered highly suitable as a supplying source. The selected sources were also considered based on the presence of current and working stream gauges which is important for providing the historical data used to determine the reliable yield and by extent the surplus. Also, an assessment conducted (Thomas, 2000) on the selected sources found them favorable for inter-basin transfer. Results from this study showed that all three rivers have high reliable surface yields and exceedance probabilities.

### *Future Hydrological Sustainability of the Potential Supplying Sources*

The reliable yield calculated for the Rio Bueno, the Laughlands Great River and the White River are 247 $Mm^3$/year, 131 $Mm^3$/year and 132 $Mm^3$/year respectively; with Q95 of 112 $Mm^3$/year, 11 $Mm^3$/year and 60 $Mm^3$/year respectively. The Q95 is therefore interpreted as the minimum volume of water that is expected to be flowing in the river 95% of the time. Precipitation is also taken into consideration as the Dry Harbor Mountains Hydrological Basin receives rainfall between 1,250 mm to 2,250 mm per annum, (mean annual rainfall of 1,672 mm) which is greater than the average rainfall of the Rio Cobre and the Kingston Hydrological Basins which both receive average rainfall between 999 mm to 1,750 mm per annum (WRA, 2005); this recharges the aquifers via infiltration and the rivers via direct runoff. The water demand for the Dry Harbor Mountains Hydrological Basin is 159.4 $Mm^3$/year and is more than compensated for by the other surface and groundwater resources within the Basin. Based on that, it is therefore expected that the selected sources will have enough water resources for self-sustenance after the transfer of the calculated surplus surface water. Also, the base flow and BFI indicates that the sources are indeed capable of sustained flow during droughts and/or low rainfall periods.

### *Plans to Improve Water Efficiency and Use in the Receiving Hydrological Basins*

The unsustainable urban water use in recipient basins is a typical negative aspect of inter-basin transfers and is usually owing to the lack of demand management strategies during pre-planning (Pittock *et al.*, 2009). To prevent negative outcomes from water management plans (including inter-basin transfers), the Government of Jamaica (GOJ) under the Ministry of Economic Growth and Job Creation (MEGJC), have developed a Water Sector Policy and Implementation Plan in alignment with the Vision 2030 development goals for Jamaica. The first three principles and goals of the Jamaican Water Sector Policy include Sustainability, Efficiency and Integrated Water Resources Management (IWRM) (MEGJC, 2018). Plans to improve the efficiency and sustainability of water use include:

- Demand management strategies as a set of coordinated measures to improve water services by inducing changes at point of consumption for water use efficiency. One is the strict utilization of regulatory instruments for allocations and water use limits; for example, rationing through lock-offs done by the National Water Commission (NWC) during droughts and water shortages in the KMA (NWC, 2011).
- Wastewater Management strategies to reduce groundwater use by utilizing treated effluent where possible (such as for irrigation) and to exploit opportunities for groundwater recharge.
- Reduction of non-revenue water by leak-detection and repairs, rainwater harvesting systems and increased storage capacities by addition of new storages; as there currently are only two surface reservoirs in the island (NWC, 2011).

## Conclusions and Recommendations

The issue of projected water shortages and demands in the Rio Cobre and Kingston Hydrological Basins can be mitigated by inter-basin transfer of water from the Dry Harbor Mountains Hydrological Basin. The selected rivers; Rio Bueno, Laughlands Great River and White River in the Dry Harbor Mountain Hydrological Basin have a combined surplus of 267,081 $m^3$/day or 97.5 $Mm^3$/year and is feasible to augment the water supply in the Rio Cobre and Kingston Hydrological Basins without any adverse effects on the hydrological environment.

The findings from this study can also be applied in the next and crucial steps involving the hydrological planning (via IWRM) and implementation of the future proposal and project for inter-basin transfer of water from the selected sources in the Dry Harbor Mountains Hydrological Basin.

The implementation of hydro-electric power generation is to be considered as a secondary output from the conveyance mechanism, as it is one major benefit from inter-basin transfer.

Also, assessment and inclusion of additional surface water sources can be done so as to completely supply or augment water supply to the receiving hydrobasins. This may be from the Dry Harbor Mountains Hydrological basin as well, or from another hydrological basin that can sustainably meet the extra demand for inter-basin transfer of water to Kingston and Rio Cobre Hydrobasins.

Water demand and population growth are correlated, hence a controlled monitoring of population growth in the water-stressed areas and hydrobasins will result in a reduction of the projected water demand. It is thus being recommended that the social and economic development of other parishes be implemented with focus on water demand management, in order to reduce future water demand stress on PMA and KMA.

While benefits of inter-basin transfer include hydropower generation, additional water supply and mitigation against climate change (Pittock *et al.*, 2009); caution is to be of high priority for limitations such as requirement of large financial resources as well as risks and potential impacts to environment and aquatic ecosystems.

## Acknowledgement

Special thanks to colleagues from the Water Resources Authority of Jamaica who provided insight and expertise that greatly assisted this study. I thank Kevin Chambers, Senior Hydrogeologist and Geoffrey Marshall, Chief Hydrologist for assistance with development and writing of the paper. Thanks also to Peter Clarke, Managing Director, Michael Wilson, Deputy Managing Director, and other valued colleagues for comments and assistance that greatly improved the manuscript.

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# Irrigators' commissions: irrigation systems, norms, and obligations

*Abraham Arteta Jaramillo[1]*

**Abstract**

Access to water in Peru is linked to the controls and uses that local populations manage to obtain as a result of the legal regulations enforced by the State to regulate its use. However, the organizational laws that govern water management do not reflect the different realities rural populations in the high Andean areas have to adapt to make efficient and controlled water use for agriculture.

This research presents a case study in which the aim is to analyze the communal organization around water management for irrigation in the rural community of Pongobamba, Peru. The information has been generated by an ethnographic method, remaining and doing on-site work in the community through observations and interviews. The study focused on the village of Pongobamba because it is one of the few communities around the district that maintains its irrigation systems supplied almost all year round. The irrigators' commission is the organizational structure in charge of water management for agricultural use. The commission protects, maintains, and renews the irrigation system from two main natural springs found in the community: Hatun Ñahuin and Huran Ñahuin. The article focuses on this user organization that has set up a series of obligations and rules adopted at community level (the communal agreements) to maintain efficient water use and control for agriculture. However, external factors hamper the improvement of the systems and curtail the community's management capacity.

**Keywords:** Water management, agriculture, communal water management, irrigation systems, irrigation commissions, communal agreements.

## Introduction

Over the decades, water has become a crucial topic to be addressed comprehensively by different disciplines, both scientific and social, sharing experiences and approaches to account for the complexity of water-related social developments (Damonte and Lynch, 2016). In recent years, these approaches have diversified. Water studies have broadened to create room for variables such as gender, climate change, and experiences of water protection and management. Oré and Muñoz (2018) argue that water is once again regarded as a crucial issue due to the number of struggles and conflicts—especially when it comes to communal management and rural environments—resulting from little understanding of the social aspects associated with this resource that goes beyond the technical or physical elements. Therefore, it is necessary to address water issues by acknowledging communal forms of organization to assert and make communal management visible. This is "to assert the rights of the rural/indigenous people themselves and to generate a leading creative capacity in water management: a capacity for analysis and (counter) proposal" (Boelens and Hoogendam 2001: 14).

This study aims to contribute to the analysis of the role of communal governments and user commissions in irrigation water management within the context of climate change, water disputes, and water justice. The main objective is to study the communal organization around irrigation water management in the rural community of Pongobamba. The article begins with a brief description

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of the ethnographic method used. The community, its distinctive features, its irrigation system and the irrigators' commission, were prioritized as the sample. Then there is a discussion about the findings and ideas about water access and use in the community, based on their adoption of state frameworks, agreements, and interactions with different stakeholders. And to conclude, it is argued that the communal organization allows for other forms of organization based on the users' commission and their communal agreements to maintain and improve water management for agriculture at the community level.

## Methodology

This article is a case study that seeks to explain and analyze community organization structures for irrigation water access and management within the community. The ethnographic method was used to understand the social aspects and processes through the perspectives of the members of the unit of analysis (Guber, 2001). The fieldwork was undertaken in two stages: the first was a scoping field trip in 2018, and the second was a stay in the community for two months between March and May 2019. The fieldwork trips made it possible to observe different community decision-making settings, such as the community's and the irrigation commission's general meetings. It was also possible to interact with community members and visit the community's natural springs, the canals, and the Piuray Lake. Information gathering tools have focused on understanding the community organization and water management structures. Thus, among the activities carried out were open and semi-structured interviews, conversations, tours of the canals, mapping, and participatory activities.

### *Pongobamba rural community: an approximation to the settings under study*

The case study focuses on the Pongobamba community located in the Chinchero district in the province of Urubamba, in the Cusco department, at altitudes between 3,700 and 4,100 meters above sea level. This community is part of the Piuray Ccorimarca microbasin, along with 22 other communities, sectors, and associations. The Piuray Lake is the main body of water in the microbasin, and it is part of the drinking water supply system for the city of Cusco. The surrounding population regards this water source as "essential for life, food security, and local culture development, as it is their main resource and livelihood" (Estrada, 2016).

The Pongobamba community has approximately 375 cultivated hectares divided among its 452 inhabitants (INEI, 2017). The area consists of small peat bogs, flat farming areas, terraces, and grazing areas. In ancient times, disasters such as floods, landslides, and *huaycos* (other mass movements such as mudslides and flash floods), among others, were frequent. On more than one occasion, depending on the intensity of the disaster, these caused severe problems. In the late 1990s, a number of landslides caused the loss of more than 10 hectares in Pongobamba and other adjacent areas (Estrada, 2016). According to the communities and studies, these could be explained by several reasons: 1) The overexploitation of resources (land and water) and 2) the impact of climate change. However, recent years' efforts, together with project interventions (among which PRONAMACHCS,[2] ARARIWA[3], and recently the CBC[4] stand out), have focused on adaptation and mitigation strategies to address the effects of climate change on the community's natural resources. They have done so through infiltration trenches, planting of native species, and the adoption of strategies such as the prohibition of grazing to reduce the impact on land degradation in recent years and water regulation policies (Estrada, 2016; Vogel, Rojas and Sallo, 2003).

What makes Pongobamba particularly special and why there is a special focus on the strategies deployed is that it is one of the communities (if not the only one) around the micro-basin that keeps its irrigation systems supplied almost all year round based on the protection and management of two natural springs: Huran Ñahuin (lower natural spring) and Hatun Ñahuin (larger natural spring). The Hatun Ñahuin-Pumapata water users' commission is in charge of enhancing and maintaining the efficiency and control of the water used from these sources, as it is the basis for agriculture in the community. The commission is consists of three committees (Simachayoq, T'anqarmayo, and Pumapata), and they are in charge of organizing the irrigation system and irrigators in the community.

The strategies developed by the water users' commission are underpinned by communal agreements, which are the obligations taken within the communities to manage any resources. These agreements oversee issues such as the maintenance, obligations, and penalties linked to irrigation systems. For the registered users, these agreements involve the participation in annual and sectorial tasks to keep the canals and water sources clean. The irrigation system is based on gravity irrigation and turn-taking. Each user must sign up for their slot with the *tomero*[5]. The community establishes the slots, and the users have to wait for their turn to irrigate. Under another communal agreement, users discuss and set water use rates. The meetings are scheduled in advance to discuss the price that each user will pay for the water license granted by the National Water Authority. These agreements are binding, and there are different penalties established in the event of breaches or violations of any of the above.

However, the findings show that in recent years there has been a decrease in the number of registered irrigators (Table 1). These community members do not participate in all the agreements but still use the water for irrigation. Even though they are not part of the communal systems, they use other mechanisms to access the community's irrigation system.

2 The National Program for Basin Management and Soil Conservation (PRONAMACHCS), under the Ministry of Agriculture, has carried out technical projects and interventions to promote sustainable economic and social development of rural institutions and organizations.

3 ARARIWA is a development institution that seeks to improve the conditions and quality of life of vulnerable populations in rural areas. It is mainly located in Cusco.

4 Bartolomé de las Casas Regional Studies Center (CBC) is a non-profit civil association that seeks to promote and encourage the study and support of the Andean rural world taking into account its past, present and possibilities for the future.

5 Tomeros are community positions directly related to the irrigation water use organizations. Their main role in the community and commission is to compile the user list and assign their slots to use the water from the water sources. Community members view *tomeros* as clerks: they are in charge of counting those who register daily, enroll, validate and sign them up for the water use slots that are scheduled and carried out each day.

Table 1. Registry of irrigators enrolled since 2002 to date.

| | Men | Women | Total |
|---|---|---|---|
| Current registry[6] | 108 | 71 | 179 |
| 2013 Registry | 221 | 71 | 292 |
| 2002 Registry | 270 | 61 | 329 |

Source: Compiled by the authors. Based on information collected and provided by the community.

## Results and discussion

As mentioned before, the results of this study show that the main role of the Hatun Ñahuin-Pumapata Water Users' Commission is to run, look after and preserve the water infrastructure (both water sources and canals), oversee water distribution for agricultural purposes (irrigation), and to collect and manage the water fees for registered users. However, it should be noted that the community user commission (and the communities in general) have had to adapt to the Water Resources Law No. 29,338 of 2009. The State has begun to acknowledge the rural and non-rural user organizations as necessary institutional structures for integrated, participatory, and multisectoral water management. They are conceived as "civil associations that work towards the organized participation of users in the multisectoral management and sustainable use of water resources" (Law No. 29,338 Art. 27, 2009), and they are part of the National Water Resources Management System. These adaptation processes comprise the creation of commissions and committees (at lower levels) to be able to issue licenses to use the water sources in the communities. This law and its derivatives help community structures and organizational forms integrate vertically thanks However, users already have mechanisms in place for efficient use and monitoring based on customary or social practices and assemblies rather than on written laws (Guevara, 2014; Oré, 2005; Boelens and Hoogendam, 2001).

Because of the above, community water management in communal settings has been under constant pressure due to state bureaucracy, laws, and development/intervention projects with top-down approaches that conceive water as an economic commodity (Zwarteveen and Boelens, 2014). Instead, the nature of water entails more complex aspects than the economic factors alone. There are cultural (perceptions, beliefs) and political (water authorities) aspects that redefine the character and governance of this resource (Boelens, 2014; Zwarteveen and Boelens, 2014). In Peru, this has been done through assimilation and higher authorities that regulate water resources. The State has fostered a sort of hierarchy among agricultural user organizations to keep them under their control. Irrigators committees are regarded as the smallest unit of user organization. They can register in a user commission in their area or community, and, lastly, the user commissions or irrigators' commissions can organize in user boards. With regards to farming activities, these organizations—at the commission or committee levels—are the ones that have to make the arrangements to obtain authorizations or licenses to use communal water sources. These permits are usually complicated due to their technical specifications and the production level required and fail to address the fact that water use in many rural communities is devoted to family farming and exchange.

Even considering the different legal hurdles that the communities and their organizations have to go through, user commissions such as those in Pongobamba can be taken as an example for the improvements and maintenance work they do to achieve efficient water use and control for

6 These are estimated figures. Although the information on the table is documented, there was a higher count in many of the activities (192 approximately).

agriculture. These strategies focus on the commission's role as the main pillar to preserve the infrastructures, irrigation method, and community agreements.

In terms of infrastructure, all the users who belong to the irrigation commission must commit to different tasks. For example, it is mandatory to clean the canals, which is done collectively. The main canals are cleaned once a year, but smaller cleaning tasks are also carried out in the canals near each user's home or plot. These tasks are a way of renewing and maintaining the commission members' user status, which is essential to keep their access to water as a user and for irrigation under the communal agreements' provisions.

The users' commission is also responsible for irrigation management to preserve and improve water management efficiency. Gravity irrigation is still used, and although many of the canals are natural (soil), in recent years, the commissions have arranged with external actors, such as the Municipality, among others, to build concrete canals to improve water flow and availability. In the past, it would take about two hours for water to flow downstream from the natural springs to the community members' plots. Thanks to these concrete canals, water availability has increased, and the flow time has dropped to less than 40 minutes. Through the irrigation lists and user slot allocation, irrigation management is essential for the community so that water is equitably distributed among users throughout the irrigation seasons. This way, considering a context of scarcity and climate change, each community member can use water in small amounts and in an orderly manner to irrigate the land throughout the different agricultural periods.

The roles appointed to the irrigators' commission show the importance of the regulations established by communal agreements, for example, the provisions allocating irrigation slots and members' involvement in the different tasks. The agreements establish the irrigation system's particularities, defining who the water beneficiaries are, when to use it and through which means they will have access to this resource (fulfilling collective work tasks, payments, etc.). Communal agreements are negotiated in assemblies where each party has the right to participate, notify and define the obligations and penalties to be imposed since they are also a critical component of the system.

Although the Hatun Ñahuin-Pumapata Water Users' Commission is the organization that implements these strategies to preserve and improve water use for agriculture, it is noted that the number of registered users has decreased over the years (Table 1). On the one hand, the number of men has decreased considerably and, on the other hand, the number of women has increased slightly and stayed the same. This should be analyzed thoroughly paying attention to the circumstances of the people who left the commission. There are several possible answers as to why this happens. First, many people no longer own any land in the community due to land sales, migration, or other circumstances, so they do not need to be registered in the commission. Second, irrigation systems should be considered systems interconnected through canals and catchment centers that do not belong to one community exclusively. Therefore, neighboring communities may have their own commissions with their own lists and communal agreements. And third, although the registration of the community members in the Pongobamba users' commission lists provides formal access to water for irrigation, this is not the only way to gain access to water.

It is worth mentioning that Ribot and Peluso (2003) stress that access to water is not only defined by the regulations or authorizations around this resource, but it is also defined by the power relations between the people and groups that coexist in the same environment. Thus, people who live in the same environment but are not part of the same circle may use different mechanisms to access this resource. In the Pongobamba community, many people have access to irrigation because they are "community members," which is their rooted social identity or because they can prove that they are related to someone with land in the community. Others gain access by using technologies such as carriages or other tools that allow them to reach the canals and irrigate their land at specific hours and know when to irrigate without being penalized. These alternative forms of access to water for irrigation take place at times when there is little surveillance capacity in the community, for example, at night. Slot allocation systems, which should typically be used to control water use, are left aside to take advantage of the canals by blocking the water, preventing it from accumulating overnight, and reducing the levels of the water sources[7] used by the community.

Among all these results and information collected, it is especially worth highlighting the role of the Pongobamba community users' committee in maintaining efficient control of the use of water for agriculture and the organizational and infrastructure enhancement capacities developed to improve the irrigation system. Given the low water levels in the area and in the community itself, Pongobamba is acknowledged by all the surrounding communities in the micro-basin as a community that safeguards its resources and "has water availability" in times of drought. When agriculture in the area is not very productive, they manage to maintain efficient irrigation at the natural spring and family farming levels.[8] The outlook for natural resources in the community and micro-basin is uncertain due to external factors such as pollution and climate change, and unpredictability. The community is also affected by the impact of projects that seek to obtain drinking water supply from the micro-basin sources. Furthermore, the airport's potential construction in the Chinchero district (Moscoso, 2019; Hidalgo, 2019) would demand a considerable amount of water, increasing the struggle of the rural communities in the area.

It is important to understand that the communities' user organizations are not the only institutional structures in place for water management. They work together with different institutions organized with or around them. The community of Pongobamba has set up the Hatun Ñahuin-Pumapata Water Users Commission, a communal organization responsible for water management for agriculture and irrigation. However, it is also part of the Piuray Ccorimarca micro-basin. The State recognizes this community, and it works with the Municipality of Chinchero and private institutions. Thus, there is interaction and coordination among these stakeholders as they are each part of a larger system that affects water management. Sometimes this interplay leads to improvements in the organization by protecting resources and implementing positive agricultural intervention projects for the community. Yet, this situation leads to clashes, controversy, and tensions.

## Conclusions

As previously stated, through communal organization, users coordinate commissions to arrange water access and use for irrigation. Thus, communal agreements are set forth to a) coordinate the participation in annual and sectoral tasks for canal and water sources maintenance, b) define proper means to access and use irrigation through slot allocation, c) discuss and determine water use rates, and d) establish penalties in case of violations or non-compliance with any of the above. These communal agreements help the community itself keep a balanced use and surveillance of water for agriculture. They also help improve efficiency in terms of distribution, availability, and order, thanks to changes in infrastructure and the obligations and penalties set forth to enforce compliance with irrigation conditions. Thanks to the irrigation conditions implemented by the irrigators' commission and the communal agreements that preserve and enhance efficiency in

7 Community members mentioned that water levels were around 18 liters per second. We are talking about water levels that are already low considering that gravity irrigation is in place (water efficiency dropped about 60% or more), distributed through soil canals (concrete only in the upper sections) and over 300 hectares to irrigate.

8 Agriculture for family consumption. Exchange of products among family members and acquaintances. Little or no market sales.

the use of the little amount of water available in these lands, the members of the community can farm their own food, even if it is just at a family farming scale. The current water level is low, and although it could be improved with new techniques, infrastructure, and technologies, it is currently distributed efficiently thanks to the communal agreements and thanks to the strategies carried out by the irrigators' commission. However, the commission is not the only means to gain water access for irrigation, nor is it the only actor within the irrigation systems. Non-registered users undermine the capacity to sustain and improve water use efficiency because they irrigate at times that are not permitted, for example, at night, and use unauthorized means (covering canals outside the time slots allocated) that reduce the amount of water available and prevent water accumulation in the canals and sources. Additionally, the diversity of actors and roles found in the micro-basin and within the community itself leads to tensions and disagreements that cause uncertainty and hinder community development.

It is essential to understand that the irrigation systems in rural communities are closely linked to the forms of organization that revolve around water for agriculture and the different approaches surrounding it. Therefore, it is important to stress that many times projects or laws fail to be adopted by the communities due to the way how they are introduced. The approaches are sometimes paternalistic and attempt to restructure all previous forms of organization in a way that is not sustainable in time or because water is only conceived as an economic commodity to increase agricultural productivity to enter the market. The aim is to understand the concept of water as a source of life in its social and cultural dimensions to build participatory models of sustainable development around water and agriculture for families and their communities.

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# Calibration of the FAO-PM equation to determine ETo and optimize water use in greenhouses in the high Andes

*Clara Butrón Mamani[1] and Magali García Cárdenas[2]*

**Abstract**

In dry, high Andean tropical areas such as the Bolivian Altiplano, greenhouse crop management can be beneficial as it reduces the impact of adverse events such as frost and drought. Greenhouse crops always require irrigation, and therefore it is necessary to determine water needs. This value is calculated by quantifying the reference evapotranspiration (ETo) of each particular area, which, in turn, depends on the availability of meteorological information for greenhouses. The lack of accurate ETo values reduces the efficiency of irrigation planning and application. ETo can be calculated accurately using the FAO-Penman-Monteith (FAO P-M) equation, but this equation was not developed or calibrated for greenhouses. In this study, the FAO P-M equation was calibrated to determine ETo in greenhouses in a tropical, high-Andean area, and we looked for alternatives to deal with the lack of data to be able to calculate ETo under these conditions. The ETo in the greenhouse was determined by installing lysimeters that simulated the reference crop and had meteorological stations. These data were used to calculate the ETo with the FAO P-M equation, comparing the reference crop consumption values with the ETo calculated. Finally, we focused on finding a solution to the lack of greenhouse meteorological data, estimating a correction to the data of open-air stations in the same area where the greenhouses are located. Solar radiation determines ETo in greenhouses, and it can be accurately estimated with open-air data. The greenhouse ETo—calculated with the FAO P-M equation using only estimated solar radiation data—shows a correlation coefficient of 0.93 compared to the ETo calculated with actual data, which proves the feasibility. Crop water consumption in high-Andean areas can be reduced by up to 40% using well-managed greenhouses.

**Keywords**: Greenhouse, reference evapotranspiration, irrigation, efficiency

## Introduction

Arid areas require an intense water-saving program for agriculture, not only due to the ever-present water deficit but also due to the impact of global warming. Agricultural activity in the high tropical Bolivian Andes, typically arid, is generally concentrated in the summer. It depends heavily on the start, duration, and end of the rainy season. This season determines the availability of water and the higher, or lower, risk of radiation frosts. The few attempts there have been to implement irrigation systems have clashed with the resource's low availability, both from surface and underground sources. Given this situation, high dependence on extreme weather events, and their potential intensification in the future, it is necessary to look for productive alternatives to address the combined effect of low temperatures and low water availability.

Greenhouses are used in agricultural production in many countries since they adapt to difficult areas and weather conditions and make it possible to adapt and control environmental conditions for better crop development and intensification. Also, greenhouses are one of the solutions to the water scarcity problem worldwide as these use controlled irrigation systems that allow for more efficient use of this resource (Valera, 2013).

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However, crop water requirements, which are generally difficult to estimate, are more complex in greenhouses. The energy balance is different to open-air settings and even more so in the highlands, where local research is virtually non-existent.

The water requirement is associated with evapotranspiration (ET) in a given environment and crop management type (Pereira et al., 2010). To determine ET, it is necessary to accurately estimate the reference evapotranspiration (ETo) value in each area. In turn, the potential estimation alternatives are subject to the availability of meteorological information in each region. Therefore, ETo is a weather index associated with the area under study (Trezza, 2008).

The main problem for irrigation planning in controlled environments is that there is a lack of ETo data. This parameter has not been sufficiently studied due to the limited availability of quality meteorological data within these environments. Although it can be calculated with little data using the FAO-P-M equation (Allen et al., 2006), in many cases, the only meteorological information available is that from outside the greenhouse.

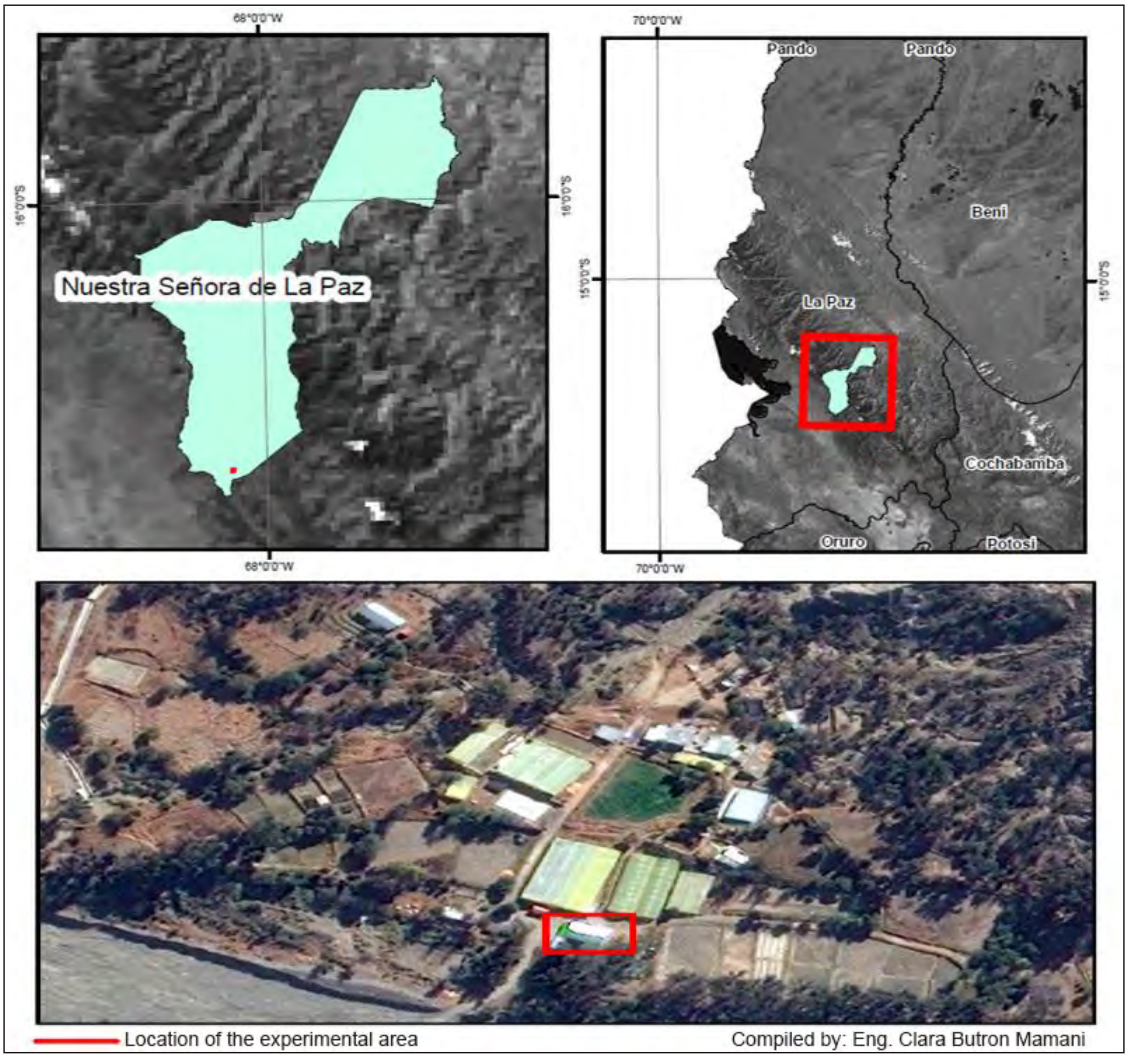
## Objective:

This study seeks to calibrate the FAO P-M equation to calculate the ETo under greenhouse conditions in a high-Andean area in Bolivia (3,400 m a.s.l.) by describing the dynamics of the energy and aerodynamic components of the equation inside the greenhouse compared with a grass crop that simulates the reference crop defined for the equation. Finally, we considered the feasibility of using correction factors to calculate the FAO P-M equation with open-air data for irrigated agriculture under temperate conditions in tropical highlands.

## Methodology

This research study was undertaken in greenhouses at the Experimental Center of the Higher University of San Andres (UMSA) in the department of La Paz, Bolivia (Figure 1), located about 20 km from the city center of La Paz. The Experimental Center is located at latitude 16°32’09’’ south and longitude 68°03’48.7’’ west, and an altitude of approximately 3,500 m a.s.l. The assessment was carried out between February and July 2015.

Figure 1. Location of the Experimental Center where the study was undertaken located at 3,500 m a.s.l..




Source: Compiled by the authors based on Google Earth.

### *Research planning*

For this research, we built a 10 m x 6.7 m greenhouse. We installed a lysimeter to measure the soil water balance of a green grass surface similar to the reference crop growing optimally without water or nutrient limitations. The soil water balance made it possible to calculate ryegrass water consumption (mm) throughout the period, which approximates the ETo inside the greenhouse. We also included four drainage microlysimeters to measure the ETo in the field in an area of 0.209 $m^2$. The lysimeters were distributed in adjacent greenhouses (main and control samples). The Soil Water Balance equation was applied to all the lysimeters. Considering that rainfall inside the greenhouse is zero, the equation can be simplified as follows:

$$ET = R - D - \Delta S$$

Where R is the irrigation, ΔS is the moisture difference in the soil during the period, and D is the drainage.

### *Weather and soil station monitoring*

We installed three full Vantage Pro 2 Davis automatic weather stations and three soil stations with soil moisture sensors and stainless steel soil temperature sensors. The first weather and soil station was installed outdoors, and the other two were installed in the monitoring greenhouses, both close to the main lysimeter and the microlysimeters.

### *Calculating ETo with the FAO P-M equation*

We used the FAO P-M equation to determine the hypothetical values of the ETo (Allen et al., 2006) based on the meteorological information from the stations installed, both in the greenhouses and outdoors.

$$ETo = \frac{0{,}408\, \Delta\, (R_n - G) + \gamma\, \frac{900}{T + 273}\, u_2\, (e_s - e_a)}{\Delta + \gamma\, (1 + 0{,}34\, u_2)} \tag{3}$$

Where ETo is the reference evapotranspiration (mm day-$^{1}$), Rn is the net radiation over the crop surface (MJ m$^{-2}$ day$^{-1}$), G is the soil heat flow (MJ m$^{-2}$ day$^{-1}$), T is the mean air temperature (°C) at 2 m height above ground, $u_2$ is the wind speed (m s$^{-1}$) at 2 m height above ground, ($e_s$) is the saturation vapor pressure (kPa), ($e_a$) is the actual vapor pressure (kPa), ($e_s$ – $e_a$) is the vapor pressure deficit (kPa), $\Delta$ is the vapor pressure curve (kPa °C-1), and $\gamma$ is the psychometric constant (kPa °C$^{-1}$).

ETo analysis was done through a simple regression between the values calculated with the FAO P-M equation and the associated weather variables.

## Results and discussion

### *Meteorological data inside and outside the greenhouse*

Table 1 shows the monthly mean weather values for the period under study in the open air (outdoors) and greenhouse conditions (indoors). We can clearly see the greenhouse effect on temperature levels, which increased by about 90% compared to open field conditions. This is due to the typically tropical latitude with intense radiation reception that is significantly absorbed and retained. At the same time, the atmospheric humidity is very high due to reduced mixed air, while the mostly diffuse radiation is lower compared to the outside.

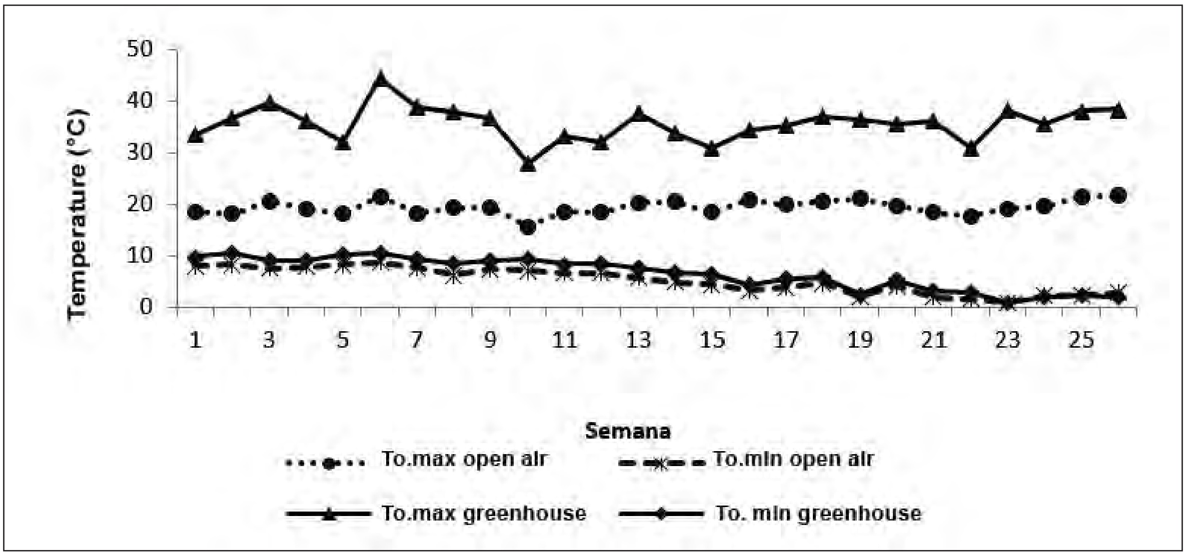
Table 1. Monthly mean temperature, relative air humidity, solar radiation, wind speed, and reference evapotranspiration calculated using the FAO P-M equation.

| Period | Temperature (°C) | | Actual vapor pressure $e_a$ (kPa) | | Solar radiation (MJ $m^{-2}$) | | Wind speed (m $s^{-1}$) | | ETo (mm.$month^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Outside | Inside | Outside | Inside | Outside | Inside | Outside | Inside | Outside | Inside |
| February | 13.5 | 22.9 | 0.97 | 2.13 | 19.9 | 7.7 | 0.7 | 0 | 100.36 | 54.83 |
| March | 13.5 | 23.7 | 0.97 | 2.31 | 18.7 | 7.1 | 0.5 | 0 | 102.11 | 57.71 |
| April | 12.6 | 21.0 | 0.95 | 1.93 | 15.6 | 6.2 | 0.2 | 0 | 78.12 | 47.57 |
| May | 12.2 | 20.2 | 0.64 | 1.51 | 17.3 | 6.8 | 0.1 | 0 | 74.33 | 47.88 |
| June | 11.6 | 20.2 | 0.58 | 1.40 | 17.1 | 7.0 | 0.1 | 0 | 64.48 | 44.91 |
| July | 10.9 | 19.0 | 0.44 | 1.30 | 16.9 | 6.5 | 0.3 | 0 | 70.79 | 44.92 |

Source: Compiled by the authors based on field findings.

The average temperature values shown in Table 2 contrast with the similarity between the minimum temperatures and the significant difference between the maximum temperatures inside and outside the greenhouse. This indicates that the greenhouse causes a substantial energy gain, clearly expressed by the Tmax. Sousa et al. (2002), Boueri and Lunardi (2006, cited in De Andrade, 2011) report that the average temperature in the greenhouse is only 17% higher compared the outside, which means that, in this case, it should only be 3.3°C higher, which does not match the field data collected. The Tmin value differences are not significant, showing that energy loss at night is high both inside and outside the greenhouse. This is the result of the tropical latitude with almost perpendicular radiation reception during most of the day. This is worth noting as it may also be relevant for other purposes.

Figure 2. Weekly maximum and minimum temperature values under greenhouse and open-air conditions.




Source: Compiled by the authors based on field findings.

The average temperature range of weekly maximum and minimum temperatures outdoors was 14.2 °C. In contrast, inside the greenhouse, the average temperature range was 29.2 °C due to the energy accumulated during the day (Tmax) and a lower energy loss during the night (Tmin). Barrientos (2011) has already reported this for Altiplano greenhouses and showed that, if poorly managed, greenhouses could produce even lower temperatures during the night than those in the open air.

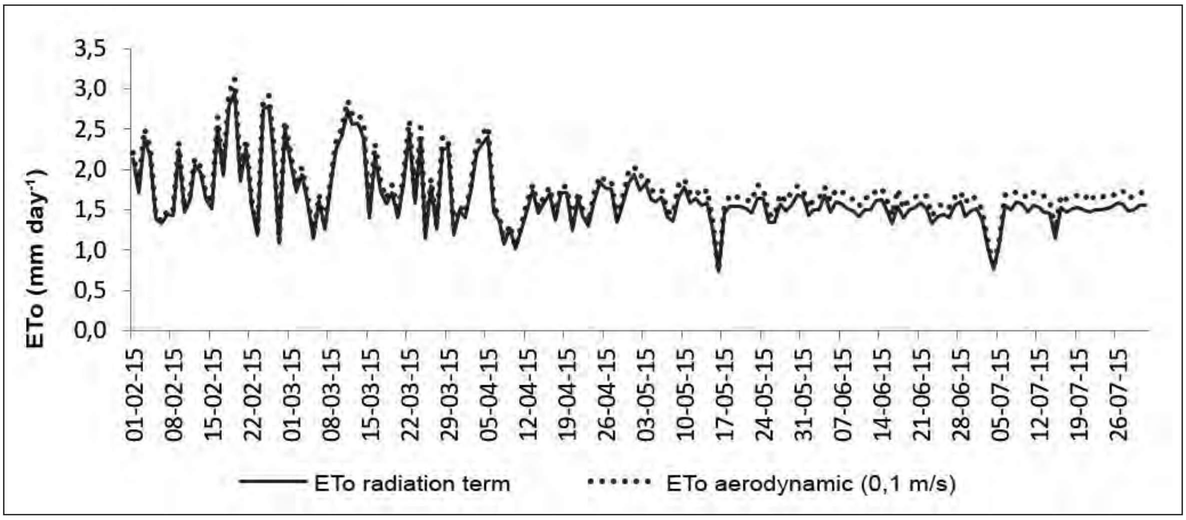
### *ETo behavior and contribution of the radiation and aerodynamic terms in the FAO P-M equation inside the greenhouse.*

The dotted line in Figure 3 shows the daily ETo value calculated with the FAO P-M equation at a wind speed of 0.1 m $s^{-1,}$ which represents a location with very low wind speed. The Figure shows that ETo values inside the greenhouse range between 1.5 and 2 mm/day, with more significant variation during the summer than winter months. During the summer months, daily variations in cloud conditions and rainfall could explain the sharp changes in ETo. Since this is a radiation-dependent value, cloud cover factors could cause a decrease in radiation levels. However, sunshine and cloud cover levels are more stable in the winter, reflected in a lower variability of the ETo.

The calculated values show that the evaporation demand of the atmosphere (ETo) inside a greenhouse is low, which agrees with efficient water use in these environments since their productivity is high.

There are two parts to the FAO P-M equation to calculate the ETo: the radiation term, which mainly takes into account the energy provided by solar radiation for evapotranspiration; and the aerodynamic term, which shows the air behavior as a receptor of the water vapor lost by the plant, as a function of wind speed and vapor pressure deficit that promote evapotranspiration. To evaluate the importance of the two main components within the greenhouse, we used the FAO P-M equation to calculate the ETo, both calculated as the sum of its two expressions and calculated only with the radiation term for the months under study (Figure 3).

Figure 3. Calculated ETo values, including only the radiation term and including both terms under greenhouse conditions.




Source: Compiled by the authors based on field findings.

The ETo behavior calculated with both terms (radiation and aerodynamic) is very similar to that calculated with the radiation term alone since the wind speed in the greenhouse is close to zero. It is only influenced by the internal ventilation, which causes a very small water vapor pressure deficit in the air since it is very low. Also, these results essentially show that evapotranspiration within a temperate environment is defined by radiation energy. This goes to show how important it is to estimate it accurately since it will determine water consumption.

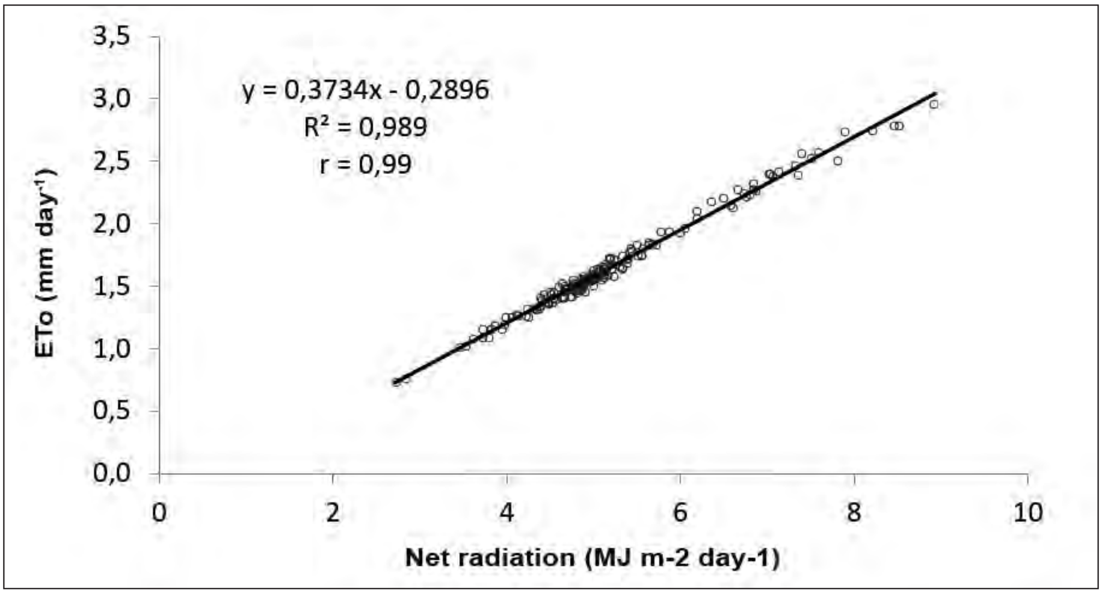
The relative importance of the aerodynamic term becomes evident, although overall it is still very low, it slightly increases in winter. This effect agrees with weather dynamics since the lower atmospheric humidity in the area occurs precisely when the aerodynamic term increases.

### *Dynamics of the radiation term*

The maximum solar radiation received inside the greenhouses was recorded in February and March. In June and July, the dry season, solar radiation inside the greenhouses is on average 37.6% lower. In this regard, Allen et al. (2006) state that the potential amount of radiation that can reach an evaporating surface is determined by its location and time of year. In this case, despite differences, the amount of solar radiation received is substantial, even in those months when there is lower reception due to the tropical latitude.

The correlation between net radiation inside the greenhouse and ETo (r = 0.99) indicates a strong relationship for both variables (Figure 4). The $r^2$ suggests that 98% of the ETo depends on the solar radiation received inside the greenhouse since wind speed inside this controlled environment is very low or non-existent. Esmeral (2011) indicates that the study carried out by Jolliet and Baileya (1992) on the effects of climate on transpiration in a greenhouse crop suggests that the transpiration rate in a greenhouse increases linearly with solar radiation. They also found that air temperature and $CO_2$ concentration do not have a significant impact.

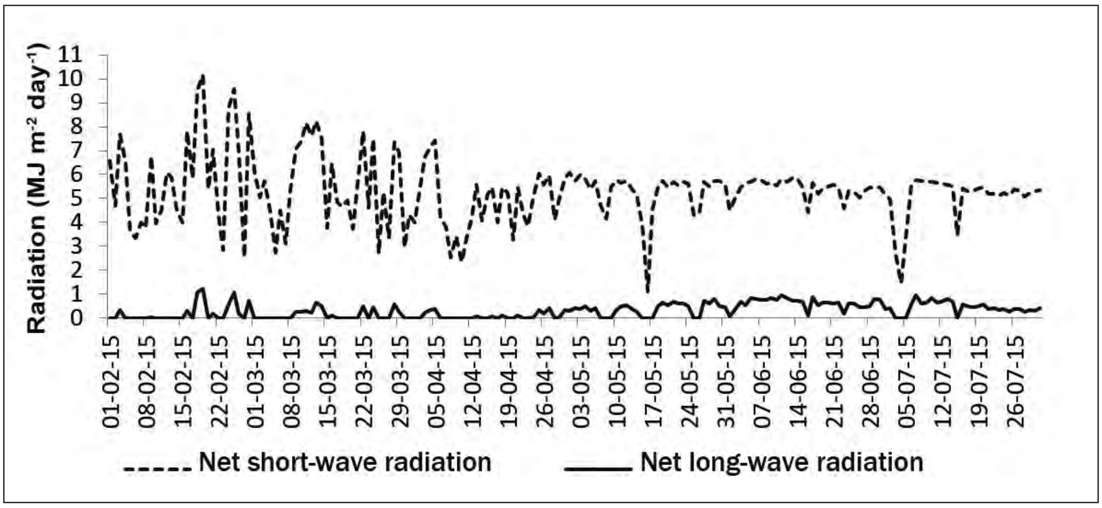
Figure 4. Correlation and linear regression between net radiation and ETo inside the greenhouse.




Source: Compiled by the authors based on field findings.

Net radiation components (net short-wave radiation balance minus net long-wave radiation balance) show a significant difference (Figure 5). Therefore, temperatures inside the greenhouse are higher due to the fact that there is practically no ground radiation loss, which causes energy accumulation, resulting in heat accumulation and temperature increase.

Figure 5. Greenhouse behavior of short-wave and long-wave balance.

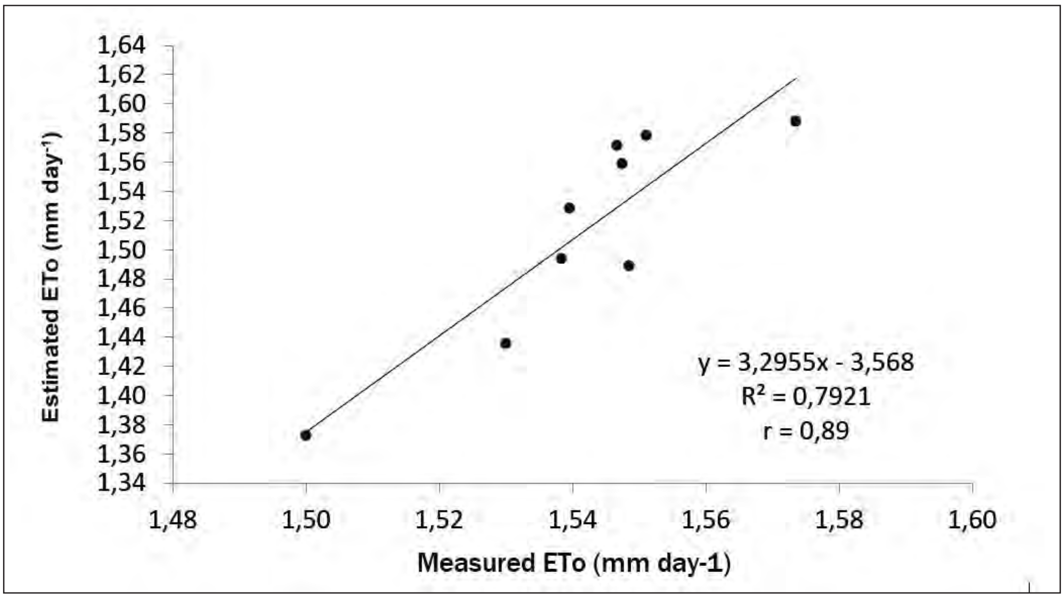



Source: Compiled by the authors based on field findings.

### *Lysimeter evaluation of ryegrass water consumption*

Ryegrass (crop that simulates the hypothetical reference crop) water consumption is measured using a lysimeter inside the greenhouse. It has a high correlation with the values calculated with the FAO P-M equation (Figure 6). This not only shows that the equation accurately calculates ETo values in the greenhouse, but it also confirms that water consumption inside controlled environments is low.

Figure 6. Daily reference evapotranspiration (monthly averages), estimated with the FAO P-M equation, and evapotranspiration measured with a lysimeter inside the greenhouse.




Source: Compiled by the authors.

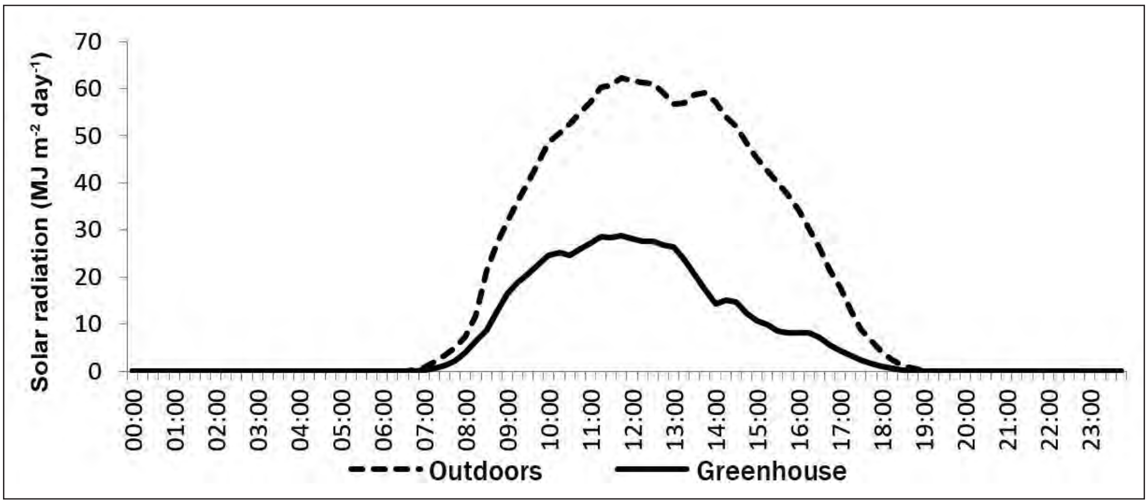
The correlation between the ETo measured and the ETo calculated with the FAO P-M equation is high. This shows that the ETo values obtained with the FAO P-M equation are validated with the ETo values found with the direct lysimeter method inside the greenhouse and that the equation can be used inside greenhouses if sufficient weather information is available.

***Relationship between the ryegrass water consumption and the factors that determine the ETo values calculated with the FAO P-M equation.***

Grass water consumption is physically determined by the same variables involved in the FAO P-M equation. As shown above, solar radiation is the primary indicator of ETo in a greenhouse, and this is why we present an analysis of its behavior.

The insulating material transmits solar radiation inside a greenhouse. In the case under study, the insulating material is plastic. The radiation transmission produced by this material determines the energy available for the evapotranspiration of the grass. This is why Figure 7 shows the greenhouse plastic transmission level (proportion of external solar radiation that penetrates inside the greenhouse).

Figure 7. Behavior of solar radiation under open-air and greenhouse conditions




Source: Compiled by the authors based on field findings.

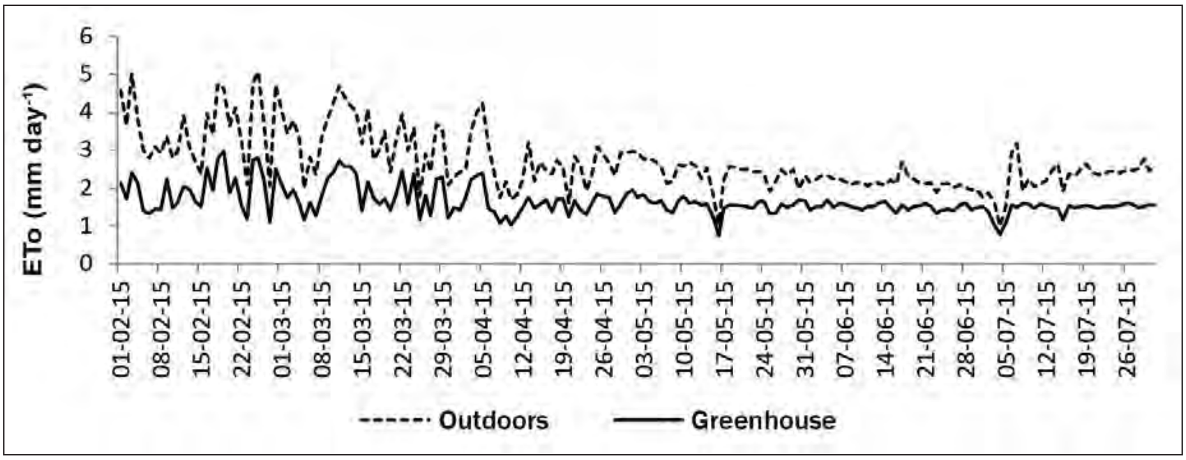
The daily solar radiation received inside the greenhouse was on average 60.7% lower than the one measured in the open air for the period under study. Similarly, in a recent greenhouse study at the Mexican Institute of Water Technology (IMTA), Pacheco et al. (2014) concluded that the solar radiation inside a greenhouse was 51% lower than the solar radiation measured outside. The behavior and the difference in the solar radiation transmitted inside the greenhouse during the course of a day show that the most significant differences occur during the hours of more sunlight exposure when the solar radiation directly received outside the greenhouse is significantly lower. In this regard, Sentelhas (2001, cited in Fernandes et al. 2003) indicates that the plastic used in greenhouses significantly changes the radiation balance with respect to the external environment. This is due to the attenuation (absorption and reflection) of incident solar radiation, which reduces the internal radiation balance that transforms into diffuse radiation, which, consequently, impacts evapotranspiration. Diffuse radiation is adirectional and causes greater spatial uniformity within the greenhouse. Other authors cited by Lorenzo (2012) have stated that increasing the diffuse portion increases the radiation absorbed by the crop, radiation use efficiency (RUE), and crop productivity. Therefore, diffuse radiation produces the best photosynthetic efficiency, and this is why greenhouse crops increase their productivity.

This study shows that greenhouses in high altitude areas in the tropics are particularly useful and highly efficient. This is because the large amount of direct radiation received in high altitude areas is attenuated and transmitted as diffuse radiation, providing high photosynthetic efficiency with lower evapotranspiration demand. Thus, it is possible to produce more using a smaller amount of water, which provides a great comparative advantage in relation to other latitudes.

### *ETo behavior in open-air and greenhouse conditions*

The comparison of daily ETo values in open-air and greenhouse conditions calculated using the FAO P-M equation (Figure 8) shows a comparatively higher evaporation demand of the atmosphere in the open air, leading to higher irrigation requirements.

Figure 8. Daily reference evapotranspiration (ETo) values estimated through the FAO P-M equation, in open-air and greenhouse conditions.




Source: Compiled by the authors based on field findings.

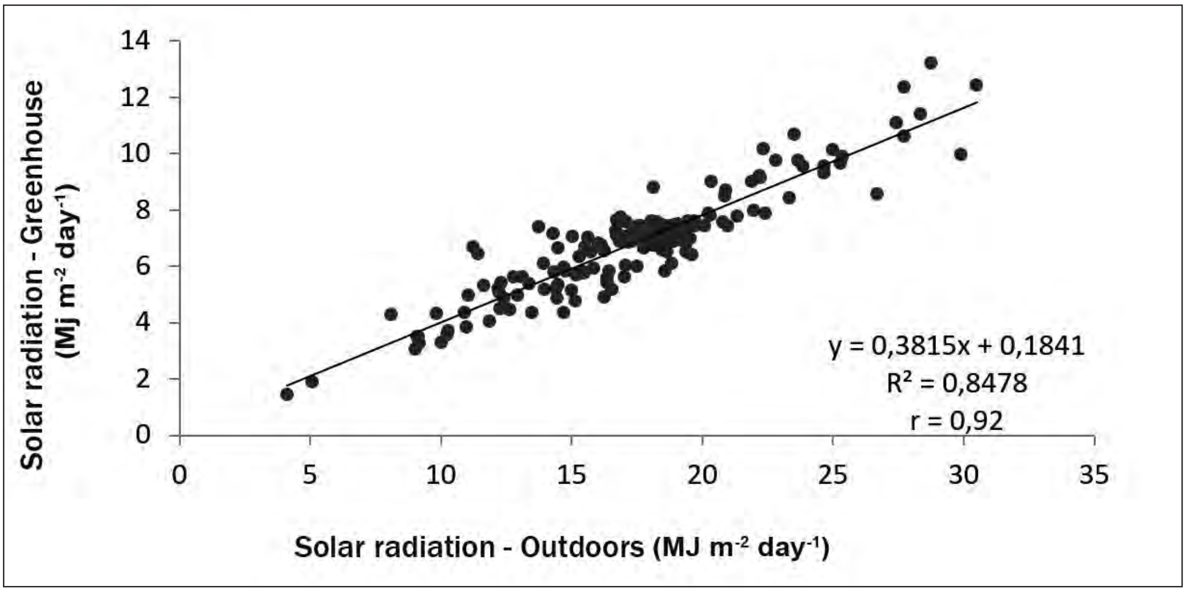
Given the water demands of the crops, the results indicate that water consumption in greenhouses would be close to 50% of the water demanded by open-air crops. Several authors (Farias et al., 1994; Martins et al., 1994; Braga and Klar, 2000, all cited in Fernandes et al., 2003) also reported that evapotranspiration was lower in greenhouses than in the open air.

The physical reasons for these differences focus on: a) a lower diffuse incident solar radiation inside the greenhouse, which increases its photosynthetic efficiency, and b) a less significant influence of the aerodynamic term, which in open-air conditions has a much more significant relative impact on the total ETo value.

### *Estimation of solar radiation in greenhouses based on open-air data*

Having already established the relevance of radiation to estimate ETo in greenhouses, we should now examine the impact of the lack of meteorological data inside the greenhouse. The most sensitive factor is the solar radiation data (Rs), which is then used to calculate the net radiation. To do so, we compared the Rs of the open-air meteorological station with that in the greenhouse (Figure 9).

Figure 9. Linear regression between solar radiation measured inside and outside the greenhouse, between February and July 2015.




Source: Compiled by the authors based on field findings.

The correlation between open-air and greenhouse solar radiation is clear. This shows that it is possible to estimate solar radiation inside the greenhouse using open-air radiation information. Allen et al. (2006) indicate that the temperature difference's square root is closely related to the daily solar radiation at a given location. Using this methodology, the solar radiation derived from temperature differences is calculated using the Hargreaves equation:

$$R_s = k_{Rs}\,\sqrt{(T_{max} - T_{min})}\,R_a$$

Where Ra is the extraterrestrial radiation (MJ $m^{-2}$ $day^{-1}$), Tmax is the maximum air temperature (°C), Tmin is the minimum air temperature (°C), and kRs is the adjustment coefficient.

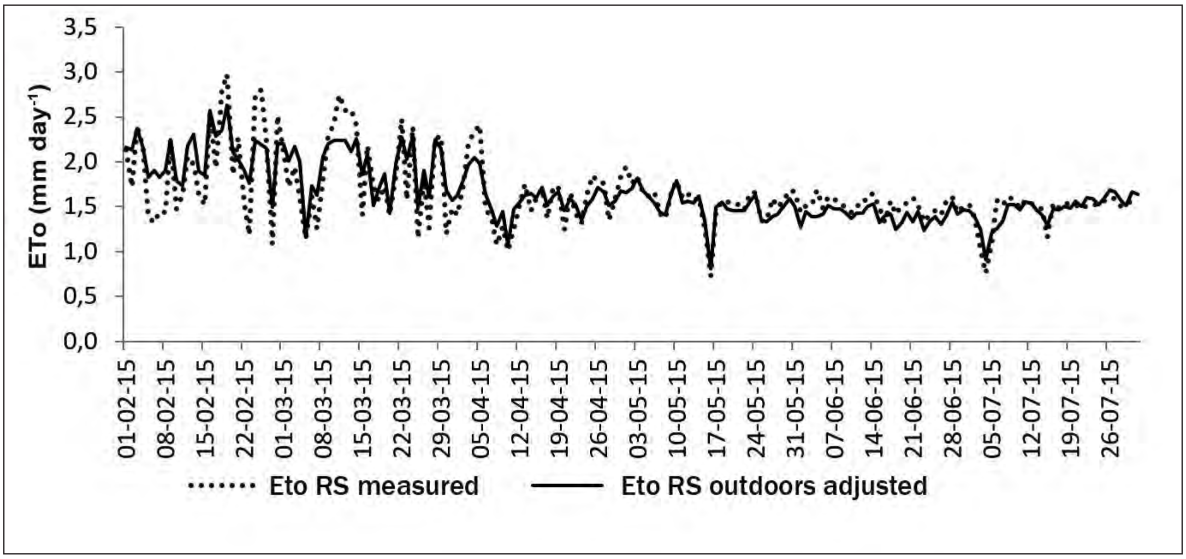
The relationship between the open-air solar radiation estimated with the Hargreaves equation was then compared with the one measured in the greenhouse, finding a linear relationship where $r^2$ was 0.65, which is given by:

$$Rs_{\ (estimated\ greenhouse)} = 0{,}613 * Rs_{\ (estimated\ outside\ HG)} - 2.9184$$

Where $R_s$ (estimated greenhouse) is the adjusted solar radiation inside the greenhouse, $R_s$ (est. outside HG) is the solar radiation value estimated with the Hargreaves equation under open-air conditions.

To evaluate the impact of the solar radiation values estimated with the linear equation determined, we compared the ETo values calculated with the estimated solar radiation compared with those calculated with the Rs measured by the weather station (Figure 10).

Figure 10. ETo calculated for greenhouse conditions with Rs estimated based on open-air values, compared to ETo calculated with Rs measured at the station.




Source: Compiled by the authors based on field findings.

The ETo calculated with open-air solar radiation adjusted for greenhouse conditions shows similar behavior to the ETo calculated based on the solar radiation measured inside the greenhouse. Therefore, the abovementioned equation can be used for temperate environments in areas where there is no open-air or greenhouse solar radiation data available, which usually happens in Bolivia because meteorological stations rarely record solar radiation.

## Conclusions

The ETo values measured in the greenhouse for a ryegrass crop simulating the reference crop defined by Allen et al. (2006) showed a clear correlation with the values calculated with the FAO P-M equation based on the data collected by the meteorological station installed in the same greenhouse. It should be noted that the ETo calculated and determined in greenhouses shows values close to 50% of those calculated for the same area but in the open air. This indicates that proper greenhouse management could yield substantial savings in irrigation water in an area that is very deficient in this resource.

The weather parameters of solar radiation, wind speed, and vapor pressure deficit in the greenhouse were, on average, lower than in the outdoor conditions. Meanwhile, the temperature is much higher than in the open air, which shows strong energy retention due to the temperate environment, mainly due to little terrestrial radiation loss. In addition, this shows the significant influence of the tropical latitude that causes high solar radiation reception, even at higher altitudes. It was also determined that ETo inside the greenhouse is primarily influenced by radiation energy and, conversely, the impact of aerodynamic energy is marginal. Therefore, approximations and estimates of Rs in greenhouses based on external data can make up for the lack of greenhouse meteorological information. We calculated a linear equation that correlates the solar radiation calculated with Hargreaves in open-air conditions with the solar radiation in greenhouse conditions, assuming that only Tmax and Tmin data were available. The greenhouse ETo calculated with the FAO P-M equation as a function of solar radiation adjusted with the linear equation mentioned above shows a very high correlation, indicating that this methodology can be used to determine adequate ETo values in greenhouses even if the only data available for open-air conditions is temperature.

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# Efficient water use in three species (quinoa, aloe, and Prosopis) and deficit irrigation strategies. A literature review as a contribution of desert farming to food production in the context of climate change

*José Delatorre-Herrera[1]; Jorge Arena[1]; José Delatorre-Castillo[2]; Felipe Carevic[1]*

**Abstract**

The production of food and other products derived from Renewable Natural Resources (RNRs) remains a challenge. Organizations such as FAO point to food insecurity as a major problem due to an increased demand for food caused by population growth and the degradation of RNRs. One factor that increases the uncertainty of the food supply is unpredictability; it is also essential to see how farmers adapt to climate change. This implies facing problems such as a change in precipitation patterns, which affects the distribution and availability of water in areas of traditional agriculture practices. This and the increase in temperatures will imply a greater crop water demand for water from crops and higher soil evaporation rates. This adds to the fact that fresh water must be a priority for human consumption, which poses the great challenge to produce food and raw materials with less water and lower quality water. Considering the above arguments, the objectives of this paper are a) to evaluate how the production of food and raw materials will be affected by a reduction in water availability. b) To describe the strategies exhibited by quinoa (*Chenopodium quinoa* Willd), aloe (*Aloe vera* (L) Burm f) and *Prosopis spp*, widely known for their resistance to droughts to achieve high levels of water use efficiency (WUE). They can then be used to improve productivity in arid zones., And c) establish management strategies based on deficit irrigation. Experiences of these techniques will be analyzed for both quinoa and aloe.

**Keywords:** climate change, water deficit

## Introduction

It is estimated that there will be 9.07 billion humans globally by 2050, 62% percent of whom will live in Africa and Southeast Asia. Given these projections, the global challenge is to provide food to the population in the context of climate change (CC). The expected consequences of CC for the world, and especially for agriculture, are increased temperature, increase in wind power, change in rainfall regimes, degradation of natural factors of production such as soils, water, and diversity (FAO, 2013; FAO, 2003), among other major environmental factors that have a significant influence on plant growth and development (The World Bank, 2012). Furthermore, the increase in population will result in a higher demand for food (Pérez et al., 2018) and hence greater food insecurity (FAO, 2006). The degradation of natural resources connected with agricultural production leads to abandoning certain business lines and urgently searching for alternatives to crops with plants better suited to the new climatic reality. Otherwise, there is a risk of definitive abandonment of agriculture (Delatorre-Herrera, 2015). In this regard, Bastin et al. (2019) point out that in an optimistic CC scenario, where 1.7°C changes are predicted, Europe will have climate

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modifications equivalent to having moved 1,000 km to the south. There is reasonable uncertainty about plants' ability to adapt to climate change, especially crops, which are highly homogeneous and depend on various agronomic factors, particularly irrigation. The crops included in this review are suppliers of food and raw materials; quinoa, native to the Andean peoples, provides grains with a high nutritional value, especially given its protein content and quality (Cai and Gao, 2020). Prosopis, 44 species which are endemic to the Americas, such as locust beans (*P. fleuxosa, P. nigra, P, pallida, etc.*), produce sugar-rich pods used in food for humans, infant food supplements, or fodder. Aloe, a dryland plant, was introduced from Africa given its commercial value in medicine, pharmacology, cosmetics, and food (Kock, 2015).

This leads to the following questions: how will the production of the primary, traditional food, and raw material producing species be affected by the decrease in water available for irrigation (quantity and quality) due to CC? Specifically, if we focus on these crops—quinoa, aloe, and Prosopis—that adapt to water scarcity and are known in South America as drought-tolerant and efficient in water use, which strategies do they implement to improve their water use efficiency (WUE)? Which are the lessons these plants teach us through their efficient water management? Which can be applied to address the impacts of climate change?

Various strategies can be implemented in this scenario: growing species that tolerate water deficit, using marginal waters, or managing irrigation either by using technologies that allow for greater efficiency or through water restrictions, known as deficit irrigation.

Deficit irrigation is an alternative tool that allows for the rational use of water, with a minimum impact on production (Rodríguez et al., 2014). Deficit irrigation can provide economic returns per unit area equal to or greater than conventional irrigation (Hargreaves and Samani, 1984) and improve WUE. Considering the above arguments, the objectives of this paper are a) to evaluate how the production of food and raw materials will be affected by a reduction in water availability. b) To describe the strategies exhibited by quinoa (*Chenopodium quinoa Willd*), aloe (*Aloe vera* (L) Burm f) and *Prosopis spp*, widely known for their resistance to droughts to achieve high levels of water use efficiency (WUE). They can then be used to improve productivity in arid zones. And, c) establish management strategies based on deficit irrigation, analyzing experiences with quinoa and aloe.

## Materials and methods

A systematic literature review was conducted to describe the studies' main characteristics of water efficiency and controlled deficit irrigation in three species (quinoa, aloe, and Prosopis) worldwide, especially in Latin America. A paper search was conducted in the primary literature databases available in the digital library of Arturo Prat University, Chile: PubMed/MEDLINE, SCOPUS, and WoS. Descriptors were classified into two sets: water use efficiency (WUE) (in Spanish or English) and controlled deficit irrigation (CDI) (in Spanish or English).

Also, we manually searched for reports from agencies such as the UN, FAO, and state institutions in Bolivia and Chile and theses not included—or partially included—in the above databases.

Inclusion criteria: The resulting reference documents were limited to WUE and deficit irrigation management, mainly in quinoa, Prosopis, and aloe. Congress papers and communications were excluded. If a paper was found in several publications, the one published in the journal with the most significant impact factor or the one published most recently was included.

Handling of information: The information collected was systematized according to the objectives of the review. The objectives were to determine the effect of climate change on agriculture, specifically on food production, and to determine the strategies implemented by the three crops in arid areas (aloe, quinoa, and Prosopis) to maintain their production under water-deficit conditions.

## Results and discussion

### *Agriculture and water in the context of climate change*

Reports from different climate change panels (IPCC, 2007; Bates et al., 2008) point to significant changes in the agroecosystems. Increasing temperatures between 1 °C and 3 °C increase crop productivity, but at the same time, limit water availability. In this regard, an increase is expected in drought frequency in some locations, and in floods in others.

Rodríguez (2007) highlights the importance of water for achieving the millennium goals in terms of food production, as well as the water productivity challenge in agriculture. Pérez et al. (2018) propose high-tech eco-intensive agriculture based on sustainable high-tech management (computers, remote sensors, drones, and cyber management). Therefore, agriculture faces the challenge of developing new and more efficient irrigation technologies that are better suited for the social, cultural, and economic realities with agricultural activities (Rodríguez, 2007). Various technologies become relevant, such as those that help save water or grow crops in water deficit conditions—such as deficit irrigation—and the use of resistant species such as quinoa, aloe, or Prosopis.

## How traditional food and raw material production will be affected by reduced water availability as a result of climate change

According to Nelson et al. (2009), wheat and rice under irrigation will be significantly affected. On average, yields in developed countries will be less affected than in developing countries given their access to technology. In the Amazon and San Francisco basins, rainfall is estimated to decrease between the 2020s and 2080s from 9% to 19% and from 15% to 35%, respectively (Marengo et al., 2012). Urrutia and Vuille (2009) stated that the Andes' tropical mountain areas will be more affected by future climate change than the surrounding lowlands. Projections indicate significant warming in the tropical Andes, which worsens with altitude.

Therefore, a decrease in yields is expected due to water stress in irrigated crops, such as rice, wheat, and corn. Yields are expected to be relatively more significant in the driest scenario of a study conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), reaching 6.7% losses (Nelson et al., 2009), which entails a decrease irrigation reliability in these crop areas. According to our calculations and considering irrigation efficiencies ranging from 90% to 50%, the water requirements of corn range from 9,000 to 14,000 $m^3$/ha/ season. These high consumption rates contrast with crops such as quinoa, which can produce up to 1,200 m3/ha/ season.

Canedo and García (2015) modeled quinoa's behavior in the Bolivian Highlands to study its production ability in a climate change scenario. There are greater ranges of variation in the probability of precipitation in the northern and central sectors, and precipitations tend to concentrate in a few weeks within the annual cycle. However, the Southern Altiplano shows a range with less rainfall, increasing the likelihood of water deficit. Future precipitation variation shows a decrease of between 1% and 4% for 2020-2029, amccounting to a maximum reduction of 12 mm/ year-1. For the 2046-2055 decade, the precipitation decrease of between 1% and 8% intensifies, with a maximum of 23 mm/ year-1 decrease. This decrease in projected precipitation (Andressen et al., 2007) increases vulnerability and water deficit in the agroecosystem of Bolivia's southern highlands and in the Chilean highlands, where rainfall does not exceed 120 mm/year, or its equivalent to of 1,200 m3/ha/year.

Furthermore, the data show a decline in quinoa productivity in Bolivia. In this regard, the Ministry of Rural Development and Land (MDRyT) (2014), in its 2014-2018 Agricultural Development Plan, reports that quinoa yields have decreased from 637 kg/ha in the 2001-2002 season to 466 kg/ha in 2012-2013, amounting to a 26.8% decrease. These data agree with those reported by Bedregal (2012), which could be attributed to the reduction in rainfall and soil fertility degradation.

It is essential to remember quinoa's ability to prosper with very little water, so a decrease in water supply will undoubtedly impact production. However, it is necessary to highlight the main difference between quinoa and traditional crops that require large volumes of water (between 500 and 1,000 mm) to achieve adequate yields, demonstrating high water use efficiency.

## Strategies of quinoa, aloe, and Prosopis to achieve high WUE levels

Quinoa has various strategies to adapt to stress conditions caused by a decrease in soil water potential. These strategies may be morpho-physiological (Hariadi et al., 2011; Adolf et al., 2013a). Morphologically, quinoa can manage transpiration by modifying stomatal density and stomatal aperture (Orsini et al., 2011; Shabala et al., 2012, Adolf et al., 2013). In this regard, a reduction of up to 50% in stomatal density has been found in BO78 (southern Chile genotype), accompanied by a decrease in stomatal length under conditions of decreased soil water potential due to salts (Orsini et al., 2011).

Decreased stomatal conductance reduces not only water loss but also $CO_2$ assimilation. This contributes to a decrease in water use efficiency, as less biomass is produced per unit of water. This is illustrated in a test conducted with two quinoa varieties, for which the soil water potential is decreased. Utusaya is tolerant and Titicaca is sensitive. Utusaya has a mere 25% reduction in net CO2 assimilation compared to Titicaca's 67% reduction (Adolf et al., 2013).

The above is also verified by Delatorre-Herrera (2008) when comparing two contrasting Chilean varieties: a tolerant variety obtained from the Altiplano (yellow) and another from the southern zone (Hueque) (Delatorre-Herrera et al., 2009). Both selections showed a decrease in stomatal conductance. This decrease was significantly greater in the Hueque selection (sensitive variety), as stomatal conductance (g) fell from 471 to 201 mmol H2O /$m^2$s, i.e., a decrease equivalent to 57.3% of the original value. Meanwhile, yellow quinoa—the tolerant variety—showed only a 17.4% decrease. This decrease was proportional to the assimilation rate decrease, which was 37.7% for yellow quinoa and 65.1% for Hueque.

Additionally, quinoa's phenotypic root plasticity is an adaptation mechanism that creates a specific anatomical modification, providing it with a greater transport ability to explore the soil's dry layers. This is how quinoa is not affected in its root–shoot ratio and root length when there is a water deficit. Due to its root architecture in the shape of a fishbone, there is less competition between roots of the same plant and between the roots of neighboring plants (Zurita et al., 2014; Sánchez and Olave, 2019). Moreover, quinoa has a root system with a robust central axis enabling it to explore deep layers more quickly and more efficiently: this is essential for the plant's success in the early stages (Zurita et al., 2014). These strategies, jointly with other biochemical processes such as osmotic adjustment or trehalose synthesis (Delatorre-Herrera et al., 2019; Ruiz et al., 2015), allow quinoa to adapt to temporary water deficits, such as deficit irrigation.

Meanwhile, CAM (Crassulacean Acid Metabolism) plants like aloe open their stomata at low temperatures, when the vapor concentration gradient between the leaf and the air is small, minimizing water loss. This occurs at night (Gil-Marin et al., 2006). Another strategy is succulence and how it delivers the water stored in its leaves. This is achieved through sugar synthesis, especially neofructans and inulin, which create an intricate network slowing water passage (Delatorre-Herrera et al., 2010; Salinas et al., 2016). Water deficiency causes morphological and physiological changes, such as the degree of succulence of its leaves, an increase in cuticle thickness with a thin layer of wax and an increase in the number of stomata per leaf area, a reduction in the size of ostioles, and an increase in the number of parenchymal cells (Silva et al., 2014). These morphological modifications reduce water loss by improving WUE under stress conditions (Delatorre-Herrera et al., 2010; Oyarce, 2019).

Prosopis grows in such an environment that its species are resistant to multiple types of stress, such as water deficit, salinity, high radiation, and low temperatures (Ewens et al., 2012; Delatorre-Herrera et al., 2009). Therefore, this genus species has different morphological and physiological mechanisms to avoid or tolerate the lack of water. For example, they can deepen their roots by osmotic adjustment (Nilsen et al., 1981; Acevedo et al., 1985). Because of the decrease in the water supply at certain times of the year, phreatophyte plants with persistent leaves can produce osmoregulating substances to reduce their osmotic potential, thereby inducing osmotic adjustment (Carevic et al., 2014). This allows them to absorb water with higher saline content; in *Prosopis glandulosa*, the osmotic potential at full turgor reaches -2.98 MPa, while at plasmolysis, it reaches -4 MPa (Nilsen et al., 1981). This agrees with what was reported by Acevedo et al. (1985) for *Prosopis tamarugo*, presenting osmotic adjustment at 210 days after -0.8 Mpa stress started. They have large xylem vessels that allow them to adapt to seasonal climates (Baas and Wheeler, 2011; Palacios, 2017; Garrido 2018); maintain root volume and present a decrease in leaf area, stomatal closure, photosynthesis rate decrease but not disappearance (Delatorre et al., 2008); morphological root adaptations (Guevara et al., 2010; 2011).

## Strategies for improving WUE with controlled deficit irrigation

Controlled deficit irrigation (CDI) has been defined as a strategy to optimize irrigation when crops are the most sensitive to irrigation requirements, mainly during establishment, flowering, and fruit set. Irrigation may be restricted outside these periods. Water restriction can be associated with the crop coefficient (Kc) since the higher the Kc, the more sensitive the crop to water deficit (Segura, 1995). In turn, Doorenbos and Kassam (1979) introduced an empirical yield response factor (Ky) to integrate the complex relationships between water production and consumption for crop production, limiting its applicability to make accurate estimates of yield responses to water. Adjustments should be made for site-specific conditions because other factors such as nutrients and different varieties grown also influence the yield response.

Various studies show the benefits of CDI; for example, in paprika (Rodríguez et al., 2014), quinoa (Hirich et al., 2012; Geerts et al., 2010; Huanca 2008) and aloe (Silva et al., 2014; Delatorre-Herrera, 2010), among other crops. FAO's AquaCrop model allows us simulating crop response to various environmental conditions (FAO, 2012). The ORDI (optimized regulated deficit irrigation) model

(Domínguez et al., 2012), based on nonlinear optimization, aims to determine this combination of stress levels for arable crops.

The application of CDI requires these technological tools and the following information to be analyzed and validated:

a) *Crop characteristics.* Both species and varieties have their own patterns of behavior. This implies that they may have different sensitivities to water deficit, depending on their phenological stage.

b) *Time of year and agrometeorological conditions of the sector*. Crop behavior will depend on sowing and harvest time, influenced by environmental factors such as altitude, winds (speed and origin), relative humidity, temperatures, and length of day (FAO, 1981).

c) *Soil characteristics.* This relates to the soil's ability to retain moisture. A crop growing on sandy soil would be more sensitive to a deficit than loam soil.

d) *Reference crop evapotranspiration.* This value depends on the sum of many environmental variables, which will make it possible to estimate the demands of the crop's various phenological status and the water demands throughout crop development (Allen et al., 1998).

e) *Expected crop characteristics.* This implies that harvests can occur during different crop stages: root (carrot), tuber (potato), stem (asparagus), inflorescence (artichoke), fruit (tomato), grains (quinoa), leaves (aloe), dried pods (carob beans), etc.

f) *Irrigation method.* Pressurized irrigation methods allow for better control of irrigation and water applied than gravitational irrigation.

Furthermore, by calculating the irrigation rate and based on crop evapotranspiration, it estimates an irrigation flow for optimal yield, which can entail greater water requirements. The challenge analyzed in this paper is irrigating in a scenario where irrigation water available for crops is increasingly scarce. Controlled deficit irrigation (CDI) is defined based on the above scenario. In this regard, FAO (1999) defines the estimation of water deficit that would affect crop yields (Equation 1):

$$\left(1 - \left(\frac{Ractual}{Rpotencial}\right)\right) = Ky * \left(1 - \left(\frac{ETactual}{ETc}\right)\right) \qquad \text{Ecuation 1}$$

where

| | |
|---|---|
| $R_{current}$ | Crop yield under deficit conditions |
| $R_{potential}$ | Crop yield under normal conditions |
| Ky | Effect of water deficit on yield |
| $ET_{current}$ | Crop evapotranspiration under deficit conditions (mm/period) |
| ETc | Crop evapotranspiration under normal conditions (mm/period) |

Ky values (Table 1) depend mainly on the crop and its phenological stage when the water deficit occurs. It is essential to consider that before applying the indicators in Table 1 directly, it is necessary to validate these indicators for the local conditions where irrigation restriction is to be used, as well as stress tolerance according to the crop's phenological stage.

Table 1. Ky values for different crops

| Crop | Vegetative growth | | | Flowering | Harvest formation | Ripening | Total |
|---|---|---|---|---|---|---|---|
| | Initial | Final | Total | | | | |
| Alfalfa | | | 0:7 - 1.1 | | | | 0.7 - 1.1 |
| Onion | | | 0.45 | | | 0.3 | 1.1 |
| Corn | | | 0.4 | 1.5 | 0.5 | 0.2 | 1.25 |
| Calendula | 0.25 | 0.45 | | 1 | 0.8 | | 0.9 |
| Potato | 0.45 | 0.8 | | | 0.7 | 0.2 | 1.1 |
| Bean | | | 0.2 | 1.1 | 0.75 | 0.2 | 1.15 |
| Quinoa | 0.8 | | | 1.2 | 0.8 | 0.5 | 1.1 |
| Tomato | | | 0.4 | 1.1 | 0.8 | 0.4 | 1.05 |
| Vine | | | | | | | 0.85 |
| Source:: | FAO 1981. Agrometeorological crop yield prediction. FAO 73. | | | | | | |
| | https://es.slideshare.net/rubenramiromiranda/riego-deficitario-de-la-quinoa-y-modelizacin-de-la-productivi-dad-del-agua-del-cultivo-geerts-sam-y-et-al-rm | | | | | | |

Source: FAO, 1981.

The higher the value of Ky, the greater the water deficit's effect on yield, both in the harvest and harvest quality. Therefore, crop phenology knowledge allows us to define an irrigation schedule for each crop, considering greater water use efficiency and a connection between water use and the expected yield under the local conditions where this irrigation restriction is implemented.

For quinoa, Yucra et al. (s/a) propose a CDI application where plants undergo water deficit for 50 days until the floral bud grows and starting from the thirteenth pair of leaves. The crops should then be under supplementary irrigation until the milky grain stage for 65 days. Irrigation is suspended as of the dough stage. This model should be validated for other quinoa varieties and regions and should be improved by considering post-anthesis drought (Geerts et al., 2008). The reported values of seed yield per unit of water consumed (WUE) were relatively low: they ranged from 0.3 to 0.6 kg/m3. Low soil fertility can have a significant influence on seed yield (Geerts et al., 2009). Some communities of the Bolivian-Chilean highlands have intuitively applied controlled deficit irrigation since ancient times in areas where water deficit is frequent (Delatorre-Herrera et al., 2008). Sowing takes place in September-October on soils that have rested for two years. This means that they have accumulated water in the lower soil strata at a depth of 40 cm. Sowing is done at a specific depth to take advantage of the moisture stored. This allows quinoa to remain irrigated until the first November-December rains. If rains are insufficient, additional irrigation should be applied (Lanino et al., 2008).

In the case of aloe, poor irrigation can be more extreme due to its remarkable ability to tolerate water deficit. In this regard, Delatorre-Castillo (2019) say that aloe plants subjected to 222 days of water deficit lose only 15% of leaf volume. Meanwhile, Oyarce (2019) finds similar results, evidencing a decrease in the water content of *Aloe vera* leaves as the restriction period progresses. It is also true that WUE increases at the following values: 14.7 kg of dry matter per m3 of water in plants, with 25% irrigation and 12 kg of dry matter per m3 of water in systems with 100% irrigation.

Improving WUE is a significant challenge, especially in the area of extensive crops, since, in the case of intensive crops such as vegetables, this improvement involves controlling environmental conditions. High yields are achieved with the same amount of water under controlled conditions and with advanced technologies. This shows that atmospheric demand plays a significant role in the use of water for agricultural production. The water needs of greenhouse crops are lower than those of open field crops (Salazar-Moreno et al., 2014). In regions with high solar radiation, a plastic greenhouse can reduce crop water use by 30%. In Almeria, Spain, water use is reduced by between 40% and 50% due to the decrease in solar radiation and wind (FAO, 1991; Fernández and Camacho, 2005). Greenhouse evapotranspiration can be reduced by up to 70% compared to outdoor evapotranspiration (Antón et al., 2003).

Fernández and Camacho (2005) report that tomato production in Almeria, Spain, requires 27 $m^3$/ton (37 kg/$m^3$) compared to open field production, which uses 50 to 60 m3/ton (16-20 kg/$m^3$). The above figures show a notable increase in water productivity when switching from open fields to greenhouses (Salazar-Moreno et al., 2014). The challenge is to improve WUE in extensive crops, where water demand is high, and the plant has stomatal closure mechanisms that reduce the photosynthesis rate, thereby lowering WUE. CDI makes sense in this situation because few management alternatives can be applied to reduce water consumption, improve the efficiency of irrigation systems, and optimize soil fertility.

## Conclusions

An increasing body of evidence indicates that climate change will substantially impact food production and food security by 2050 worldwide, with Asia and Europe being the most affected continents. The tolerance patterns of the crops analyzed—quinoa, aloe, and Prosopis—allow them to adapt to a wide variation in environmental changes that implies an increase in temperatures or water deficit, according to an optimistic climate change scenario (1.7°C). The productivity of traditional crops and those analyzed in this study can be improved with the application of CDI, especially in quinoa. Deficit irrigation is a tool that can be applied to any crop given the technical considerations described in this paper, such as the validation of information to adapt to local realities and each crop.

In this regard, researchers must determine tolerance to water stress in the less critical phenological stages that would make it possible to implement CDI for various crops.

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# Automated system for hydroponic fodder production with low water consumption

*Gabriel Mancilla[1] and Christopher Vivanco[2]*

**Abstract**

The Coquimbo region (Chile) features arid and semi-arid climates, with rainfall ranging from 80 mm to 300 mm per year. Goat farming is a traditional activity in this region and the source of livelihood for hundreds of rural families. However, frequent droughts, climate change, and the increase in agricultural water demands have considerably reduced natural fodder production in the fields. Furthermore, goat grazing accelerates soil compaction, favors surface runoff and soil erosion, and reduces groundwater recharge. An automated system for accelerated hydroponic fodder production was tested to help solve this problem. The system included a conditioned container with seven rows of grass trays, programmed automatic irrigation, extended light exposure, and controlled temperature. It produced almost 5 tons of green fodder monthly on 83.1 $m^2$ of cultivated area in growing trays and consumed 8.59 $m^3$ of water: 1.7 liters/kg produced. This is equivalent to only 1.49% of the water used for one kilogram of alfalfa dry matter in natural form. Therefore, the water use efficiency was about 600 times greater. Additionally, nutritional, protein, and energy analyses and nutrition tests in adult and young animals had good results. Consequently, the system would not only allow greater efficiency in the productive use of water, but also a) it would partially solve the problem of lack of fodder in the fields; b) it would allow farmers to keep the goats in stabled, reducing soil damage; and c) it would enable breeders to plan activities based on a more specific fodder availability.

**Keywords**: adaptability, water use efficiency, accelerated hydroponic green fodder (AHGF), goat farming, automated AHGF production system.

## Introduction

Hydroponics began in the 17th century when Irish scientist Robert Boyle experimented with water crops (FAO, 2001). Hydroponic green fodder (HGF) consists of grain germination and growth under controlled conditions of light, temperature, aeration, and humidity, but with no soil. When implemented for food purposes, HGF mainly uses cereal or legume seeds. HGF has multiple advantages: the lower amount of water per unit of dry matter produced, lower susceptibility to pests and diseases, the possibility to program HGF production according to needs; it does not require large tracts of land for production; it can be implemented regardless of local soil quality, among others (Romero et al.*;* 2009; Salas et al.*;* 2012). HGF is, therefore, an ideal technique for feeding animals in areas of low water availability, either due to aridity or drought (FAO, 2001; Lopez-Aguilar et al.; 2009; Maldonado et al.; 2013). This is the case in vast territories of Latin America.

Goat farming is a traditional activity in the Coquimbo Region, Chile. There are approximately 5,000 goat farmers (INE, 2007), each owning an average of between 60 and 70 goats. These parameters show that goat farming is essential for the livelihood of many families. Over the past 30 years, the Coquimbo Region has sustained recurrent drought events linked to the usual climate

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variability in arid and semi-arid areas but also to the effects of climate change. Reduced water availability has multiple consequences: natural grasslands have reduced fodder production, so goats must travel longer distances to get food, reducing their gain in weight and vigor but also affecting more extensive tracts of land. As a result, goat breeding is less profitable, causing the goat population in the region to decrease from over 405,000 animals in 2007 to around 310,000 in 2017 (INE, 2007; Contreras et al.*;* 2018a).

As it is was necessary to adapt to such processes, new technology was tested to prevent goats from grazing in the fields and improve their gain in weight and vigor. An automated accelerated hydroponic green fodder (AHGF) system was implemented to this end. It included a water recirculation method for greater use efficiency, which provided complementary food to Creole and Saanen caprine breeds. The system proved to be useful, the food was well accepted by the animals, and caprine productivity regarding growth and milk production had good results. The system was far more efficient in using water for fodder production compared to natural conditions. However, investment costs require changing the system's design or requesting state subsidies to adopt the system under real goat farming conditions in the region's rural areas.

## Materials and methods

This study was conducted between 2016 and 2018 in the Romeralcillo Agricultural Community, located in Limarí, Coquimbo Region, Chile (Figure 1). A production module including an automated AHGF production system and a pen were set up. It started operating with eight Creole and eight Saanen animals to test the food produced (Figure 2).

Figure 1. Location of the study area


Source: Developed by the authors from Google Earth images.

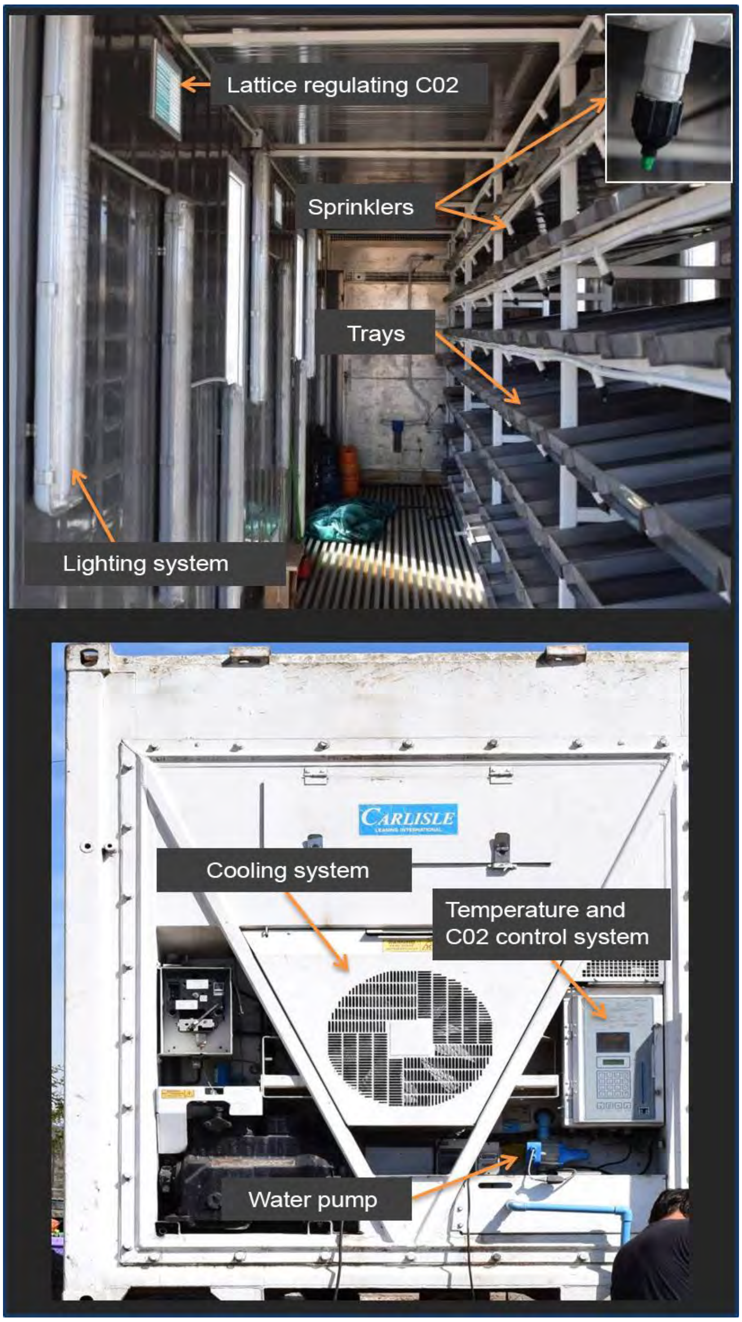
Figure 2. AHGF production module. In the foreground, The automated system is visible in the foreground, and the pen and goats appear behind.

Source: Photo taken by the authors.

The automated system included a container measuring 12.19 m long, 2.44 m wide, and 2.90 m high, with a 68 $m^3$ capacity. The inside had an iron shelving system with seven rows that were 25 cm apart. Each row would hold 25 trays for sowing seeds and growing hydroponic fodder; each tray was 95 cm long by 50 cm wide. It also had fluorescent lights to promote photosynthetic activity when there was no sunlight. The system also included automatic irrigation: a series of 10 sprinklers in each row of trays, regulated by solenoid valves and an irrigation controller that activated a 1 HP pump (Figure 3). Upon activation, the pump drew water through a hose connected to a 500-liter barrel that was part of the system's water supply source and was located outside the automated system.

The system's internal temperature was regulated with the original container cooling system and a coil. In addition, there was thermal insulation by polyurethane injection in the container walls. There were six lattices per wall for ventilation, while ambient humidity was measured with a hygrometer. AHGF production included barley, oats, and, to a lesser extent, corn seeds. Before sowing, the seeds were washed, cleaned and disinfected, and then pre-sprouted in fresh water for 24 hours. The trays were disinfected before each sowing. The seeds were evenly distributed in each tray to a thickness of 1-1.5 cm. They were then covered with dark plastic for two days to stimulate seed germination. After this, the plastic was removed, and the sprinkler irrigation process was applied directly and automatically every four hours at a rate of 6.48 liters/minute, for 20 seconds (12.9 liters/day for each sprinkler). The excess water was recycled through collecting pipes that returned the liquid to a 500-liter barrel, from which the pump extracted water for the irrigation process. The system allowed natural light in during the day and provided artificial light at night, always keeping $CO_2$ below 0.2% and a room temperature of 20 ºC.

Figure 3. Automated system components
The image above shows the internal components, with a close-up of one of the 70 sprinklers.
The image below shows the external elements that control the internal environment.




Source: Photo taken by the authors.

Hydroponic green fodder was ready for harvest after applying this process for five days. In other words, the sowing-to-harvest time was seven days. The harvested grass was between 20 and 30 cm long (Figure 4).

Figure 4. Trays with seeds sown before irrigation (top image)
and AHGF soon to be harvested (bottom image)
The bottom image shows AHGF soon to be harvested.

Source: Photo taken by the authors.

About 88% of the harvested AHGF was made up of water, making the grass unappealing to goats. Therefore, it was air-dried three days before feeding the test animals.

The weight and milk production capacity of the original test animals and of newborns were recorded every 15 days, for one year and eight months. In addition, lab tests were run to determine the quality of milk produced and the nutritional characteristics of AHGF. The following treatments were developed:

- T1 treatment: Four adult Saanen goats were fed with AHGF. They were fed the equivalent of 3% of their weight daily. This included fodder (70% dry alfalfa and 30% AHGF), 30 grams of corn, and free consumption of mineral salts. Three Saanen goats born in a pen were selected for the weight study of newborn animals. Their diet was similar to that described above.
- T2 treatment (control): Four adult Saanen goats were not fed with AHGF. They were fed the equivalent of 3% of their weight daily. This included fodder (100% dry alfalfa), 30 grams of corn, and free consumption of mineral salts. Three Saanen goats born in a pen were selected for the weight study of newborn animals. Their diet was similar to that described above but without AHGF.

- T3 treatment: Four adult Creole goats were fed with AHGF. Similarly, they were fed the equivalent to 3% of their weight daily. It included fodder (70% dry alfalfa and 30% AHGF), 30 grams of corn, and free consumption of mineral salts. Three Creole goats born in a pen were selected for the weight study of newborn animals. Their diet was similar to that specified above.
- T4 treatment (control): Four adult Creole goats that were not fed with AHGF. They were fed the equivalent to 3% of their weight daily. It included fodder (100% dry alfalfa), 30 grams of corn, and free consumption of mineral salts. Three Creole goats born in a pen were selected for the weight study of newborn animals. Their diet was similar to that described above but without AHGF.

The volumes used at each stage of production were carefully measured to determine the water efficiency of the green fodder production system.

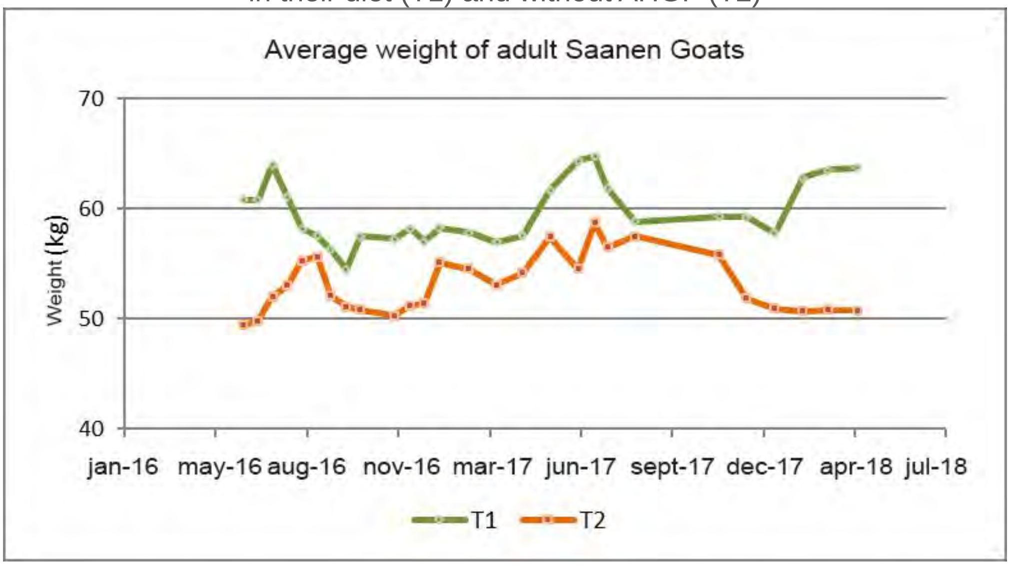
## Results and discussion

### *Weight of adult animals*

The adult animals already had a feeding plan before this trial, so they underwent a period of adaptation to AHGF. The extent to which such adaptation may have affected the results could not be determined but did not appear relevant.

Saanen goats (Figure 5) showed significant differences in the mean goat weights in both treatments (T1 and T2-control). The differences remained steady until the final measurement. The Shapiro-Wilk homogeneity of variance test yielded the expected results. Therefore, a paired sample t-test was performed, which showed significant differences between the mean weight in both treatments (0.05). This remained steady throughout the process, regardless of the variations observed with pregnancy, births, or deaths. This clearly shows that feeding some animals with AHGF did not alter their development patterns, confirming it as a reliable food supplement.

Figure 5. Weight sequence of adult Saanen goats with AHGF in their diet (T1) and without AHGF (T2)



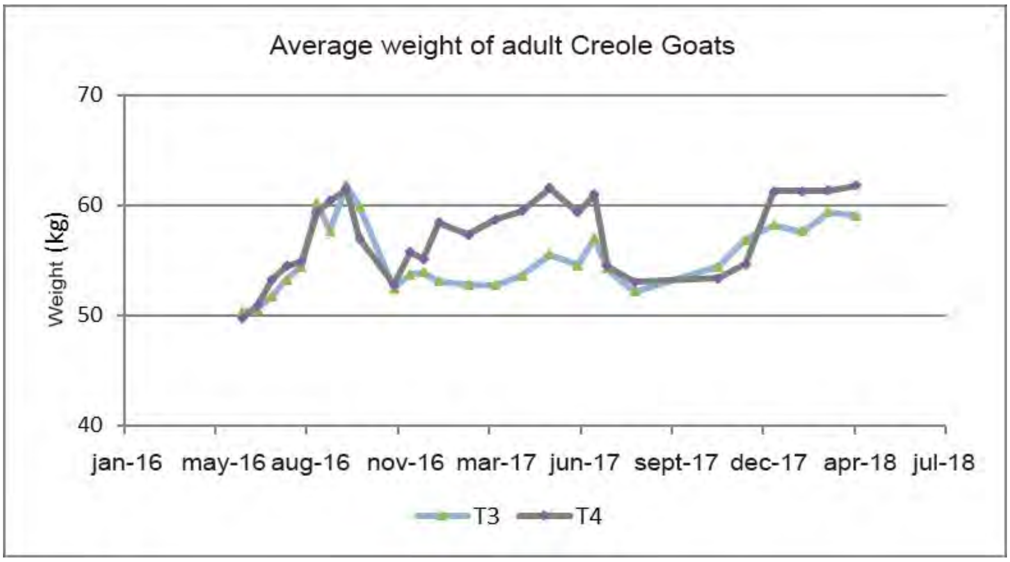

Source: Developed by the authors.

Creole goats (Figure 6) were divided into T3 and T4 treatments (control). Statistical tests (paired sample t-test of mean weights) showed considerable differences at the 0.05 significance level. This evidences differences in mean weights throughout the trial. At baseline, the mean goat weights in both treatments were similar. However, after birth processes between late 2016 and early 2017, subsequent weight recoveries were faster in T4 individuals (control, no AHGF), which explains the statistically significant difference. After the second birth process (late 2017 and early 2018), there was greater uniformity in subsequent weight gains. Therefore, two factors seem to explain the late weight recovery observed between 2016 and 2017:

(i) adult Creole goats may have taken longer to adapt to AHGF because they were originally fed on grasslands;

(ii) adult Creole goats did not come from a stabled system, so they underwent a stress period that affected their diet.

Figure 6. Weight sequence of adult Creole goats with AHGF in their diet (T3) and without AHGF (T4)




Source: Developed by the authors.

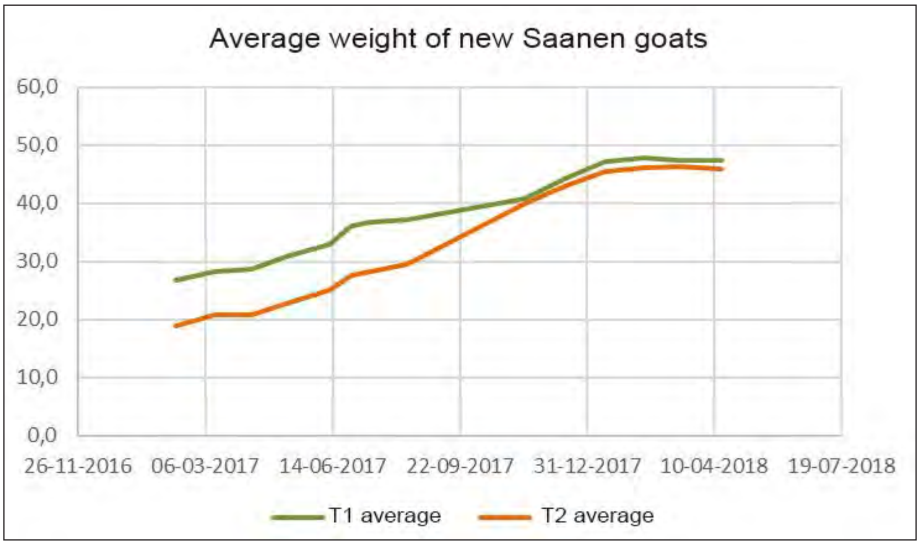
Consequently, the type of feed does not explain the differences in the above results. This agrees with Contreras et al. (2018A), who showed that Creole goats fed dried alfalfa and HGF in different amounts but with a maximum 50% ratio showed no changes attributable to the feed. López-Aguilar et al. (2009) reached slightly different conclusions in Nubian goats fed corn HGF. The daily weight gains of goats fed with 25% and 70% HGF were estimated to be greater than those of the control group (no HGF). This suggests that the effects of HGF may differ according to animal breed.

### *Weight of young adults*

AHGF testing in young animals had the advantage that the goats started eating this type of food immediately after weaning: they did not need an extended adaptation period as did adults. Additionally, the young animals were not used to a grassland system as Creole adults were, which facilitated the designed AHGF test.

Figure 7 shows the direct comparison of the mean weights of the young goats under T1 and T2. This shows the mean weight lines from the time the animals were allocated to each treatment group, i.e., February 2017. Saanen goats allocated to T1 (AHGF) had a greater initial mean weight than their peers allocated to T2 (no AHGF), but the difference was considerably lower by the end of the trial. This happened because an individual allocated to T2 had a very accelerated weight gain, raising the mean value of animal weight in T2. However, the overall trend of weight development of Saanen goats born in pens was remarkably similar, with and without AHGF. This seems to show that AHGF provided the necessary nutritional value for the Saanen goats to grow healthily and consistently from the start.

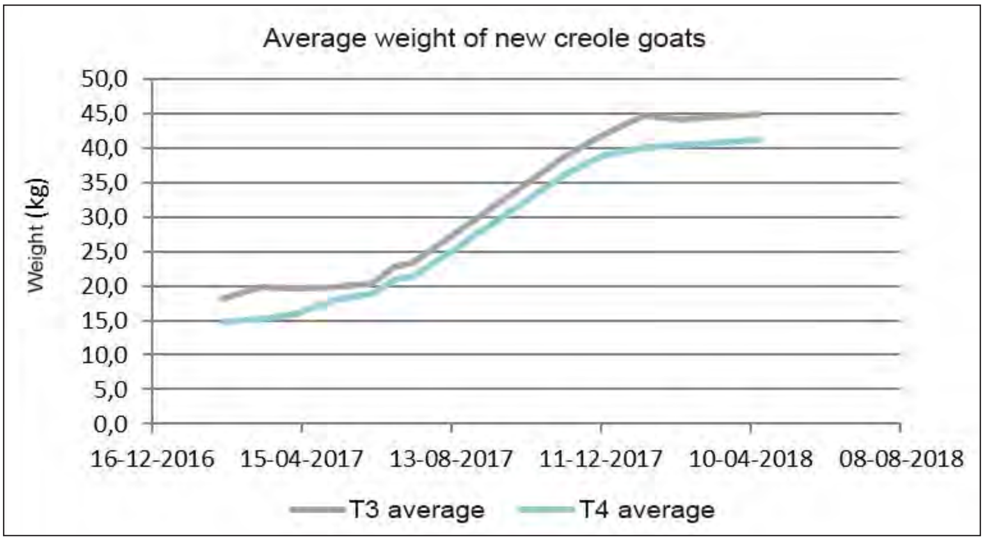
Figure 7. Weight sequence of young Saanen animals born in pens, with AHGF (T1) and without AHGF (T2)




Source: Developed by the authors.

Young Creole goats allocated to T3 and T4 showed an average weight growth dynamic from the moment they were allocated. Figure 8 shows that both groups of goats initially underwent a period of adaptation to decreased breast milk consumption and fodder replacement. After this, both groups had an equal weight growth rate from around June 2017. This shows their full assimilation of the new diet. After that, weights stagnated because birth processes led to a decrease in animal mass. Significant conclusions can thus be made for Creole goats.

Figure 8. Weight sequence of young Creole animals born in pens, with AHGF (T3) and without AHGF (T4)




Source: Developed by the authors.

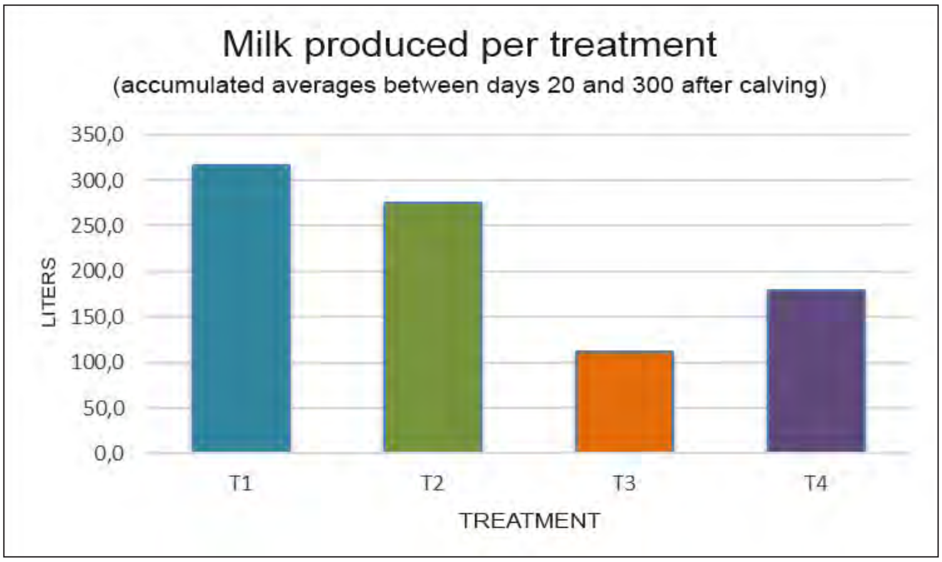
- Goats can assimilate AHGF as a food supplement; it is not better or worse than traditional feed, so it can be used to feed Creole and Saanen goats.
- AHGF production should be strongly encouraged as a goat food supplement when drought events decrease available grassland fodder. It is also recommended to promote better grassland management by reducing animal load.
- These results prove that Creole animals should start eating AHGF from an early age, once weaned. However, more research is necessary in terms of AHGF types and quantities to be provided, the degree of humidity that makes it more appealing, among other things.

### *Milk production and quality properties*

Before analyzing milk production and properties, we must remember the significant differences between the milk produced by these two breeds. Saanen goats tend to be better milk producers: this is confirmed in this study, where they produced milk up to 300 days after calving. On the other hand, Creole goats usually produce milk in smaller volumes daily and for fewer days after giving birth. The latter was fully verified in this study.

Figure 9 shows the average accumulated milk production of the goats allocated to each treatment between days 20 and 300 after calving. Saanen goats (T1 and T2) had considerably higher volumes than Creoles (T3 and T4), which confirms Saanen as a milk-producing breed. In this study, the Saanen goats produced an average of 2.1 liters daily, while the Creole goats produced 0.89 liters a day.

Figure 9. Total milk produced per goat and treatment between 20 and 300 days after calving




Source: Developed by the authors.

Milk production of Saanen goats with and without AHGF in their diets showed significant differences. The average accumulated milk production between days 20 and 300 after calving was 317 liters for T1 and 275 liters for T2. However, we cannot conclude that adding AHGF affects production volumes directly, as this would require further data. However, this study has shown AHGF to be a reliable food supplement that did not alter this breed's milk-production capacity. An opposite trend was detected when comparing the average milk production of Creole goats with and without AHGF in their diets. In this case, the average accumulated milk production between days 20 and 300 after calving was 111 liters for T3 and 180 liters for T4. However, it cannot be inferred from this that AHGF affects Creole goat milk production negatively, as further data is needed to be conclusive. In addition, the genetic variability in Creole animals must be isolated. For now, it can be concluded that AHGF does not alter this breed's development. Similarities and differences can be found when comparing the results of this study with similar other studies . For example, García-Carrillo et al. (2013) used 15% and 30% ratios of corn HGF to feed Saanen goats, and the rest was dry alfalfa. They determined that milk production was 1.73 l/goat/day in the control treatment (no HGF), 1.68 l/goat/day in the feed with 15% AHGF, and 2.06 l/goat/day when 30% HGF was included. Therefore, HGF might be associated with increased milk production in Saanen goats. In turn, Tan et al. (2018a) included up to 50% HGF in the diet of Creole goats but did not find differences in milk production compared to their non-HGF peers.

Because of animal diseases and deaths, T1 included the average milk production of three Saanen goats, T2, only one Saanen goat, while T3 and T4 included two Creole goats each.

Table 1 shows the quality properties of the milk produced in each treatment.

Table 1. Properties of goat milk according to each treatment

| Treatment | pH | Fat (%) | Solids-not-fat (%) | Total solids (%) | Density (g/cm³) | Protein (%) |
|---|---|---|---|---|---|---|
| T1 | 6.47 | 2.09 | 7.30 | 9.39 | 1.025 | 3.01 |
| T2 | 6.63 | 2.33 | 7.79 | 10.12 | 1.027 | 3.20 |
| T3 | 6.46 | 4.03 | 8.94 | 12.97 | 1.029 | 3.78 |
| T4 | 6.45 | 3.90 | 9.75 | 13.65 | 1.032 | 4.27 |

Source: Developed by the authors.

While Saanen goats have the advantage of increased milk production, Creole goat milk had more fat, solids, and protein than Saanen goat milk, which is usual and desirable for cheese production. We therefore analyzed the trend of goats fed with AHGF versus goats not fed with AHGF. Total solids, density, and milk proteins tend to be slightly higher in both breeds when AHGF was not consumed. This may merit further research—as will be discussed below—since the nutritional properties of hydroponic fodder would not be quite different from those of field fodder or dried alfalfa, and this should be considered in the milk analysis. This analysis is relevant because the differences are marginal and show that AHGF is a complementary food that does not significantly affect the quality of the milk produced by goats. However, the findings of García-Carrillo et al. (2013) do not coincide with our results. The use of HGF in Saanen goats yielded slightly higher percentages of total solids, solids-not-fat, and protein in milk in animals with 30% HGF in their diet compared to peers with 15% HGF in their diet and control individuals who did not consume HGF.

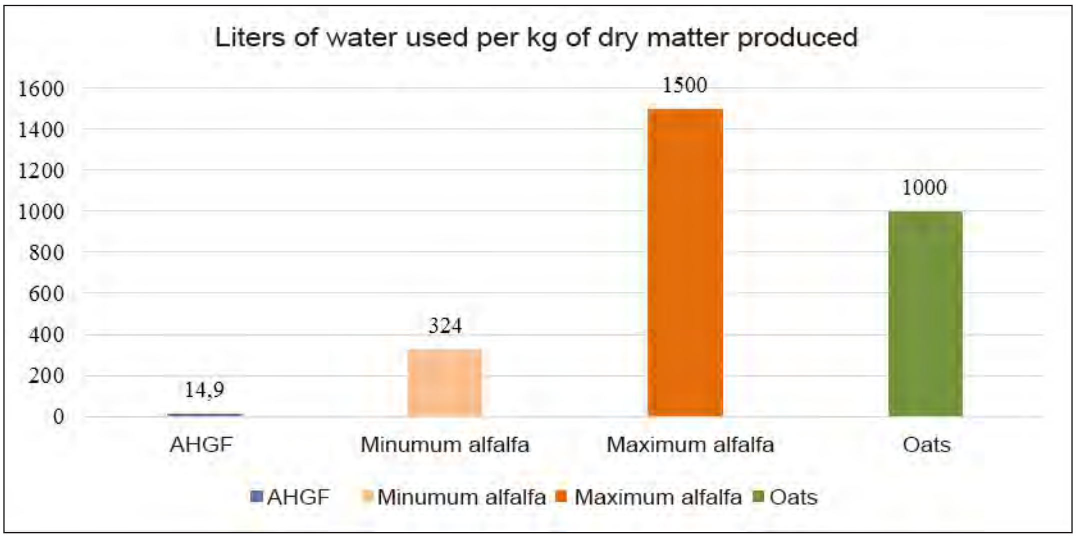
### *Water used by this automated system for AHGF production*

One of the main points of this study, especially as we are in a region with chronic water scarcity, was the water used by the automated system for AHGF production. The results in this area were favourable. The system at full production level—7 rows of 25 trays each—uses 6.34 m3 of irrigated water. Of this volume, the crop effectively consumes 2.86 m3, and the surplus (3.48 m3) is recovered and reused for a different production batch. Considering that each full AHGF production yields about 1,600 kg of green grass, actual water consumption is 1.79 l/kg grass. This AHGF contained 88% water, i.e., the equivalent dry matter weight of each automated system batch was 192 kg, and water use efficiency was then 14.9 l/kg dry fodder.

The water efficiency ratio of this AHGF production system compared to dry matter is quite positive. It is estimated that 1 kg of alfalfa dry matter uses between 324 (with subsurface irrigation) and 1,500 liters of water (Godoy-Ávila et al.; 2003; Montemayor et al.; 2010; Camilo González, 2015, agronomist, personal communication). These values show that the system tested in this study required between 22 and 100 times less water per kg of dry fodder. In the case of oats, 1 kg of dry matter in the field would use about 1,000 liters; that is, the system tested in this study is 67 times more efficient in water use.

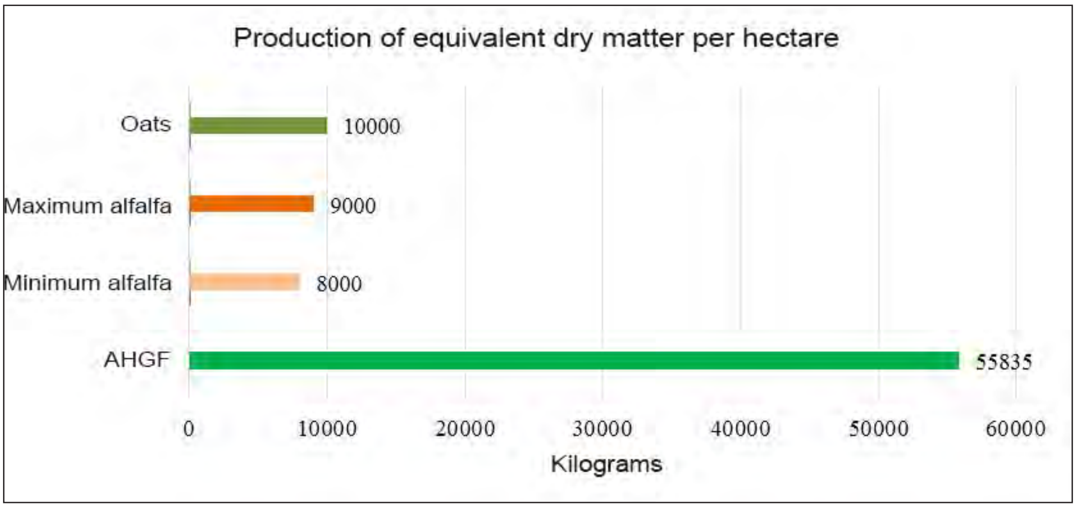
The following figures compare these results, presenting the volumes of water consumed (Figure 10) and the equivalent of dry matter production expressed per hectare (Figure 11). The latter assumes that the automated system uses a 29.74 $m^2$ area (12.19 m long by 2.44 m wide).

Figure 10. Water consumption per kilogram of dry fodder produced
The system used in this trial (AHGF) is compared with data found
in the literature and personal communications.




Source: Developed by the authors.

Figure 11. Equivalence of fodder production based on one hectare
The system used in this trial (AHGF) is compared with data
found in the literature and personal communications.




Source: Developed by the authors.

Additionally, various studies were reviewed (Table 2). This made it possible to compare some nutritional parameters of different AHGF crops (oats, barley, and wheat) with green alfalfa and alfalfa hay. On average, total protein levels were 23% higher in AHGF than alfalfa hay, while the energy supply provided by AHGF seems to be 7% higher. Lignin and NDF (neutral detergent fiber) levels in AHGF crops were lower than their alfalfa hay counterparts, indicating better food digestibility. This makes AHGF a sound nutritional alternative for feeding goats.

Table 2. Nutritional parameters of AHGF oats, barley, and wheat according to various bibliographical sources and comparison with alfalfa hay

| Fodder | DM (%) | Protein (%) | Energy (MCal/kg) | NDF (%) | Lignin (%) | Cellulose (%) | Source |
|---|---|---|---|---|---|---|---|
| Oats AHGF | 28 | 13,9 | 1,7 | 63,5 | 8,8 | 24,3 | Contreras *et al.* (2018b) |
| Oats AHGF | - | 23,3 | - | 56,1 | 7,0 | 28,2 | Arias *et al.* (2019) |
| Oats AHGF | - | 13,9 -17 | 2,1 - 2,4 | 46,8 - 55,3 | 3,4 - 3,8 | 23,8 - 24,1 | Cerrillo *et al.* (2012) |
| Barley AHGF | 4,6 | 17,2 | 2,3 | 50,4 | 4,7 | 20,2 | Contreras *et al.* (2018b) |
| White wheat AHGF | 3 | 22,6 | 2,4 | 56,5 | 5,2 | 23,9 | Contreras *et al.* (2018b) |
| Common wheat AHGF | 29,4 | 27,3 | 2,6 | 48,1 | 6,5 | 17,2 | Contreras *et al.* (2018b) |
| Green alfalfa | 15,5 | 26,15 | 2,42 | 31,1 | - | - | Anrique *et al.* (2014) |
| Alfalfa hay | 85,1 | 16,2 | 2,1 | 56 | 11 | 29 | Contreras *et al.* (2018b) |

Source: Author's compilation of specified sources.

## Conclusions

Accelerated hydroponic green fodder with low water consumption is a suitable and safe alternative to complement the nutrition of Saanen and Creole adults and offspring. This study detected no negative impacts of AHGF on weight, milk production, or quality. It is essential and advisable to feed animals with AHGF from the beginning, right after weaning. This helps bypass the period of assimilation or adaptation to this food supplement without slowing down animal development.

AHGF technology is seen as emergency or exceptional food. Stabling animals does not seem desirable for breeders, although they are convinced that climate change and droughts may force them to do so. The water volume used to produce one kilogram of AHGF in the module under study is relatively low and very efficient. Estimates indicate that water consumption is a maximum of 4.5% of that used by fodder grasses. This water saving justifies the project's spirit, as fodder can be produced in extreme drought conditions with minimal water available.

## Acknowledgments

The authors would like to thank the Regional Government of Coquimbo, Chile, which, under the Regional Fund for Innovation and Competitiveness (FIC), funded the project "Research on Accelerated Production of Low Water Consumption Fodder - Limarí Province," the study this article is based on.

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# Strategies for efficient irrigation water use in Colombian sugarcane crop fields

*Edgar Hincapié G.*[1]

**Abstract**

Water availability for crop irrigation has diminished significantly due to local and global climate variability, hydrological alteration of watersheds, high sediment and pollutant loads, and increasing demand for human consumption and industrial purposes. Consequently, there will be a water shortage unable to meet crop requirements in the future, which must raise awareness to search for strategies to increase agricultural water use efficiency. In Colombia, strategies for water use reduction in sugarcane crop irrigation are being evaluated and implemented, i.e., irrigation scheduling, water requirement adaption to soil and crop characteristics, use of efficient application methods according to soil type and both water availability and quality, followed by the evaluation of the irrigation quality. As cane growers begin adopting these strategies, the objective is to achieve precision irrigation to balance production, profitability, and quality while preserving and protecting soil and water resources. This document describes irrigation scheduling in sugarcane farming as one of the strategies that contribute to irrigation management.

**Keywords**: Irrigation scheduling, water balance, soil matric potential, sensors.

## Introduction

Irrigation scheduling comprises a set of techniques to determine the right time to apply the necessary water amount required by a crop at a given moment. There are several methods for irrigation scheduling. Some are based on quantifying the different water balance components to estimate the acceptable level of soil water depletion, whereas others are based on monitoring soil or plant water status (Howell and Meron, 2007).

Water balance entails quantifying the water amount that goes into the system and exits at a given soil volume and time interval. It is a widely used method for irrigation scheduling in different crops. Torres et al. (2004) and Cruz (2015) recommend this method for sugarcane farming in the Cauca river valley as a strategy to improve water use efficiency. Allen et al. (2006) describe the method and offer parameters to be used for different crops. This method does not always provide satisfactory results due to the uncertainty in soil water distribution, high rainfall variability, soil physical properties, and difficulty estimating some model parameters. Therefore, continuous functions have been generated and evaluated to estimate the soil water balance components accurately. At the same time, other irrigation scheduling methods are being developed, including the use of sensors to monitor soil water availability for crops.

The functions were developed based on information obtained from the study of soil water dynamics, crop water use, and the determination of hydro-edaphic conditions to estimate crop evapotranspiration, permeability (K) coefficients, and the soil's capacity to store water. Soil water flow was simulated based on the information obtained and then compared with direct field measurements. This made it possible to improve irrigation scheduling using the water balance method.

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The irrigation scheduling method with sensors consists of measuring the moisture content or water tension of the soil. Moisture sensors based on time domain reflectometry (TDR) (Topp et al., 1980; Evett, 2000), capacitance (EM), and apparent electrical conductivity, among others, are used to monitor water content. Meanwhile, different tensiometers, gypsum block type sensors coated with a granular matrix, and thermocouple type temperature sensors were developed for soil matric potential monitoring (McCarthy et al., 2014; Nolz et al., 2013; Pedro et al., 2013; Evett et al., 2012; Iwashita et al., 2011; Malazian et al., 2011; Varble and Chavez, 2011; Cardenas-Lailhacar and Dukes, 2010; Migliaccio et al., 2010; Blonquist et al., 2006). Moisture or tension sensors have been used for decades in multiple crops with different systems to irrigate at the most appropriate moment, determine the amount of water required, and evaluate the work quality. Since 1951, there are reports of the use of electric resistance blocks for irrigation control in sugarcane fields in Hawaii and, nowadays, both moisture and tension sensors continue to be used in many regions of the world (Paraskevopoulus and Singels, 2014; Wiedenfeld, 2004; Varble and Chavez, 2011; Blonquist et al., 2006; Cardenas-Lailhacar and Dukes, 2010). It has been observed that the irrigation scheduling method helps achieve more efficient water use since the amount of water that the crop needs can be applied more accurately, thus preventing excessive losses due to deep percolation or runoff and reducing groundwater pollution.

## Irrigation scheduling in sugarcane farming in Colombia

### *Water balance method*

Water balance quantifies the amount of water entering and exiting the system in a given soil volume and time interval, making it possible to estimate the amount of water available for crops. It is calculated using the following function:

$$LARA = Pe + R - ETc - D$$

Where LARA is the quickly usable (available) water layer, Pe is effective precipitation, R is irrigation, ETc is evapotranspiration, and D is deep percolation or drainage. Each of these variables has been determined for the Cauca river valley in Colombia.

#### *Evapotranspiration*

It is calculated as ETc = ETo * Kc, where ETo is the potential evapotranspiration, and Kc is a crop factor. A model was developed for sugarcane farming to estimate the ETo for the different conditions of the Cauca river valley, based on meteorological variables measured through the Network of Meteorological Stations of the Agroindustrial Sugarcane Sector of Colombia (Torres et al., 2004). The Kc crop factor values were determined using drainage lysimeters and adjusted for new varieties using weighing lysimeters. Table 1 shows the Kc values to estimate ETc based on the age of the sugarcane grown in the Cauca river valley in Colombia.

Table 1. Kc values obtained for commercial sugarcane varieties grown in the Cauca river valley, Colombia.

| Kc value | Crop age (months) |
|---|---|
| 0.3 | 1-3 |
| 0.4 | 3-4 |
| 0.6 | 4-5 |
| 0.7 | 5-6 |
| 0.8 | 6-8 |
| 0.7 | 8-9 |
| 0.6 | 9-11 |

Source: Cruz, 2015.

### *Rapidly available water layer (LARA)*

The LARA was calculated for the different areas growing sugarcane and classified by soil consociations, using the method recommended by the American Society of Agricultural and Biological Engineers (ASABE). This information is available to users through an automated application that can be accessed anywhere through an internet connection.

### *Effective precipitation (Pe)*

The variable percentage method is used for sugarcane, which considers Pe as 90% of the total rainfall for the year's rainy months and 80% for the dry months.

Since the Pe has a determining impact on the accuracy of the water balance method, this process is currently being studied using a rainfall simulator to generate a function that makes it possible to estimate the Pe based on variables such as rainfall intensity, quantity, soil type, the slope of the plot and initial moisture, among others.

### *Water supply through irrigation*

The percentage of water stored in the soil after irrigation will depend on irrigation efficiency, and it is crucial for computing the water balance and making irrigation management decisions. It is calculated by measuring soil moisture levels before irrigation and 24 hours after. The same is done for the different systems. Table 2 shows the efficiency levels of the irrigation systems used in sugarcane farming in Colombia's Cauca river valley.

Table 2 Efficiency of two irrigation systems used in the Cauca river valley, Colombia, for sugarcane irrigation.

| Irrigation system | Efficiency (%) |
|---|---|
| Gravity/furrows | 49 |
| Self-propelled traveler irrigation | 71 |
| Pivot irrigation | 80 |
| Surface drip irrigation | 90 |
| Subsurface drip irrigation | 95 |

Source: Compiled by the authors.

## The water balance method

The water balance method is used in Colombia's sugarcane agroindustrial sector to determine the irrigation needs of sugarcane crops in the Cauca river valley. For this purpose, the Prioritized Water Balance application was developed, which operates online and is linked to a network of 38 automated weather stations, providing detailed soil and geographic information for each of the sugarcane farms (Torres et al., 2004). This application allows users to enter the farm, rainfall, irrigation, and crop information and make calculations for irrigation scheduling and its administrative management.

## Adequacy of the method

The water balance method for irrigation scheduling can be used for other crops and regions. Therefore, it is necessary to determine and define strategies for estimating each of the balance parameters.

## Advantages and limitations

- This method is simple, low cost, and easy to use and makes it possible to learn the approximate soil water availability for crops to schedule and prioritize irrigation.
- It can be used with large crops.
- It is a tool to improve irrigation management in different crops.
- The accuracy of the water balance depends on how accurately each of its components or parameters are determined, so it is necessary to gauge each specific site.
- The water balance method for irrigation scheduling in Colombia's sugarcane crops has made it possible to reduce water use by up to 50% compared to other scheduling methods, such as the fixed calendar method or crop observation.

## Irrigation scheduling using sensors

This method uses sensors to measure moisture content or soil water availability for plants to schedule sugarcane crop irrigation based on these variables (Hincapié, 2018; Shock and Wang, 2011).

The study unfolded in several stages. In the first stage, it was necessary to define the variable, or variables, to measure and evaluate different sensors to measure the selected variable. In the second stage, it was necessary to establish the technical criteria (value ranges to start and end irrigation) to use the irrigation scheduling sensors. In the third stage, a monitoring system or network was rolled out.

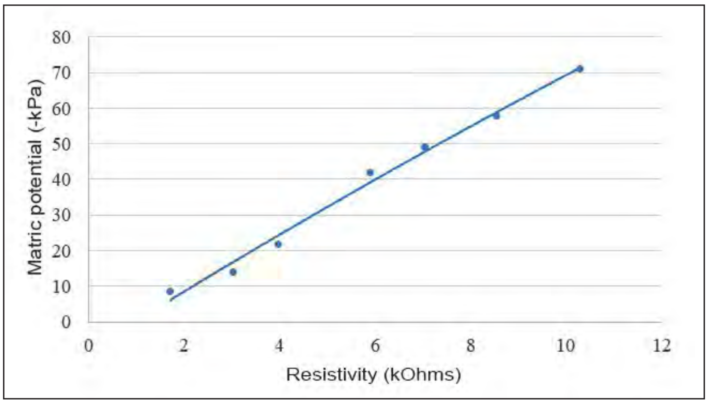
## Selection of the sensors and variable to be measured

The soil water tension or matric potential was defined as the most appropriate variable based on ease of measurement, accuracy, availability of adequate sensors, costs, and potential for automated measurements, among other criteria. This variable measures the energy with which the soil retains water, and, therefore, it is an indicator of water absorbed by the plants.

After the soil matric potential variable was selected, different sensors were assessed, for example, tensiometers with electronic transducers, resistive type sensors, and dielectric and temperature sensors. Resistive sensors were selected as the most suitable to be used in the irrigation scheduling method.

The resistive sensors used to measure soil matric potential consisted of two electrodes embedded in a porous cylinder wrapped in a metal mesh that allows water to enter and exit the sensor. The matric potential sensor's operation is based on the principle of variable electric resistance. Once the sensor is buried into the soil, it mimics the moisture content of the soil. When the soil is wet, and so is the sensor, the sensor conducts electric current efficiently; however, if the soil is dry, making the sensor dry, electric resistance increases. Thus, the current flow value through the sensor is used to estimate the soil matric potential using a calibration function. This type of matric potential sensor needs to be calibrated for every plot where they are installed. A soil sample is taken at the site where the sensors are installed, covering the sensor scanning area, an area with an approximate depth of 10 cm and a diameter of 10 cm. The soil sample is bagged and taken to the soil laboratory, where it is air-dried and then packed in cylinders and subjected to different potentials using Richards plates. The sensor's output signal is measured at each potential, and replicates of three or more samples are made for each calibration. Once the matric potential and sensor output values are obtained, the calibration curve and polynomial are created. Figure 1 shows the calibration curve for a resistive sensor type in a soil classified as Pachic Haplustoll, fine-loamy family.

Figure 1. Calibration curve for a matric potential sensor in a Pachic haplustoll, fine loam soil.




Source: Compiled by the authors.

The number of sensors installed in the field, the distribution, and the depth at which they should be installed are determined.

## Criteria for the use of matric potential sensors for irrigation scheduling in sugarcane farming.

The optimum soil matric potential range (RPMSO), under which water extraction by sugarcane roots is not affected, was determined. The relationship between soil water availability and production of different sugarcane varieties under greenhouse and field conditions was evaluated (Hincapié, 2018). The biomass and sugarcane production per hectare results are analyzed and adjusted to other models. Results are presented for an experiment conducted on sugarcane plants during the stage of maximum water extraction (3.5 months to 7 months of age) under greenhouse conditions. Tables 3 and 4 show the variance analysis and adjustment parameters of a log-normal model, which presented the best adjustment. Figure 2 shows the adjustment curve and the confidence interval of the model.

Table 3. Analysis of variance

| Source | DF | Sum of squares | Mean square | F value | Pr > F |
|---|---|---|---|---|---|
| Model | 3 | 437.20 | 145.70 | 309.42 | <,0001 |
| Error | 44 | 20.7250 | 0.4710 | | |
| Total | 47 | 458.00 | | | |

Source: Compiled by the authors.

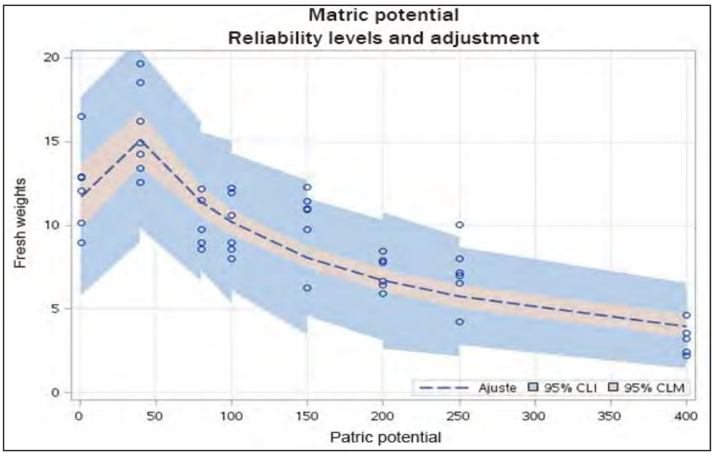
Table 4. Estimated parameters of the log-normal model

| Parameter | Estimated value | Approx. standard error | Confidence interval (95% prob.) | |
|---|---|---|---|---|
| a | 19,4542 | 1,3122 | 16,8097 | 22,0987 |
| Xo | 8,6718 | 0,8574 | 6,9439 | 10,3997 |
| b | 2,1496 | 0,1122 | 1,9234 | 2,3757 |

Source: Compiled by the authors.

Parameter a corresponds to the stress value at which maximum biomass production is obtained, and Xo and b are model adjustment parameters.

Figure 2. Model to estimate the optimum soil matric potential range (RPMSO) for cane between 3.5 and 7.0 months old, using the biomass fresh weight variable.




Source: Compiled by the authors.

Once the optimum soil matric potential range is defined, it is validated under field conditions through irrigation scheduling according to this range. Table 5 shows sugarcane production output obtained under different irrigation scheduling treatments in the Manuelita consociation lands. In this location, the soil is taxonomically classified as Fluventic Haplustolls, fine loam family.

In general, it was observed that the maximum water extraction by the sugarcane crop and maximum production level occur when the soil water conditions are close to -30 kPa (field capacity) and are drastically reduced when the soil goes over -150 kPa. Thus, it was possible to determine that crop production is not affected when the optimum soil matric potential range is between -20 kPa and -75 kPa. When no water is supplied through irrigation, production is reduced by up to 65% compared to a crop with no water restrictions.

Table 5. Sugarcane production obtained under different stress values for irrigation initiation under field conditions in a sugarcane crop in the Manuelita consociation.

| Soil matric potential to start irrigation (kPa) | Cane production (t.ha-1) | |
|---|---|---|
| | Plant cane | First ratoon |
| -75 | 148,78 a | 161,76 a |
| -100 | 142,00 a | 134,02 b |
| -125 | 137,78 a | 125,84 b |
| -150 | 137,71 a | 122,30 b |
| Testigo (sin riego) | 76,79 b | 56,10 c |

The different letters between treatments indicate significant differences at 95%, according to the Tukey test.
Source: Compiled by the authors

## Implementation of a pilot network for monitoring soil matric potential

The first version consisted of a hybrid IoT network, with monitoring stations based on Zig-Bee and mobile wireless technologies (GPRS, HSDPA, UMTS) that integrate acquisition, processing, and communication features, implemented through XBee® radio frequency modules and cellular modems.

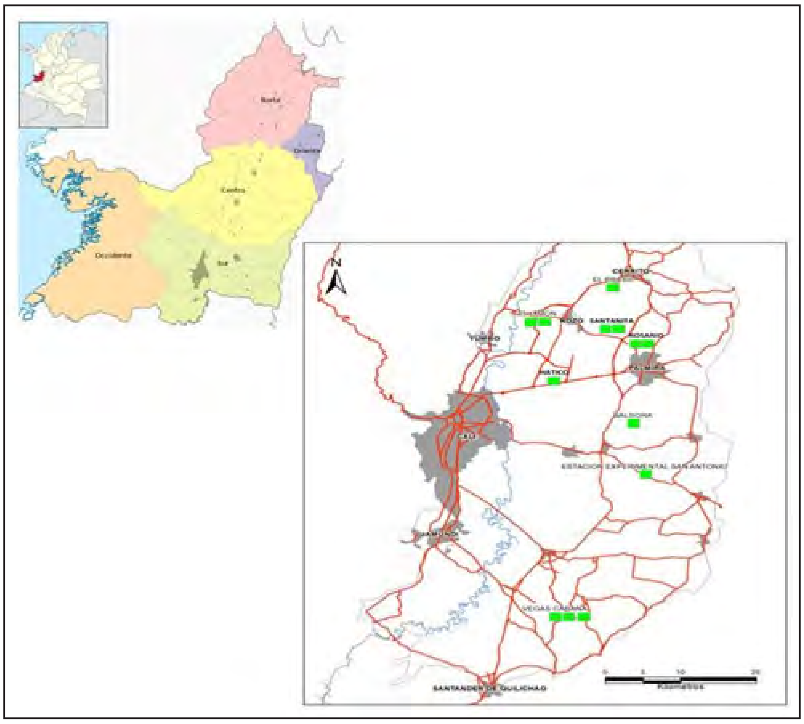
Each station consists of one or more nodes and a hub. A hub is the combination of XBee® receiver and cellular modem, which connect via RS232. These set up a wireless connection to send data via text messages to a receiving modem; the data is stored both in a datalogger and on a server. Once the data is on the server, it is managed by a mobile application.

Each node consists of a Cenilogger (datalogger) to which six matric potential sensors are connected plus an XBee® module. The radiofrequency modules provide the local network between the nodes and the hub at each site, creating the monitoring stations.

The cenilogger is an electronic circuit designed at Cenicaña for sensor reading and data storage. The first test version was based on the Arduino platform (Ruiz et al., 2018; Popovic et al., 2017; Mohanraj et al., 2016) because the hardware is easy to use, open-source, affordable, and it features different microcontrollers according to the application requirements. In a second version, robust, compact, weatherproof, and low power consumption ceniloggers were designed and built.

A pilot network with eight automatic stations and thirteen nodes was set up in the central area of the department of Valle del Cauca, Colombia, to monitor soil matric potential. Figure 3 shows the location of each of the stations and the nodes.

Figure 3. Location of the matric potential monitoring stations.




Source: Authors' records.

## Operation and performance of the monitoring stations

One of the objectives of implementing the pilot network was to evaluate its operation and performance under outdoor conditions in sugarcane fields. Some of the most common failures were battery discharge due to the station components' high energy consumption and communication loss due to low mobile reception coverage, which causes intermittent data transmission and high electric consumption.

A second version of the IoT network was developed and built based on the pilot network's performance. It consisted of:

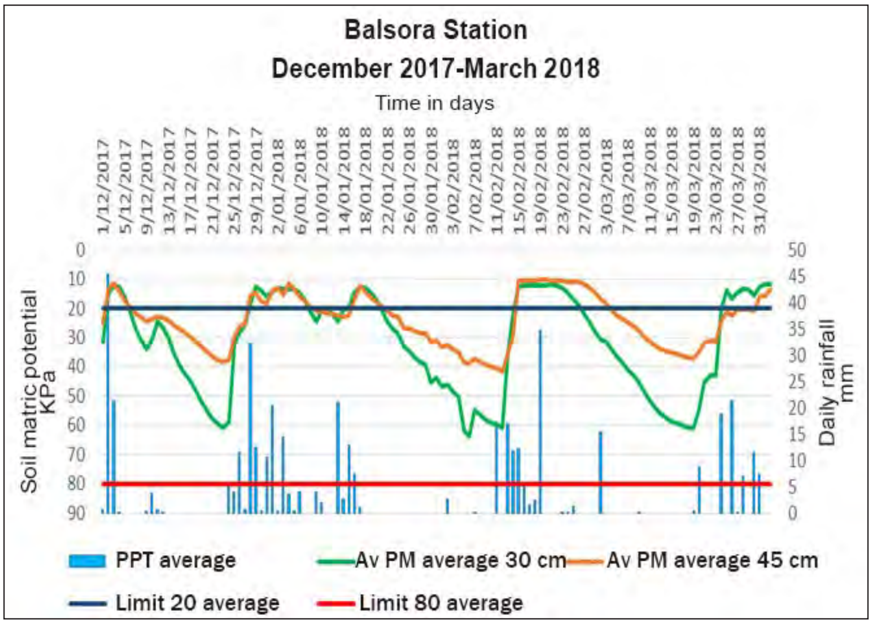
- A series of monitoring stations consisting of a battery of six resistive-type sensors, a temperature sensor to correct this variable's effect on the resistive sensors, a robust, low power consumption, weather-resistant, and low-cost cenilogger, and a solar panel.
- An IoT communication system based on LoRaWAN platform, with stations or relays strategically located along the Cauca river valley.
- A mobile application to see the information and use it as a tool for decision making.

## Using the method for irrigation scheduling in sugarcane farming

The soil matric potential data recorded at each of the monitoring stations were used for irrigation scheduling in each of the sugarcane crops where the station was installed.

Figure 4 shows the soil matric potential dynamics measured in a sugarcane crop cycle at two depths, 30 and 45 cm. The readings collected with the sensors installed at 30 cm were used for the sugarcane crop irrigation scheduling based on the above criteria. The readings collected with the sensors installed at 45 cm were used to verify that the irrigation water reached that particular depth as an irrigation quality indicator.

Figure 4. Behavior of soil matric potential during a sugarcane production cycle (13 months) in a fine loam class soil.




Source: Compiled by the authors.

Changes can be observed in soil matric potential due to water input from rainfall and irrigation (upward peaks) and water output from crop extraction (evapotranspiration). Part of the rain or irrigation water infiltrates and accumulates in the soil profile, increasing water availability for the crop. This process is reflected in the sensor and generates a change in the output signal, for example, from a value of -60 kPa to -10 kPa. Additionally, the sensor also shows when the crop extracts water from the soil due to evapotranspiration, going from high values (less negative), for example, -10 kPa, to lower values such as -70 kPa, indicating a gradual reduction of soil water availability for the plants. The right time to start irrigation is when the sensors reach mean values of -80 kPa ±5 kPa.

Matric potential data is presented to users as a curve similar to that in Figure 4. Since they can see it on the mobile app, this tool allows timely decision-making for irrigation management in sugarcane crops in the Cauca river valley in Colombia.

This irrigation scheduling method can be used in other crops.

It is first necessary to define the technical criteria related to the crop and the sensors.

## Advantages and limitations of the method

- It is a tool to improve decision-making, both in irrigation and drainage scheduling.
- It makes it possible to determine soil water availability at any given time, which helps optimize water use in sugarcane crops, and it has allowed reducing irrigation by up to 100%.
- It makes it possible to know the effective precipitation.
- Real-time information is available, and, therefore, it is possible to know the dynamics of soil water availability throughout the crop cycle.
- Monitoring soil water tension (matric potential) helps farmers optimize production, preserve water, reduce environmental impacts and save money.
- To use it, it is necessary to know the crop technical criteria and the monitoring system.
- It requires skilled staff for its implementation and management.
- In some cases, the cost can be high.

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# Nitrate removal using reactive barriers for groundwater application

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**Abstract**

Groundwater nitrate pollution ($NO_3^-$) is caused by infiltration associated with nitrogen fertilizers, livestock farming, and untreated wastewater discharges. The ingestion of water with a level of $NO_3^-$ above 50 mg/l by infants under the age of one may cause methemoglobinemia. This condition leads to a deficiency in oxygen transportation in the bloodstream. A permeable reactive barrier (PRB) is a technology for the remediation of polluted groundwater. PRBs are placed perpendicular to the water flow, where geochemical reactions remove or stabilize the $NO_3^-$ pollutant. Two types of PRBs were designed in this study for this purpose.

The first is a biological barrier (BB), for which we assessed four possible sources of microbial consortia based on activated sludge from wastewater treatment plants and two samples of agricultural land. Based on the performance of the consortia growth curves, we selected the sludge that had shown the most significant growth and $NO_3^-$ removal. This consortium was multiplied and fixed as a biofilm on porous volcanic rock, known locally as "*tezontle*." The second type of PRB was an anion exchange barrier (AEB).

For this, natural zeolite was physically and chemically conditioned with a 0.1 M solution. The PRB was supplied with 1.8 l/d of groundwater enriched with 100 mg/l of $NO_3^-$ for 30 days. In the laboratory, the BB had 80% removal efficiency while the AEB only 35%. In the AEB competition, we observed the anions present in the groundwater and the nitrate for the anion exchange sites.

**Keywords:** Activated sludge, biofilm, zeolite, anion exchange capacity.

## Introduction

Groundwater nitrate ($NO_3^-$) pollution has been reported around the world since 1970 (WHO, 2011). It is associated with microbial oxidation (nitrification) due to the use of nitrogen fertilizers, livestock farming (Pastén et al., 2014) and wastewater discharges, and atmospheric deposition as a result of acid rain (Hsu et al., 2016). Moreover, it is a mobile contaminant that infiltrates from grounds into aquifers (Montiel, 2015), and since it does not adsorb or precipitate as a mineral, it accumulates in water (Pacheco et al., 2004). Prolonged ingestion of water with amounts of $NO_3^-$ above the maximum permissible level of 50 mg/l (WHO, 2011) poses a health risk for children under one, as they can develop methemoglobinemia or blue child syndrome (Fewtrell, 2004; Martínez et al., 2017). Upon ingestion of $NO_3^-$ polluted water, nitrate it is reduced to $NO_2^-$ in the mouth and, once in the bloodstream, oxidizes the $Fe^{2+}$ in hemoglobin to $Fe^{3+}$, preventing oxygen from binding to the former.

The coagulation, flocculation, sedimentation, filtration, and adsorption processes are inefficient for $NO_3^-$ removal. However, processes that are based on ion exchange and biological treatments

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have shown high $NO_3^-$ removal efficiency (De Gennaro et al., 2014), although they have mainly been used as ex-situ treatments. An alternative to mitigate groundwater $NO_3^-$ pollution is to use in-situ PRBs, which consist of subsurface systems that create a gradient where the water passes through, and the pollutant is retained, immobilized, or turned into a different variety that is not harmful to health (Powell et al., 1998). This study evaluates the $NO_3^-$ removal efficiency of two permeable reactive barriers (PRB), one is biological, and the other is based on ion exchange in groundwater.

## Materials and methods

The experimental work was carried out at the Health and Environmental Engineering Laboratory (LISA), School of Engineering, National Autonomous University of Mexico (UNAM). Four microbial consortia were evaluated for BB development: (i) granular activated sludge from an upflow anaerobic sludge blanket reactor (UASB), (ii) activated sludge from a three-phase Anaerobic-Anoxic-Aerobic (A-A-A) reactor, and two layers of the agricultural soil profile of a *chinampa* in Xochimilco, Mexico City: (iii) 20-30 cm and (iv) 30-40 cm.

Aliquots were obtained from the activated sludge and soil samples, which were placed in a synthetic water solution without dissolved oxygen, simulating a nutrient solution (164 mg/l $KNO_3^-$, 31 mg/l $KH_2^-PO_4^-$, 26 mg/l $CaCl_4^-$, 0,68 mg/l $MgSO_4^-$ y 0,2 ml/l $C_2H_5OH$). The cultures were sampled periodically to determine the growth of the microbial consortia, and the following was observed: total volatile solids (TVS), chemical oxygen demand (COD), $NO_3^-$ concentration, pH, and Eh. We selected the consortium that presented the best conditions for biological denitrification and biofilm formation based on the growth curves. The selected consortium was multiplied and attached to a porous material locally known as "tezontle," with a size between 20 and 50 mm. For this purpose, the consortium was recirculated through 4 kg of tezontle placed in a PCV reactor 1 m high and 10.2 cm in diameter for 30 d. TVS, COD, $NO_3^-$ PH and Eh were checked periodically.

A natural tectosilicate, called clinoptilolite zeolite, which was screened to obtain particles between 0.5 and 2 mm, was used to develop the AEBs. The material was washed with distilled water and dried for 24 hrs at 103 ºC. Aliquots of the washed and dried material were then balanced in a $NaOH$ solution (0.1 M) by stirring 150 r/min at 40 ºC for 24 hrs. The material was then washed with deionized water to remove the excess $NaOH$ and dried again for 24 hrs at 103 ºC. Aliquots of the conditioned zeolite were used to determine the anion exchange capacity (AEC) and balanced in 0.1 $NHCl$ in a mechanical shaker for 1 hour. Before and after the $HCl$ treatment, the conditioned aliquots were titrated with a 0.2 N$Na0H$ solution, and the AEC was the difference between these results.

For the BB design, the hydraulic retention time (θ) was determined based on Eckenfelder (1989), for which we considered the $NO_3^-$ concentration in the influent ($S_o$) and effluent ($S$) as a removal efficiency parameter, the suspended volatile solids ($X$), the average temperature ($T$), specific denitrification rate ($U'_{DN}$), denitrification rate ($U'_{DN}$) and dissolved oxygen concentration ($Od$) in the groundwater (Equations 1 and 2).

$$U'_{DN} = U_{DN} \times 1.09^{(T-20)}(1 - Od) \quad \text{(Eq. 1)}$$

$$\theta\,[d^{-1}] = (S_o - S)/U'_{DN} \times X \quad \text{(Eq. 2)}$$

The PVC reactor with a 10.2 cm diameter was considered to determine the height of the BB. In addition, the hydraulic conductivity ($Ks$) of coarse (0.596<d<2 mm), medium (0.250<d<0.596 mm), and fine (d<0.250 mm) sand materials were analyzed to select the experiment conditions. Using Darcy's law, it was determined that the Ks of fine sand are similar to the permeability found in an upper aquitard of unconsolidated material (Sen, 2015). Considering the output ($Q$) allowed by the selected sand and the ($\theta$) from Equation 2, the BB height was calculated by clearing Equation 3.

$$Q[vol/time] = V/\theta \qquad \text{(Eq. 1)}$$

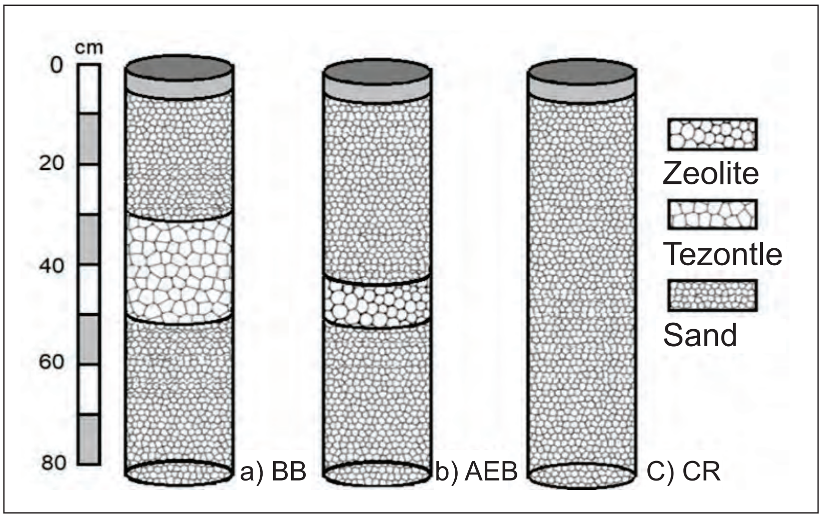
To design the AEB, we characterized the anion content in the groundwater of a well located in the UNAM School Campus and the AEC of the conditioned zeolite. In addition, we considered the used for the design of the BB, the diameter of the reactor and the $NO_3^-$ mass flow. This allowed us to calculate the height of the AEB. Figure 1 shows the configuration of the PRB. In order to compare the $NO_3^-$ removal efficiencies, we made duplicates of each reactor with the different PRBs, and of a control reactor ($CR$) with no PRB at all. We supplied each reactor with 1.8 l/d of $NO_3^-$ enriched groundwater using a peristaltic pump, adding a nutrient solution to the BB.

Equation 4 shows the removal efficiency ($ER$) of the reactive barriers' nitrate removal process.

$$ER\,(\%) = (C_o - C_f)/C_o \times 100 \qquad \text{(Eq. 4)}$$

where $C_o$ is the initial nitrate concentration and $C_f$ is the final nitrate concentration.

Figure 1. Diagram of PRBs for nitrate removal in groundwater

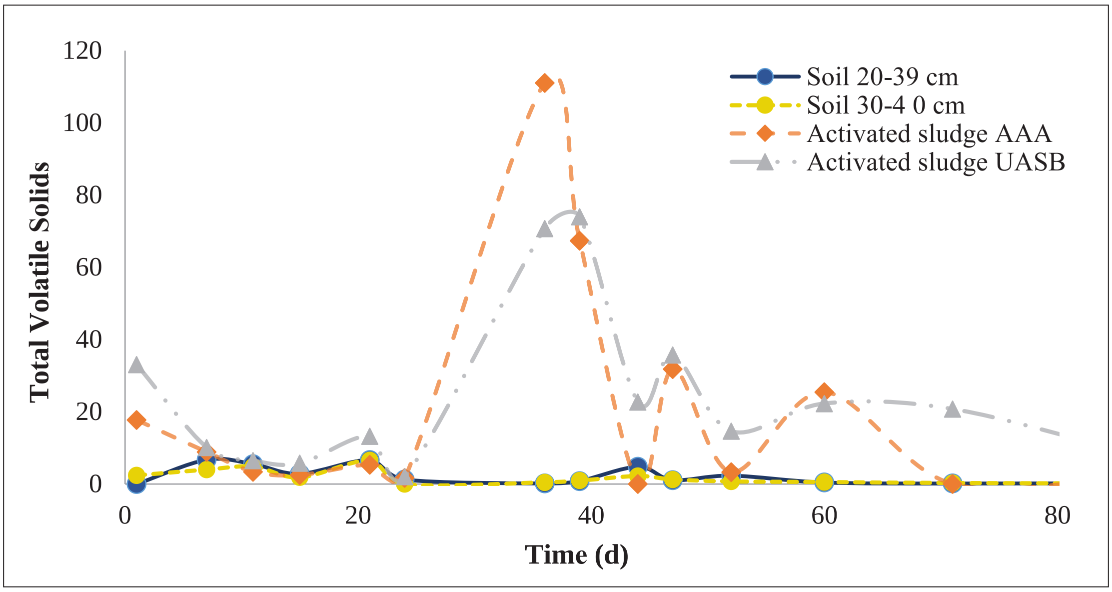



Source: Compiled by the authors.

## Results and discussion

Findings show that the activated sludge reached TVS of 110 mg/l in 30 days, reaching the maximum growth at the fourth week (Figure 2), while the soil samples did not exceed a level of 20 mg/l, although these peaked at around the third week. This is the result of factors such as the pH, $NO_3^-$ concentration and the presence of some compounds that may be toxic to the consortia (Rizvi et al., 2015).

Figure 2. Growth kinetics (TVS) to select the microbial consortium to be used in the BB.



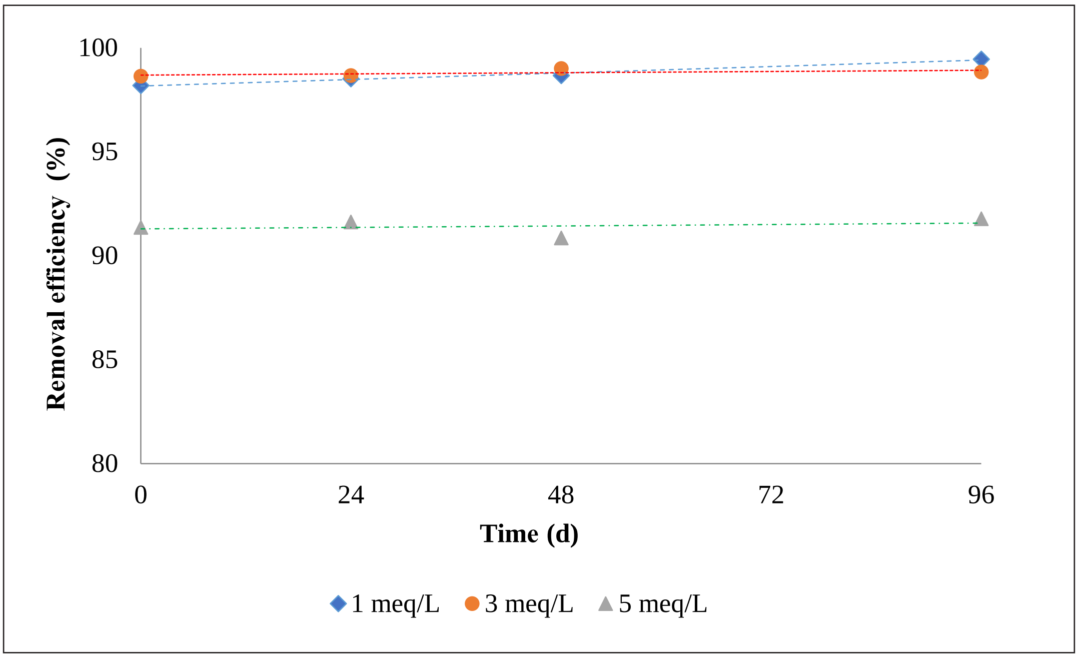

Source: Compiled by the authors.

At the laboratory scale, periods of microbial consortia development or acclimatization of up to 120 days—generating between 50 and 3000 mg/l of TVS—have been reported (He et al., 2016). The study findings have shown that the consortium from the UASB reactor sludge maintained optimal pH (Ovez, 2006) and Eh conditions (Brettar et al., 2002) for biological denitrification, with a pH level between 6.5 and 7 and an Eh level between -50 and 0 mV, respectively, in addition to a COD removal of 44%. The consortium from the A-A-A reactor showed TVS, pH, and Eh values similar to those of the UASB consortium. However, $NO_3^-$ removal was lower (87%) in the A-A-A reactor, while in the UASB consortium, it was 96%. Considering the above, the UASB consortium was selected for the biofilm formation stage in the BB.

The dimensions of the BB were calculated based on an expected $NO_3^-$ efficiency rate of 70% (Gilbert et al., 2008). By considering Equations 1 and 2, we obtained a $U'_{DN}$ = 0.45 and a $\theta$ = 20.5 h. To maintain the calculated $\theta$, the height of the BB (biofilm attached to the tezontle) was 20 cm. Using Darcy's equation and the Ks of the fine sand (2.35 x $10^{-4}$ m/s), we decided that the BB would be located after a 30 cm layer of fine sand to maintain a $Q$ level of 1.8 l/d. Meanwhile, the conditioned zeolite had an AEC of 0.94 meq/g. Based on the above, the height of the AEB was calculated at 10 cm, based on the concentration of anions in the groundwater (5.5 meq/l) and a mass flow of 10.4 meq/l.

The AEC obtained was similar to that found in commercial resins based on the exchange of anions such as $OH^-$ and $Cl^-$ (ResinTech, 2019). We used a batch test to determine the $NO_3^-$ removal efficiency of the conditioned zeolite. Figure 3 shows that the conditioned zeolite removes up to 98% of the $NO_3^-$ present in a solution of between 1 and 3 meq/l of $NO_3^-$. The efficiency decreases at higher $NO_3^-$ concentration due to the saturation of the ion exchange sites. In addition, the removal was followed by an increase in the pH of the solution due to the $OH^-$ ion exchange.

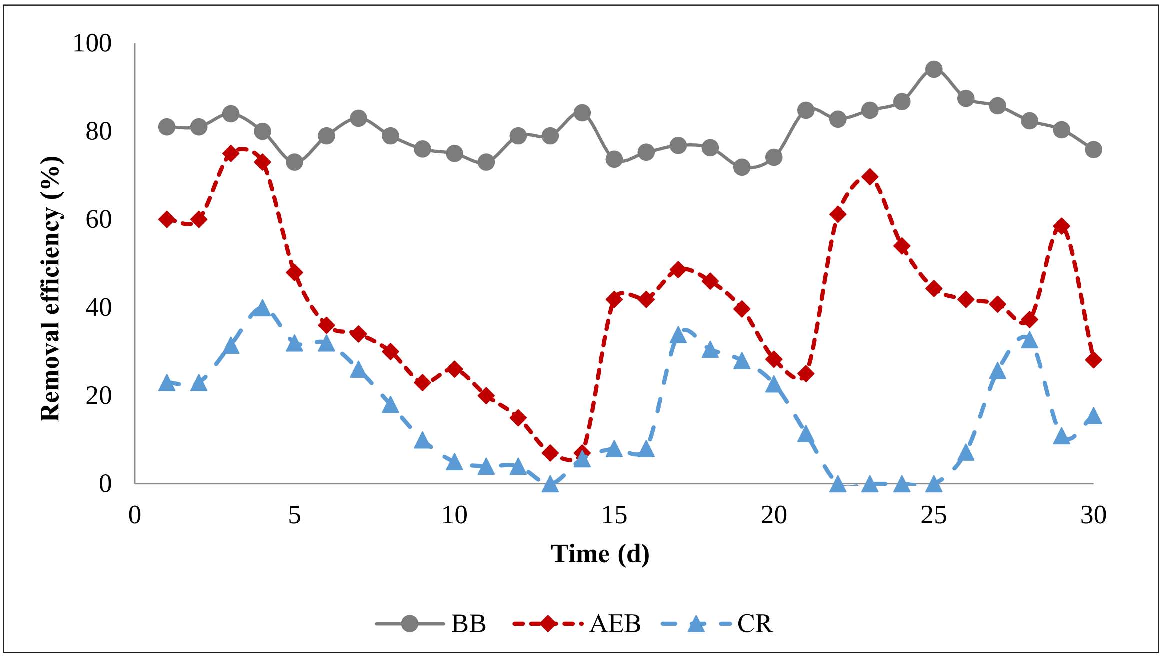
Figure 3. Nitrate removal in 5g of conditioned zeolite




Source: Compiled by the authors.

At the end of the operation period, the BB showed a higher $NO_3^-$ removal efficiency, with a significant difference ($\alpha = 0{,}05$), compared to the AEB and the control reactor. The BB's average removal percentage was 80%, while the AEB's was 35% (Figure 4). At the laboratory level, $NO_3^-$ removal efficiency rates between 44 and 93% (Hunter, 2002) and between 73 and 96% (Gilbert et al., 2008) have been observed in biological denitrification PRBs.

Figure 4. Nitrate removal in groundwater. AEB changes were performed on days 10, 17, 22, and 28 of the experiment.




Source: Compiled by the authors.

In terms of the conditioned zeolite's efficiency, the removal efficiency ($RE$) values fluctuated based on the AEB changes carried out on days 10, 17, 22, and 28 of the study. The loss of efficiency of the AEB can be attributed to two factors. The first is the presence of highly soluble anions in groundwater, such as bicarbonate ($HCO_3^-$), sulfate ($SO_3^{2-}$) and $Cl^-$, which compete with the $NO_3^-$ for the anion exchanger. According to Samatya et al. (2006), these anions increase the competition for the exchange sites. Likewise, the readings in the University Campus groundwater during the research period showed variations in anion concentration, mainly $HCO_3^-$ and $NO_3^-$, which may partially explain these variations. As a second factor, when analyzing the zeolite by X-ray diffractometry (XRD), we found that the composition of the commercial material used was only 50% natural clinoptilolite-type zeolite, and the remaining 50% was made up of calcite (43 ± 2.65%) and quartz (5 ± 3%), respectively. These minerals do not benefit ion-exchange sites. As for the control treatment, we observed a removal efficiency of up to 40% because the sand used had an AEC of 0.082 meq/g, which, combined with the reactor's dimensions, provided an AEC of up to 332.18 meq. However, on days 13, 23-25 of evaluation, we obtained concentrations at the outlet of the control reactor above those found at the inlet, so it is assumed that there was a release when the sites were saturated. A 1 $m^3$ biological permeable barrier would allow treating 1.2 $m^3$ of groundwater per day, removing 80 mg/l of nitrate, operating for at least 30 days. Meanwhile, an anion exchange barrier of the same size would remove 35 mg/l of nitrate in the same amount of water for a maximum of six days.

## Conclusions

In the absence of dissolved oxygen, we observed that a biological reactive barrier is more efficient in performing a denitrification process in groundwater thanks to developing microorganisms specific for nitrate removal, compared to a conditioned natural zeolite barrier, which gets saturated by the concentration of anions found in groundwater.

The lower efficiency of the anion exchange barrier can be explained by the competition between nitrate and other groundwater anions for anion exchange (AE) sites in the conditioned zeolite and of the content of minerals with low AE capacity, such as quartz and calcite, which have a significant impact considering the short period of actual operation before it is saturated.

## Acknowledgments

To the National Council of Science and Technology (CONACYT-SENER CVU 780094) and the Office of International Affairs and External Cooperation of the University of Costa Rica for funding.

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# Methods for Eutrophication Control and Evaluation in Water Bodies

*Abel A. Ruiz Castro[1] and Anne M. Hansen[2]*

**Abstract**

At least 50% of Mexican lakes and reservoirs are eutrophized (Conagua, 2019). This means a significant accumulation of nutrients such as phosphorus and nitrogen, leading to undesirable water quality conditions that limit these water bodies' potential use. There are different methods to recover eutrophized lakes and reservoirs, focusing on monitoring external and internal nutrient loads. Mass balances are essential tools to assess such practices. This paper examines methods to evaluate and monitor external and internal nutrient loads in water bodies to develop the most suitable remediation strategies. Two case studies are presented. The first one discusses the future El Arcediano dam in Mexico. This case study focuses on eutrophication prevention and monitoring strategies by compiling emission inventories, modeling the external nutrient load, and evaluating different monitoring scenarios. The second case comprised the evaluation of both external and internal loads in the Valle de Bravo Lake in Mexico, where nutrients and oxygen demand mass balances were carried out to scope different eutrophication control strategies. We concluded that it is necessary to consider both external and internal nutrient loads for eutrophication control in water bodies. Internal nutrient loads make it necessary to implement in-lake technologies.

**Keywords**: Nutrient loads, Eutrophication, Modelling, Mass balance, Scenario evaluation, Scoping.

## Introduction

Eutrophication is a water pollution problem observed worldwide. Statistics show that in the United States, this condition can be found in 65% of the estuaries (Bricker et al., 2008). At the same time, water quality tests in Mexican lakes and reservoirs (CONAGUA, 2019) show that at least 50% of these water bodies are classified as eutrophic. This means that there is a high accumulation of phosphorus (P) or nitrogen (N), or both, leading to increased primary production, toxic algae blooms, decreased dissolved oxygen, and other undesirable changes in water quality (Cooke et al., 2005), which affect the use of water for recreation, aquatic life, agriculture, livestock farming, and as a source of water supply.

Water bodies receive nutrient loads from external and internal sources. External load (EL) refers to nutrients from wastewater point source emissions and diffuse source runoff from urban, agricultural, livestock, and other land uses into hydrological basins. Internal nutrient load (IL) refers to N and P released from deposited sediment or suspended particles in water bodies, making these nutrients available for algae and bacterial growth (Nürnberg, 1994). Among the processes that favor the release of nutrients into the water are the reductive dissolution of iron and manganese substrates in anaerobic conditions (Márquez Pacheco et al., 2013) and microbial mineralization of organic matter (Jensen and Andersen, 1992).

There are different methods to restore eutrophic lakes and reservoirs and improve the water quality for different uses. These methods focus on the use of technologies that act either inside or outside the body of water. To select and scope the most suitable technologies, it is essential

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to analyze the specific problems that cause eutrophication and know the nutrient balance in the water body. This study addresses different technologies to assess and control eutrophication in water bodies to propose the most suitable remediation strategies.

## Methods

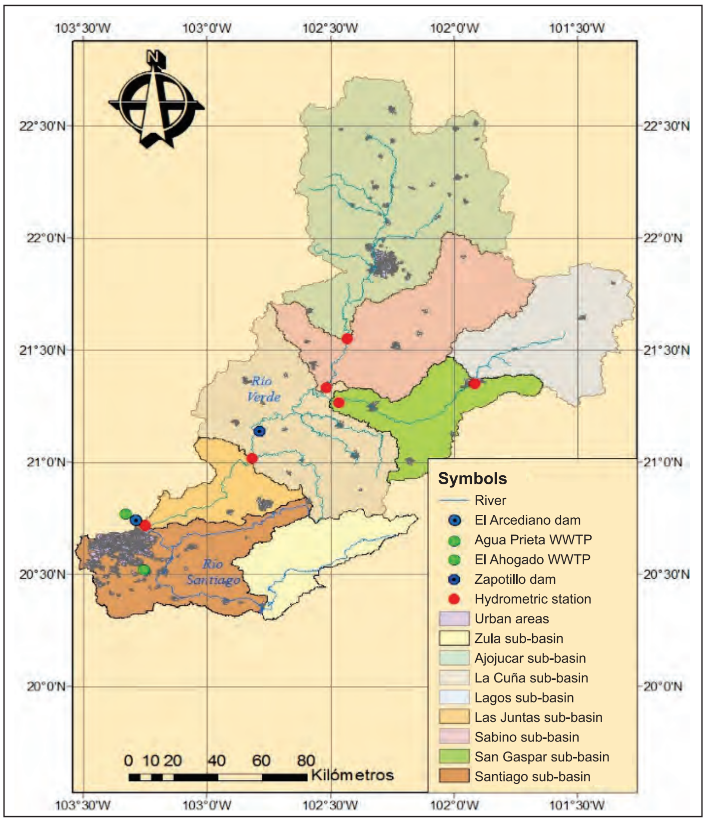
The following is a description of the technologies used for eutrophication assessment and proposed monitoring strategies in two water bodies in Mexico.

- El Arcediano reservoir (planned). Assessment of external nutrient loads and monitoring proposals in the hydrological basin.
- Valle de Bravo. Assessment of phosphorus mass balances and oxygen demand, external and internal loads for scoping eutrophication control methods.

### *El Arcediano (planned reservoir)*

Ruiz Castro et al. (2017) assessed the El Arcediano dam basin's external nutrient load using an N and P emissions inventory and a nutrient transport model for hydrological basins. Once built, the Arcediano Dam will supply drinking water to the metropolitan area of Guadalajara, Mexico. The El Arcediano Dam basin covers approximately 25,568 km$^2$, including the Verde and Santiago river sub-basins (Figure 1).

Figure 1. Hydrological basin of the future El Arcediano dam.




Source: Ruiz Castro et al., 2017.

These rivers carry significant N and P loads due to anthropogenic activities in the sub-basins, and the dams built on these rivers show signs of eutrophication (Hansen and Corzo Juárez, 2011).

Nutrient transport models in basins incorporate variables that impact the reactive transport of nutrients from emission to their final destination. These variables include the biogeophysical and hydrological properties of the basin and pollutant emissions from land use and direct discharges, transport, and natural mitigation in water and soil. This makes it possible to assess the magnitude of the nutrient loads found at the basins' outflow. These models are essential tools to develop nutrient monitoring actions (Kroeze et al., 2012). For this case study, we selected the NEWS2 (Global Nutrient Export from WaterSheds) model developed by Mayorga et al. (2010), which evaluates nutrient loads in both dissolved and particulate, organic and inorganic form, at the outflow of hydrological basins.

Ruiz Castro et al. (2017) describe the methodologies used to collect input data for the model used in the El Arcediano dam basin. The modeling results were verified with the P and N loads calculated based on the concentration levels of these nutrients and discharges obtained in the river. At the same time, to assess the impact of the external load at the mouth of the El Arcediano dam basin, we calculated the acceptable range of N and P loads to the dam using the threshold established by OECD (1982) and CEPIS (2001), which allows a mesotrophic level of nutrient concentrations. Finally, we studied the emission control scenarios presented in Table 1 and the subsequent reduction in nutrient loads that would reach the El Arcediano dam basin outflow.

Table 1. Scenarios for controlling external nutrient load at the outflow of the El Arcediano Dam basin

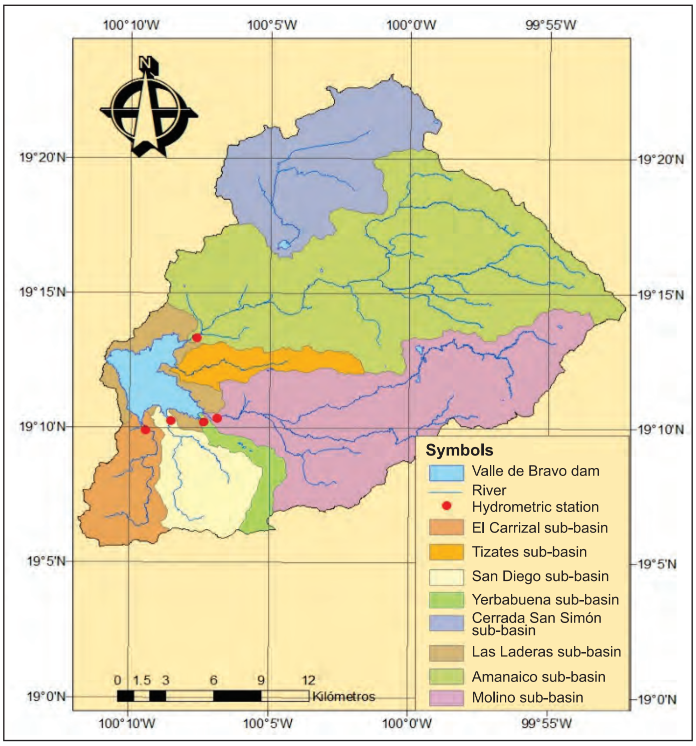
| Number | Scenario |
|---|---|
| 1 | Nutrient retention in a dam located upstream of El Arcediano dam and water extraction of 3.8 m3/s from the basin. |
| 2 | Increase in N and P removal efficiency from 40-45% to 80-90%, respectively, at the El Ahogado treatment plant, located upstream of El Arcediano dam. |
| 3 | 50% reduction in emissions from livestock farming waste across the El Arcediano basin. |
| 4 | Continuous diversion of 1.5 m3/s of wastewater out of the basin. |
| 5 | Combination of scenarios 1, 2, 3, and 4 |
| 6 | Combination of 1, 2, 3, and 4 plus nutrient retention due to sedimentation in the reservoir |

Source: Ruiz Castro, 2018: 201.

### *Valle de Bravo Dam*

The Valle de Bravo dam is a eutrophic reservoir with an approximate area of 1,680 ha and a storage volume of 328 million $m^3$. The hydrological basin covers 615 $km^2$ across eight sub-basins (Figure 2). This reservoir's eutrophic condition compromises its use as an essential source of water supply in the metropolitan area of Mexico City.

Figure 2. Hydrological basin of the Valle de Bravo dam




Source: Ruiz- Castro et al., 2017

### *Phosphorus mass balance*

Since phosphorus affects biomass growth in the Valle de Bravo dam, the methods to control eutrophication in this location focus on this particular nutrient. Márquez Pacheco et al. (2013) identified the annual P dynamics in the reservoir and used this information to scope the eutrophication control options considering the application of Phoslock®, a highly selective adsorbent for this nutrient (Afsar and Groves, 2009).

For this purpose, they developed the P balance for the dam (Eq. 1), considering two scenarios: (i) current external load and (ii) reduced external load.

$$\Delta P = CE + CI - P_{ext} - P_{sed} - ([P] - LM)\, V \qquad \text{(Eq. 1)}$$

Where

$\Delta P$ = P variation in water (t/year)

$CE$ = External P load (t/year)

$CI$ = Internal P load (t/year)

$P_{ext}$ = P extracted as biomass or dissolved in water (t/year)

$P_{sed}$ = Sedimented P (t/year)

$[P]$ = Initial P concentration in water (mg/l)

$LM$ = P threshold for mesotrophic water (mg/l)

$V$ = Water volume at the dam (million m$^3$)

*Oxygen demand mass balance*

Another method to control eutrophication in water bodies is hypolimnetic oxygenation. This method consists of supplying and dissolving oxygen at the bottom of water bodies (Beutel and Horne, 1999), which is more efficient at greater depth and lower temperature. Oxygen reacts with electron donors at the water-sediment interface, causing a decrease in oxygen demand and the formation of oxidized iron and manganese substrates, which act as P adsorbents, thus controlling the internal load of this nutrient. In order to determine the oxygen dynamics and demand in the Valle de Bravo dam, and therefore scope eutrophication control by hypolimnetic oxygenation, Hansen et al. (2017) developed the equation that describes the oxygen balance in water bodies (Eq. 2). The same authors described the methodology to collect each term of oxygen balance and demand, and use the equation to scope reservoir recovery through hypolimnetic oxygenation.

Considering the temperature and pressure conditions at the bottom of the Valle de Bravo dam, they assume that a hypolimnetic oxygenation system installed at the bottom of the dam can dissolve approximately 6 t/day or 2,190 t/year of oxygen (Alex Horne, personal communication, 2015).

$$DO_{fin} = DO_{ini} + DO_{sed} + DO_{CE} - DO_{ext} - OD_{nat} + OD_{SOH} \quad \text{(Eq. 2)}$$

Where

$DO_{fin}$ = hypolimnion oxygen demand at the end of a time interval

$DO_{ini}$ = hypolimnion oxygen demand at the beginning of a time interval

$DO_{ext}$ = Oxygen demand extracted from the body of water

$DO_{sed}$ = Sediment oxygen demand

$DO_{CE}$ = Oxygen demand due to external nutrient load

$OD_{nat}$ = Dissolved oxygen supplied through photosynthesis and atmospheric interaction

$OD_{SOH}$ = Dissolved oxygen supplied through hypolimnetic oxygenation system

## Results and discussion

Below we present the findings for the external nutrient loads that will reach the future El Arcediano dam in Mexico and potential control scenarios. We also show the results of external and internal nutrient loads in the Valle de Bravo dam, Mexico, the mass balances of nutrient and oxygen demands, and their role in scoping the use of different technologies to control eutrophication in this reservoir.

## Future El Arcediano dam

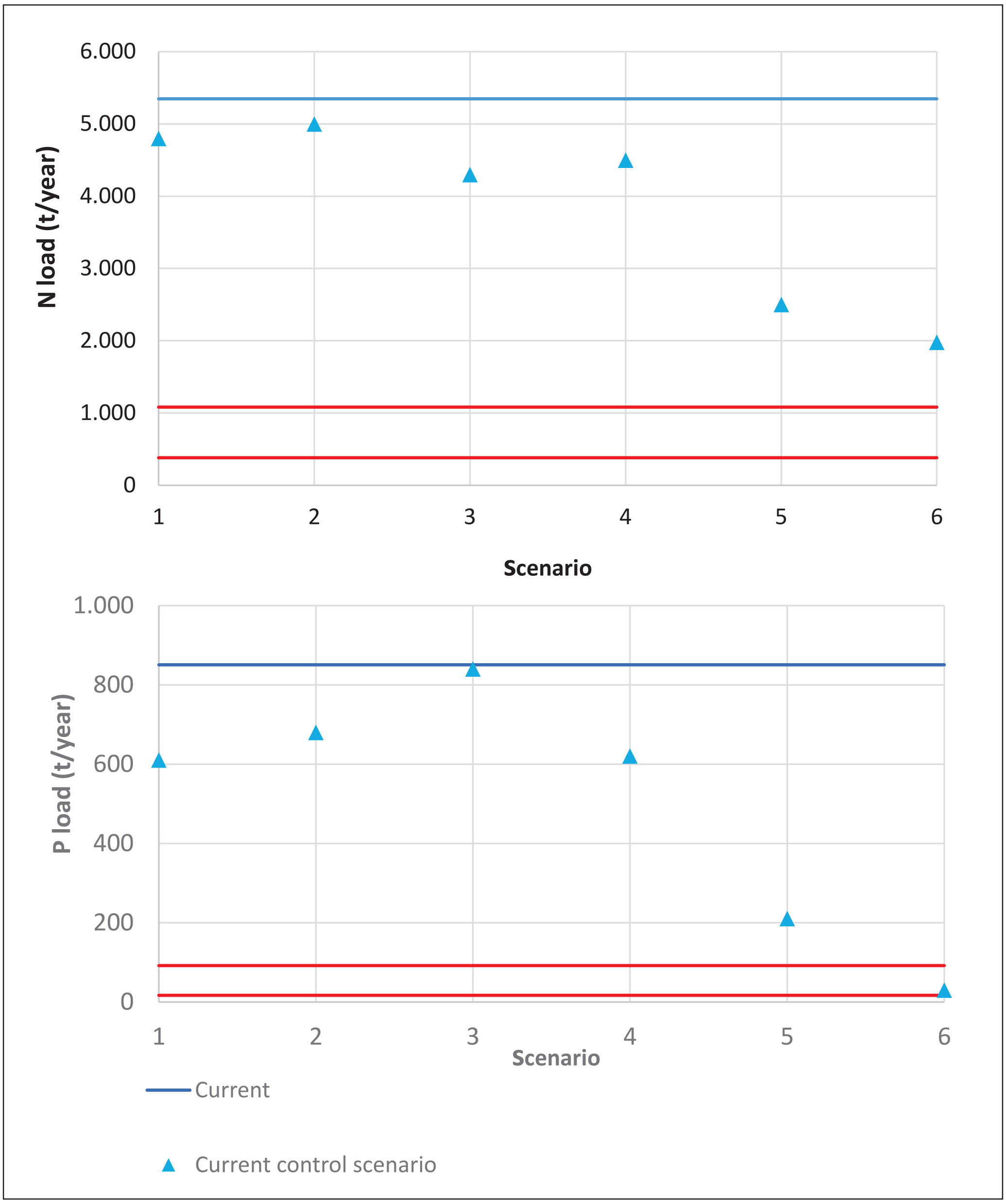
Based on the inventory of P and N emitting sources in the hydrological basin of the future El Arcediano dam, Ruiz Castro et al. (2017) estimated total N emissions of 148,500 t/year and total P emissions of 53,240 t/year. Livestock farming and domestic wastewater discharges are the sources with the highest emission levels. The authors report that the NEWS2 model helps mitigate most of these emissions, with only 1.6% of P and 3.6% of N being transported to the basin outflow. The high nutrient retention in the basin can be explained by the accumulation of nutrients in the soil and dams built on the Verde and Santiago rivers. Using curves describing nutrient retention in water bodies as a function of the hydraulic residence time (Beusen et al., 2005; Dumont et al., 2005; Harrison et al., 2005), Ruiz Castro (2018) found retentions of 85% of P and 30% of N in the dams.

According to Ruiz Castro (2018) and Jayme-Torres and Hansen (2018), the nutrient loads obtained with the NEWS2 model in rivers were within the variability range of the results observed when monitoring discharges and pollutant concentration.

Both the nutrient quantity and form of emission have an impact on their transport in the basin. Thus, although livestock farming results in higher emissions, it makes a low contribution to the nutrient load at the river outflow because, since it is deposited on the soil, it has a higher retention level. Meanwhile, the retention of wastewater emissions is lower because it is directly discharged into the rivers (Jayme-Torres and Hansen, 2018).

As shown in Figure 3, Ruiz Castro (2018) estimates that current P and N loads exceed the recommended ranges for mesotrophic water bodies. The figure also shows the results of N and P control scenarios. It should be noted that to control eutrophication in the future El Arcediano dam, all emission reduction efforts must be combined, and the nutrient retention in the dam itself (Table 1) must be considered to achieve P loads that ensure mesotrophic water. It is also noted that even implementing these measures, N will not reach the limit load for mesotrophic water. These results provide guidelines to draft a comprehensive strategy, which should be fully implemented to prevent and control P loads, thus avoiding excessive algae growth in the planned El Arcediano dam.

Figure 3. Nitrogen and phosphorus loads at the future El Arcediano dam basin outflow under the control scenarios described in Table 1




Source: Ruiz Castro, 2018.

## *Valle de Bravo Dam*

### *Phosphorus mass balance*

Márquez-Pacheco *et al.* 2013) report the annual amounts of external load, extraction, accumulation, and internal P load in the Valle de Bravo dam. With this information and Eq. 1, the authors scoped eutrophication control by applying a P-selective adsorbent in water and sediment under different application and external load scenarios (Table 2).

Table 2. Required amount of adsorbent and application frequencies for P control in Valle de Bravo dam.

| Scenario | Adsorbent application | | |
|---|---|---|---|
| | Water (t) | Sediment (t) | Total (t) |
| *EL estimated by Villanueva Beltrán (2011)* | | | |
| First annual application | 1,998 | 9,288 | 11,286 |
| Future annual applications | 431 | 1,592 | 2,023 |
| First five-year application | 1,998 | 19,968 | 21,966 |
| Future five-year applications | 431 | 10,681 | 11,112 |
| *With a 36% EL reduction* | | | |
| First annual application | 1,480 | 5,944 | 7,424 |
| Future annual applications | 0 | 1,019 | 1,019 |
| First five-year application | 1,480 | 12,780 | 14,260 |
| Future five-year applications | 0 | 6,836 | 6,836 |

Source: Márquez-Pacheco et al.

The scenario with estimated load for the year 2011 shows that an initial application of 11,286 t of selective adsorbent and annual reapplications of 2,023 t each year is required. With five-year applications, the initial amount would be 21,966 t with five-year reapplications of 11,112 t. Meanwhile, the scenario contemplating a P external load reduction of 36% suggests using fewer initial applications and that it would only be necessary to control internal loads in future applications (Márquez Pacheco et al., 2013).

### *Oxygen demand mass balance*

Hansen et al. (2017) report oxygen demands in water and sediment due to external load and extraction. Also, the natural dissolved oxygen inputs through photosynthesis, dissolution, and the oxygen supply through hypolimnetic oxygenation systems at Valle de Bravo Dam. Using this information, the authors were able to scope eutrophication control with these systems, specifying the number of oxygenators and time required to obtain and maintain excess dissolved oxygen in the hypolimnion under different scenarios of external load of oxygen demand (Table 3).

Table 3. Number of oxygenators and time required to obtain and maintain excess dissolved oxygen in the hypolimnion of Valle de Bravo dam, with and without external load reduction

| Number of oxygenators | External load of oxygen demand (t/year) | Time required (years) |
|---|---|---|
| 1 | 65.9 | 20 |
| | 48.5 | 10 |
| 2 | 65.9 | 6 |
| | 48.5 | 5 |
| 3 | 65.9 | 4 |
| | 48.5 | 3 |

Source: Hansen, 2018.

Based on these results, Hansen (2018) recommends installing and operating two oxygenators full time for six years. Under this scenario, assuming that the external load estimated in 2011 has not increased, sufficient dissolved oxygen would be obtained in the hypolimnion if there were two oxygenators for six years. With a reduced load, this time would decrease to five years. With only one oxygenator, in the scenarios using the 2011 estimated EL and reduced EL, these times would increase to twenty and ten years, respectively. Oxygenation times are not significantly reduced using three oxygenators instead of two; therefore, this option is not recommended.

The advantage of using an adsorbent is that it is faster than oxygenation. However, it is necessary to make continuous applications while there is still external load. Oxygenation is much slower than adsorbents, and, in addition, it is essential to ensure that there is enough iron in the system to form P adsorbent substrate. However, it is estimated that, once there is an excess of oxygen in the system, with sufficient oxygen application, oxygenated bottom water can be available year-round. These results suggest that a combination of P adsorbent and hypolimnetic oxygenation may offer the best overall solution for eutrophication control in the Valle de Bravo dam.

## Conclusions

This paper examines methods for evaluating and controlling eutrophication in water bodies to suggest the most suitable remediation strategies. Two case studies are described. The first one shows the creation of emission inventories, nutrient external load modeling, and the evaluation of control scenarios to formulate nutrient prevention and control strategies in the future El Arcediano dam, Mexico. The second study shows methodologies for scoping eutrophication control technologies at Valle de Bravo dam in Mexico, based on external and internal load assessments, development and application of P mass and oxygen demand balances, and the evaluation of external load reduction scenarios.

Based on the case studies presented, we concluded that the most suitable remediation strategies focus not only on external load control but also on internal load control, making the use of control technologies within water bodies indispensable.

## Acknowledgments

To UNESCO, for the opportunity to disclose these results at the seminar “Towards sustainable water management in Latin America and the Caribbean: sharing experiences on methods to preserve, increase availability and improve water-use efficiency” (Lima, Peru, August 5-6, 2019). To Suhaila Díaz Valencia for proof-reading and contributing comments on this work.

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# Conclusions

Overall, Latin America and the Caribbean have a relative abundance of water resources. These, however, must be preserved, restored, and sustained because, as shown by the different experiences presented in this document, overuse and narrow perspective focused solely and exclusively on consumption can alter the water balance in any area of the region, even those with water abundance.

In redefining water management, not from an abundance perspective anymore, but rather thinking about restrictions in any of the regions considered (whether humid or arid), water management should focus less on supply and much more on demand and rational use of water. Conversely, irrational water use is one of the main problems that the region is currently facing, probably because of this misconceived notion of abundance. Thus, we can see that efforts to increase supply will not meet growing demands if the latter are not adequately managed through proper water use and even, optimistically speaking, permanent water savings. To this end, it is necessary to begin effective and immediate monitoring of water resources using the new technologies available.

From the supply side, the shortage of usable quality water is a significant problem in many parts of LAC. The main reasons for this are associated with the aridity in many areas in the region, the irregular geographic distribution of water resources (excesses in some areas and large deficits in others), and the widespread urbanization, which has not been supported with water quality monitoring and control. Nowadays, there is a pressing need for studies on and for water reuse to prevent the loss of the valuable amounts discharged into water bodies, causing pollution in the watercourses and diminishing their potential for alternative uses. The region needs to explore innovative, fast-acting techniques and technologies for wastewater treatment and, most importantly, allocate resources for this type of research.

There is an evident lack of information in the region to enable water use monitoring and planning. Many of the papers presented in this document are based on approximations, generalizations, or regionalizations. Although these provide crucial information, at the same time, they carry a significant level of uncertainty as a result of the extraordinary geological, geomorphological, weather, hydrological, cultural, and social diversity in the LAC region. Even though many times it is not possible to compile databases to fill in those periods for which there is no monitoring and records, it is possible to undertake projects to reconstruct or estimate information on weather, soil, physiography, vegetation, etc., so it can then be used in descriptive and predictive models to inform water management.

Like the lack of information availability, the inclusion and use of widespread monitoring techniques with low-cost sensors is a pressing need in LAC. Knowing the exact amount of water that is available and used can help design and promote actions aimed at increasing water use efficiency, both in urban and rural settings. In other regions of the planet, low-cost sensors in low-cost computer systems and free access and open source computer platforms make it possible to monitor resources more efficiently with a low investment. These technologies should be more widespread, so global organizations such as IHP-LAC or others should promote these technologies and provide training for their adoption and use.

A critical issue reflected in the papers above is the fragmentation of water management under a sectoral approach. The analysis of water uses in LAC is undertaken by professionals from different areas and disciplines who have different visions and come from other institutional divisions, with low or minimal (in some cases) authority for coordination and articulation among them. This jeopardized the integration and efficiency of water planning and management efforts in many parts of LAC. It is alarming to see that water governance in the countries across the region shows poor interinstitutional and transboundary coordination. In general, water is regulated by the Ministries of Environment, the Ministries of Agriculture, Forestry, Industry, Public Works, and even Mining. This fragmentation leads to gaps in the law and overlapping responsibilities and roles, resulting in inefficient water use. In some cases, this leads to illegal water activities and pollution without any remediation actions due to poor oversight. Monitoring, early warning, and regulatory capacities should be integrated under a single authority, thus reducing the fragmentation of responsibilities and roles and making sure there is better engagement between water users and regulators. Moreover, the local organizations involved in water resource management need to advance collaborative work instead of managing water from a "competitive cultures" perspective. They can do this, for example, by making the information collected by the institutions public so it can benefit the communities in the region.

The fact that research is not widely promoted and that there are limited opportunities to share local, subregional and regional experiences is another weakness that goes hand in hand with the above. It is evident—and this document is a clear example—that many projects, research initiatives, technology development, etc., have been undertaken in the region. Still, the results are not always published, disseminated, or promoted effectively to a broader range of potential stakeholders. Thus, sometimes there excessive overlapping and obsolescence in research. Some other times we see the implementation of techniques that are not suitable for water conservation in contexts that differ from those they were developed in or strategies that have already shown their weaknesses in other contexts, but those results have not been published. All this, unfortunately, unfolds in a context of scarce financial resources, which is typical in LAC research. Thus, it is necessary to continue promoting forums or permanent spaces where to share experiences among regional researchers, experts, and users, who should display a high degree of commitment and motivation to become active participants and be involved in intra, inter, and transdisciplinary interaction. Nowadays, few settings encourage information exchange among researchers in the region, and there are no centralized systems that provide information on water-related publications or projects developed in the LAC region. Such systems would contribute significantly to disseminating knowledge and to the standardization, in some particular cases, of methodologies.

In addition, the willingness to share information is still limited, which hinders the use of methodologies to assess, with greater accuracy, how water resources management is being handled in the region, especially considering a context of climate change. Within this framework, and on top of the limitations that make it more challenging to adequately manage water resources in the region, weather projections show significant degrees of uncertainty in their results for the LAC region due to the great physiographic diversity. Thus, the estimates on the region's vulnerability to a shortage or excess of water in ecosystems—resulting from the physiographic, hydrological, weather, social and cultural diversity—are affected by high uncertainty levels and may therefore be biased depending on the region. For example, the generally humid areas may be very vulnerable to short and extreme droughts, which is not usually considered in vulnerability indices. In a region with a highly variable rainfall pattern, these considerations should be taken into account to better address the local circumstances since adaptation and development strategies are often based on these indices, which are sensitive to biases and asymmetries.

It is worth highlighting the significant role played by local communities in the LAC region. Many of these communities are highly empowered and have a great deal of knowledge, thanks to the long-standing tradition in agricultural production that runs across several generations. They can provide valuable information and potentially successful actions, which could be incorporated with a greater probability of success in local action programs. It would be useful to set up a system to exchange ecosystem information (especially water, temperature, and rainfall related) with the communities since national and regional weather services should provide information that is relevant to the communities concerned, taking their context into account. This could be achieved through a process of thorough information exchange with local stakeholders.

In terms of the always controversial water policies, it is clear that there are currently several water policies, laws, and regulations available in the LAC region. Still, they are not all widely known, and, in some cases, they have not been fully enforced. Therefore, instead of focusing on creating, adopting, or implementing new water policies, we should focus on education, dissemination, training, and empowerment of the local stakeholders that enforce or need water policies.

Finally, the need for advanced and user-friendly technologies for better water management should be addressed as a priority. We know that many environmentally friendly and relatively inexpensive technologies could be used in our region for water resource planning, management, and monitoring. Still, many of these are not available or are not widely known by local water stakeholders in the LAC region.

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