Region - Water Conservancy, 2025, Volume8, Issue1
DOI: 10.32629/rwc.v8i1.3425
ISSN Online: 2630-4902

Contribution of High-Andean ecosystems in providing the water regulation ecosystem service

Ronal Cervantes[1,2,*], José Miguel Sánchez[1], Julio Alegre[1], Eric Rendón[1], Jan R. Baiker[3,4,5,6], Bruno Locatelli[7,8], Vivien Bonnesoeur[9]

1. Universidad Nacional Agraria la Molina, Perú 2. Superintendencia Nacional de Servicios de Saneamiento (SUNASS), Perú 3.Programa Bosques Andinos, HELVETAS Swiss Intercooperation, Perú 4. Asociación para la Conservación y Estudio de Montañas Andinas-Amazónicas (ACEMAA), Perú 5. Iniciativa Regional de Monitoreo Hidrológico de Ecosistemas Andinos (iMHEA), Perú 6. University of Zurich, Suiza 7. Centro para la Investigación Forestal Internacional (CIFOR, por sus siglas en inglés), Perú 8. Universidad de Montpellier, Francia 9. Consorcio para el Desarrollo de la Ecorregión Andina (CONDESAN), Perú
*Corresponding Author:
Email address: ronalcervantes@gmail.com.

Abstract: The ecosystem service of water regulation is one of the most important services provided by high Andean ecosystems. However, knowledge about its contribution in terms of water is still scarce and its estimation is difficult, due to the complex eco-hydrological and climatic processes and environmental characteristics of the Andes. Therefore, we estimated the influence of three types of ecosystems (humid puna grassland, tropical high-Andean wetland -- bofedal and Polylepis forest) on water flows, particularly the flows that are directed towards underground storage, which are equivalent to the ecosystem service of water regulation. This study was carried out during the hydrological year 2018 - 2019 in the hydrographic unit of Rontoccocha, between 3,900 and 4,635 masl, in the Department of Apurimac, Peru. For this purpose, the water balance for each type of ecosystem was modeled with the eco-hydrological tool Hydrobal. Variables of: a) vegetation, b) climatic parameters and c) soil characteristics were used. The results reveal the contribution of vegetation cover in water regulation. In each ecosystem, about 15% of all rainfall in the basin reaches underground storage. These data, extrapolated to the entire hydrographic unit, show that the humid puna grassland regulates 80%, the bofedal 17% and the Polylepis forest 3%. Although the evaluation was carried out separately for each ecosystem, for management purposes, it is necessary to address them in an integrated manner, given that there are interdependent relationships between them.

Key words: Andes; humid puna grassland; tropical high-Andean wetland; Polylepis forest; water balance

1 Introduction

Water regulated ecosystem services, understood as the ability of ecosystems to store water during the rainy season and release water during the dry season (Llambi et al., 2012; Minam, 2019), are one of the most important services provided by the Andean plateau ecosystem for human well-being. These mountainous ecosystems provide the water that millions of people rely on for survival (Buytaert et al., 2006; Bonnessister et al., 2019). However, changes in land use and vegetation cover have become the main driving forces for altering hydrological services in these ecosystems (Ochoa Tocachi et al., 2016). On a global scale, this endangers the water security of over 50% of humanity who rely on mountainous water for drinking, irrigation, and food and energy production (Viviroli et al., 2007). Therefore, in the Alto Andean ecosystem, it is important to understand its functions to promote its protection and/or restoration, in order to ensure the sustained provision of ecosystem services.

Although the importance of ecosystems in water management in the Andean region, particularly in Puna and Harca, has been recognized, there has been little research on their functions to understand their dynamics and quantify their water contribution (Ochoa Tocachi et al., 2016; Somers & McKenzie, 2020). This measurement is a central issue in its management and various aspects of environmental and water policies, such as environmental accounting, natural resource assessment, conservation priorities, and planning (Brown et al., 2014).

Measuring the contribution of ecosystems to water management in the Andes Mountains is not a simple task. Ochoa Tocachi et al. (2016) argue that measuring ecosystem services or their impacts is challenging primarily due to the extreme diversity and complexity of the Andean region, characterized by high spatial and temporal gradients and variability in its geographic and hydro meteorological conditions. In other cases, the contribution of ecosystems to water regulation has not been fully evaluated, as vegetation has a relatively small weight in most water balance models and other models have not taken vegetation into account (Bellot&Chirino, 2013; Touhami, 2014).

It is not surprising that in the face of increasingly serious water supply problems, investments often prioritize the implementation of tangible (grey) infrastructure, while the contribution of ecosystems is hardly taken into account. However, people are increasingly recognizing the contribution of nature in solving water supply problems and its complementary role in traditional physical infrastructure methods. Therefore, investing in natural infrastructure not only helps solve water problems, but also optimizes economic resources due to lower costs (Leon, 2016).

In order to help bridge the aforementioned gap, this study aims to address the unknown contributions of three Alto Andean ecosystems (3,900 meters above sea level) to water management services: a) bofedales (high Andean wetlands), b) pajonal grassland of humid puna, and c) relict forests of Polylepis ("queñoal"). This provides an opportunity to emphasize the role of ecosystems in providing water to downstream populations and to better understand equity issues in watershed ecosystem service management (Vallet et al., 2019; Vallet et al., 2020). This will allow reorienting environmental management priorities in headwaters, such as payment for water ecosystem services initiatives or investments in natural infrastructure.

2 Materials and methods

The study was conducted in the Rontoccocha hydrographic unit, located at the headwaters of the Mariño river basin, between 3,900 and 4,635 masl, in Apurimac, Peru. It covers an area of 875 hectares and is the second largest source of human drinking water in Abankai city. There are four main ecosystems in the region: 1) humid Puna Pajonal (66.9%); 2） Bofedales (13.8%); 3) Polylepis Ruins Forest (2.2%) and Altoandinas Lagoon (4.0%), with rock outcrops accounting for 13.1% (Figure 1).

The contribution of ecosystems to water regulation is achieved by modeling the water balance in soil using the ecological hydrological tool Hydrobal proposed by Belot and Chirino (2013). This is a deterministic model, and its advantage over other models is that it considers vegetation as an important factor in water regulation (Tuhami, 2014). Hydrobal integrates meteorological conditions, vegetation characteristics and soil processes at the plot scale in ecosystems dominated by different vegetation types. With this, the outputs allow estimation of actual evapotranspiration, interception, surface runoff, soil water content and deep drainage for aquifer recharge (Bellot & Chirino, 2013). The model works as a function of Formula 1.

$\Delta SWC = P - Int - Eta - Roff - Pc$ [Formula 1]

Among them:

ΔSWC = soil water content

P = precipitation

Int = Interception

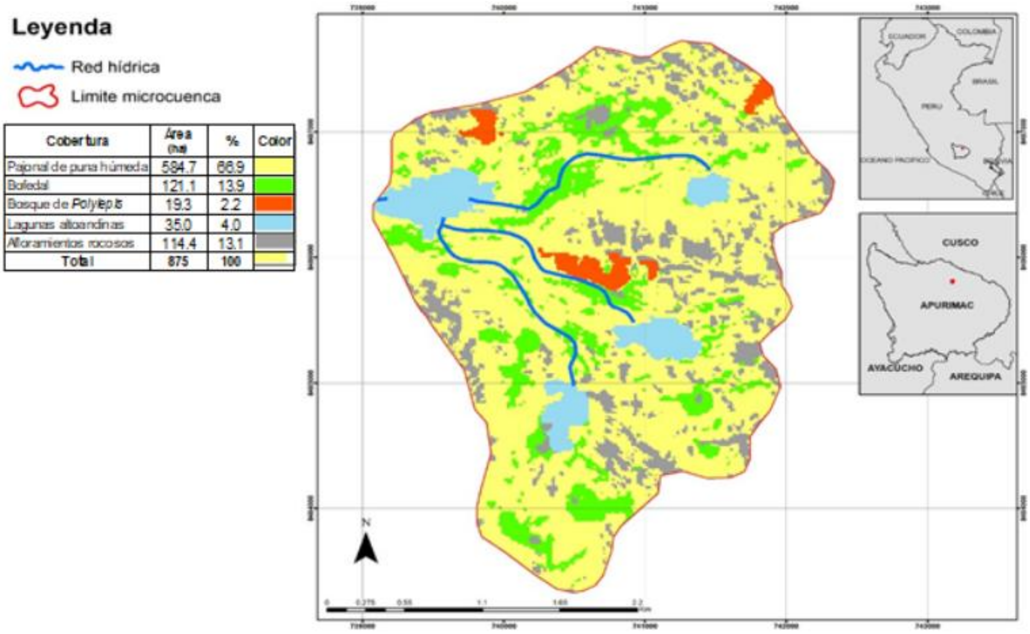
Eta = Real evapotranspiration

Roff = Surface runoff

Pc = Deep percolation

2.1 Data collection

Climatic data (precipitation and potential evapotranspiration), soil characteristics (texture, moisture, bulk density, field capacity) and vegetation (vegetation cover, composition and structure) were obtained.



Cobertura	Area (ha)	%	Color
Pajonal de puna húmeda	584.7	66.9	🟨
Bofedal	121.1	13.9	🟩
Bosque de *Polylepis*	19.3	2.2	🟥
Lagunas altoandinas	35.0	4.0	🟦
Afloramientos rocosos	114.4	13.1	⬜
Total	875	100	🟨

Figure 1. Study area: Rontoccocha hydrographic unit

Precipitation data were obtained from two digital rain gauges (onset HOBO RG3-M; data logging rain gauge) installed in the lower (4,062 masl) and upper (4,455 masl) part of the basin, which recorded information from the period 2016-2020 (Figure 2); however, for the modeling only data from the hydrological year 2018-2019 was processed. Potential evapotranspiration was obtained from the hydrological study of the Mariño watershed that processes historical data from the period 1965-2010, based on 14 stations of the National Meteorology and Hydrology Service of Peru - SENAMHI (GRA, 2013).

For soil information, six points were sampled in grasslands, six in wetlands and three in Polylepis forest. Texture, porosity, humidity and pH data were obtained from them. This first sample was complemented with data from the edaphological study of the Integral Management Project of the Mariño Microbasin (GRA, 2013) and the Project for the Recovery of Andean Ecosystems of Bofedales in six districts of the province of Abancay and Grau, Apurimac region. This resulted in a total of 14 samples in bofedal, 15 in pajonal and five in Polylepis forest. Then, with the previous data and the program "Soil Water Characteristics" of the United States Department of Agriculture (USDA, 2016), the field capacity and permanent wilting point were obtained.

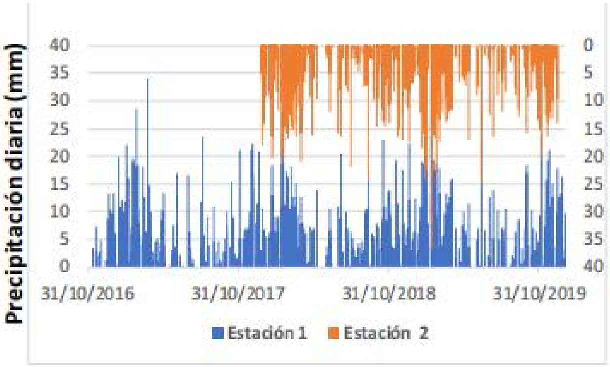


Figure 2. Daily rainfall of Rontoccocha hydrological unit

The vegetation data were worked on two levels: a) the coverage in the Rontoccocha hydrographic unit to know its distribution, and b) the composition and structure of each vegetation cover. The distribution of vegetation cover was established using cartographic material at a scale of 1:100,000 from the project "Validation and Publication of the EEZ of the Apurimac region" (GRA, 2010), updated with Sentinel-2 satellite images from the Copernicus server (ESA, 2018) (Figure 1). Meanwhile, the composition and structure of the ecosystems was analyzed at the level of the most representative and/or dominant species, given that taxonomic detail is not required for the purpose of the study. For this purpose, 12 observation plots of 1 m. were established in the pajonal and bofedal ecosystems, respectively, and six plots of 50 m. in the Polylepis forest.

2.2 Data analysis

Based on the described data, actual evapotranspiration, runoff, daily soil moisture, and deep drainage or recharge were calculated using Hydrobal. However, adjustments were made to the surface runoff of Pajonal and Polylepis forests and the deep infiltration results of Bofedal.

In the case of surface runoff, Hydrobal calculates this parameter through linear regression based on precipitation (ROFF=A+B (P)); P is the daily rainfall. Since runoff also depends on other factors such as slope, this parameter was introduced to improve the models in the Pahonar and Polilepis forest ecosystems. This process was carried out using the curve number method developed by the Soil Protection Service of the United States Department of Agriculture, which was adapted by Sprenger (1978) to include slope.

As for Bofedal, the reason for the adjustment is that it is a swamp ecosystem, and its groundwater level (depth of groundwater level) can be observed. Therefore, the regulatory capacity of the ecosystem will be the height from the groundwater level to the surface; surplus will leave the system in the form of runoff, as the soil is already saturated (USGS, 2016; Hasan&Khan, 2019). For this purpose, the maximum depth (minimum height) of the groundwater level during the dry season was measured, as since then, with the arrival of rainfall, regulation has begun. These data come from 37 permanent observation points: 20 observation points were recorded on July 7, 2019 and October 15, 2019, 17 observation points were recorded on July 17, 2018, 19 observation points were recorded on July 19, 2018, and 17 observation points were recorded on June 15, 2019. For this purpose, an observation tube ("groundwater monitoring well") was installed, which can measure the depth of groundwater level (Figure 3). The detailed information of the variables inserted into the Hydrobal model is shown in Table 1.

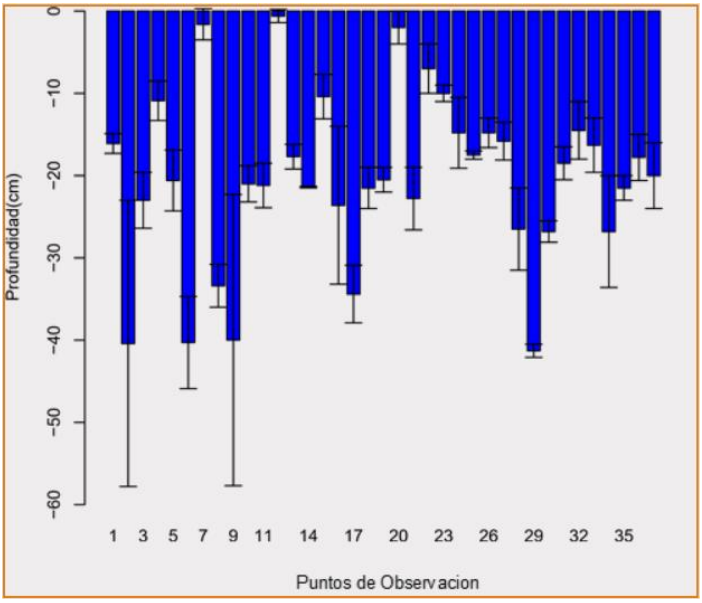


Figure 3. The average groundwater level depth at 37 observation points in the dry season of the Rontococha hydrological unit Bofedales

Table 1. Study and input the main soil characteristics in the ecosystem of the hydro ecological model

Observing humidity	Hobs. (%)	76.2 (8.27) [64.0 - 91.4]	35.3 (7.16) [26.4 -50.0]	50.3 (3.51) [47.0-54.0]
Field capacity	CC (%)	28.7 (3.50) [23.2-33.5]	29.4 (3.63) [21.1- 35.0]	27.4 (1.62) [25.7-28.9]
Permanent wilting point	Pmp (%)	16.4 (2.89) [11.1- 21.3	11.9 (2.42) [7.8- 16.4]	15.7 (1.02) [14.5-16.6]
Porosity	Ptotal (%)	72.4 (7.00) [61.2-83.4]	48.3 (4.49) [41.0- 58.2]	56.4 (2.47) [54.3-59.1]
Initial humidity	Hi (%)	16.4 (2.89) [11.1-21.3]	11.89 (2.42) [7.80-16.4]	15.7 (1.02) [14.6 -16.6]
% Soil coverage rate	Cover (%)	93.7 (6.44) [80 - 100]	82.0 (15.4) [50 - 100]	68.0 (9.13) [60 - 85]
Net rainfall*	Ln. (%)	99	99	87
Evapotranspiration k-factor	K (sin)	0.07	0.06	0.06
Texture	Tx	Organic silt loam, sandy loam	Sandy clay loam, silt loam	Sandy loam
Dep. water table	Prof (cm)	21 (11.99) [-65 - 0]		
Curve number, dry season	CN (sin)	-	47.1	45.0
Number of rainy season curves	CN (sin)	-	67.0	67.0

*Valencia & Tobón (2017).

2.3 Verification of results

To verify the validity of the results, water balance was conducted in the Rontococha Lagoon in the lower part of the micro watershed. Therefore, assuming this is the final reservoir for surface and groundwater flow in the Rontoccocha hydrological unit; Therefore, the underground flow calculated according to formula 2 (Hayashi&Van der Kamp, 2000; Lynn et al., 2006) should be consistent with Hydrobal's estimate.

$\Delta S = \Sigma Q_{in} + P - E - Q_{out} + Q_{Gwin} - Q_{Gwout}$ Formula 2

where:

ΔS = Changes in water storage; ΣQ_{in} = Total revenue from surface water sources

P = precipitation; E = evaporation; Q_{out} = Water outflow from surface sources;

Q_{Gwin}= Groundwater revenues; Q_{Gwout} = Groundwater outflows

In the Rontoccocha lagoon, since groundwater inflow and outflow were not measured directly, Formula 1 was simplified to Formula 3.

$\Delta S = \Sigma Q_{in} + P - E - Q_{out} + Q_{Res}$ Formula 3

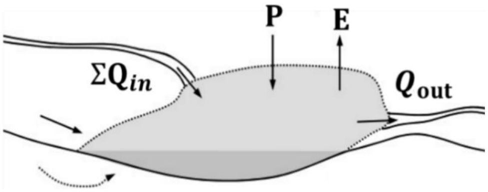
Qres or groundwater refers to the net inflow and outflow of groundwater flow (Lynn et al., 2006); For Lotanto, this value should be approximately equal to the volume calculated using Hydrobal (Figure 4). For this purpose, inflow and outflow measurements were taken using the Marino Basin Hydrological Study (GRA, 2013) and drinking water service provider Emusap Abancay. To verify these data, measurements were taken for 15 days during 2018 and 2019 on the water storage height and surface water inflow and outflow of Rontococha Lagoon.

3 Results and discussion

3.1 The behavior of major environmental variables in ecosystems

The first aspect that this study allows for analysis is the behavior of the main environmental variables that affect ecosystem water regulation: net rainfall, actual evapotranspiration, and surface runoff.

In terms of net rainfall, it can be seen that compared to Bofedal and Pajonal, the Polylepis forest has the highest interception level (9.5%) of the ecosystem, resulting in lower net rainfall (Table 2). Therefore, less water enters the soil to continue the hydrological cycle. This feature is meaningful because the interception process depends on the structural characteristics of the canopy, especially the leaf area index of the plant. Therefore, the larger the leaf area, the greater the interception (Körner et al., 1989; Bellot&Chirino, 2013; Valencia&Tohn, 2017). This explains why forests are better at intercepting rainfall than grass cover such as Pagona and Bofedal.



Hydrobal Model ≅ Qres

Figure 4. Water balance model to validate the effectiveness of water balance results; Hydrobal ≅ Q_{Res} is used for estimation Adapted from Hayashi&Van der Kamp (2000).

In terms of actual evapotranspiration, the results of Pajonal and Polylepis forests are similar, with 698 millimeters per year and 696 millimeters per year, respectively. However, in the Bofedal ecosystem, evaporation reaches 765mm/year (Table 2). This feature is due to the fact that Bofedal develops on a damp bed, allowing it to permanently obtain the water necessary for physiological development (Hayashi&Van der Kamp, 2000; USGS, 2016). Similarly, it can be seen that this is the main pathway for ecosystem water loss (averaging 54% to 59%), with the highest intensity during the rainy season (December to March) and a decrease in intensity during the dry season (April to November).

From the analysis of surface runoff, it can be seen that the behavior of these three ecosystems is similar, ranging from 24% to 25% (Table 2). For Bofedal, once groundwater reaches surface level, additional rainfall will be converted into runoff (USGS, 2016; Hasan&Khan, 2019); in the Pagona and Polilepis forests, runoff is mainly controlled by the slope and soil characteristics of their development.

Table 2. Results of water balance models for each ecosystem in the study (in millimeters, percentage of total precipitation in parentheses)

Ecosystem	Pp	Int.	Pp net	Esc.	Eta real	Recharge
Pajonal	1,290 (100%)	51.5 (4.0%)	1,240 (96.0%)	324 (25.1%)	698 (54.2%)	194 (15.1%)
Bofedal	1,290 (100%)	25.8 (2.0%)	1,260 (98.0%)	320 (24.9%)	765 (59.4%)	211 (16.4%)
Bosque de Polylepis	1,290 (100%)	122 (9.5%)	1,170 (90.5%)	311 (24.2%)	696 (54.1%)	198 (15.4%)

Precipitation (Pp), interception (Int), net precipitation (Pp net), surface runoff (Esc), current evapotranspiration (Eta).

3.2 Water regulation services in ecosystems

A comprehensive understanding of the various coverage areas studied can appreciate the input, output, and storage of water in the studied ecosystem. The water balance results indicate that evapotranspiration and runoff are the most important effluent processes in ecosystems. In terms of water management, it can be seen that Pahonar contributes 194 millimeters annually, accounting for 15.1% of all rainfall in the basin; the contribution of Bofedal is 211 millimeters per year, accounting for 16.4%, while the contribution of Polylepis forest is 198 millimeters per year, accounting for 15.4% (Table 2). In contrast, these results will be slightly higher than those found by Ochoa Tocachi et al. (2016), who achieved a water balance of 173 millimeters per year in a similar humid Puna environment in central Peru (Huamanganga/Lima Province). The authors consider that such values are low due to overgrazing in puna ecosystems.

In addition, by analyzing the water regulation (replenishment) process of a hydrological year, it can be seen that this process starts in December and ends in April, which are the beginning and end of the rainy season, respectively (Figure 5). It is also pointed out that replenishment is a dynamic process that goes hand in hand with precipitation behavior and the biophysical characteristics of ecosystems, such as soil and vegetation. However, in Bofedal, the charging process will end in February. In Bofedal, due to the groundwater level being close to the surface, when the ecosystem becomes saturated, it loses its ability to infiltrate water as subsequent rainfall is converted into runoff. Hayashi & Van der Kamp (2000) and Hasan & Khan (2019) explained this process, stating that this behavior occurs in ecosystems where the groundwater level is at or very close to the surface. Although in Bofedal, the replenishment process ends before the end of the rainfall season, it can be seen that its performance (210 millimeters) is better than other ecosystems in a hydrological year (Figure 5 and Figure 6). This fact can be explained by soil characteristics, such as the abundant porosity of peat and the small slope that reduces surface runoff and promotes infiltration.

By extrapolating these results to the entire study micro watershed, additional information about the correlation of each ecosystem in the regulatory process can be obtained (Table 3). Therefore, in Pahonar, 80% of the remaining water is regulated as a contribution to the recharge aquifer, in Bofedal, 17% of the water is regulated as a recharge aquifer, and in the Polilepis Forest, 3% of the water is regulated as a recharge aquifer. In terms of water volume, a total of 1,417,000 cubic meters can be adjusted within one hydrological year (Table 3). Compared with Q_{Res} (Table 4), this estimated quantity indicates that the results are roughly the same; Namely: 1,417,000 cubic meters ≌ 1,516,000 cubic meters. At the seasonal level, this is the thickest resolution for studying water regulation. Similar flows were observed between modeled and observed flows during the summer (May to November) and rainy season (December to April). Style: 410,415 ≌ 448,385; rainfall:1006776 ≌ 1,067,244. This result partially validates the specific calibration of the Hydrobal model to study the contribution of different high Andean ecosystems to water regulation services, but further information collection is needed to readjust and validate the calculations.

Table 3. Water regulation service for ecosystems, extrapolated to the entire area of the Rontoccocha hydrographic unit

Ecosystem	Area (ha)	Regulation (mm)	Regulation total (m^3)	%
Pajonal	585	194	1,136,000.00	80
Bofedal	121	210	240,000.00	17
Polylepis Forest	19.3	198	40,700.00	3
		Total	1,417,000.00	100

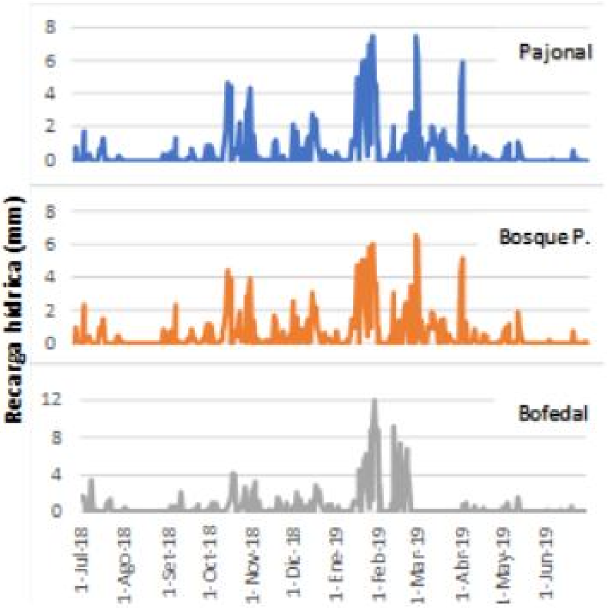


Figure 5. Water recharge process (regulation of ecosystem service) in the studied ecosystems (humid puna grassland, Bofedal and Polylepis forest) during a hydrological year

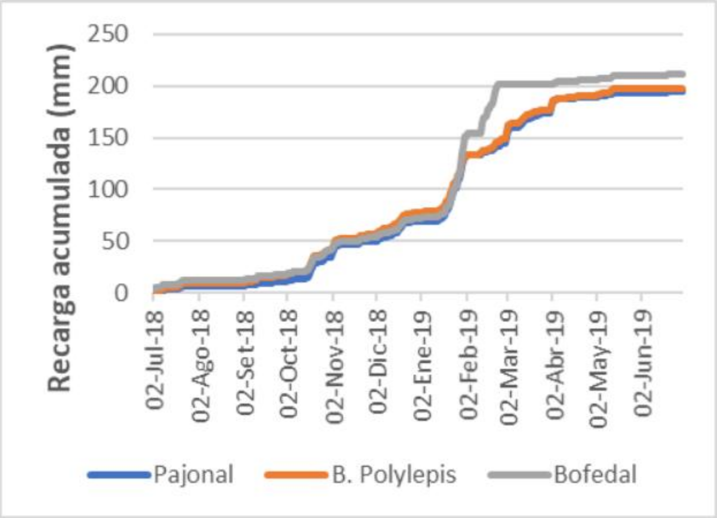


Figure 6. Research on the infiltration process of ecosystems and the provision of ecosystem services regulated by accumulated water: humid Puna Pajonal, Bofedal, and Polylepis forests

Based on the results, two central aspects of Rontococha hydrological unit water regulation ecosystem services were emphasized: its capacity per unit area and the capacity of the entire study micro watershed. Divided by unit area, the differences between the three ecosystems studied are relatively small. However, Bofedal's performance is slightly higher than Polylepis forest, which is superior to Pajonal forest. Among the entire hydrological unit, pajonal contributed the most to regulation, accounting for 79.4%. Some of the reasons for these contributions are due to the physical properties of the environment. But there are also special morphological, physiological, and ecological characteristics of mountain plants, such as being small in size, with small leaf area (LAI), shallow roots, but well developed (Tranquillini, 1964; Billings, 1974; Körner et al., 1989; Körner, 2003), which influence hydrological parameters (Bellot & Chirino, 2013; Touhami, 2014).

Similarly, the adaptation of mountain plants is also beneficial for water balance. During drought periods, these plants enter nutrient dormancy and their respiratory and photosynthetic abilities decrease, which allows them to reduce water loss compared to plants developed in low altitude areas (Billings, 1974; Körner, 2003). For example, short roots (but well-developed) limit their range to the deepest, thereby limiting their ability to extract and discharge water into the environment through evapotranspiration. On the contrary, as the soil dries, the extensive roots of trees extract water from the deepest to maintain their important functions.

Although the study presented results for each ecosystem separately, it was done for comparison and to facilitate their understanding. In reality, they are interrelated, interdependent, and functionally interconnected. For example, the interactions between ecosystems can be observed in estuaries and lagoons. Due to their location in lowlands and natural depressions, they receive recharge or infiltration of groundwater from the Cuenca Upper ecosystem (USGS, 2016), such as Pagonales. Similarly, Bofedales and lagoons hinder the rapid drainage of watershed water and aid in its storage (Hayashi&Van der Kamp, 2000; Hasan&Khan, 2019). Therefore, different elements of the watershed cannot be managed in isolation, and comprehensive management is needed. Similarly, in watersheds with dams, these interactions also reinforce the concept of complementarity that must exist between grey or tangible infrastructure and natural infrastructure, which, when combined, provide more effective and sustainable solutions (Cohen et al., 2016).

Finally, it is necessary to point out some limitations of this work. Firstly, due to the impact of ecosystem restoration, this study did not provide results on water supply. That is to say, it simulates the current situation. Therefore, further research must be conducted to measure the additional water contribution of Andean ecosystem restoration actions.

Secondly, it is necessary to continue validating the Hydrobal tool in the Andean region, as it was originally developed for the semi-arid Mediterranean region. However, its value lies in its ability to determine the impact of vegetation types on water balance and aquifer recharge (Bellot&Chirino, 2013). In both cases, it is necessary to continue monitoring the Andean Basin to enrich limited data on climate, vegetation cover, ecology, hydrology, soil, and other aspects. On this basis, the model can also be strengthened by having a larger time series.

Table 4. Water balance of the Rontoccocha lagoon and estimation of the volume of groundwater Q_{Res} to validate the Hydrobal modeling. Q_{in} (surface water inflow volume), h (height of water storage level in the lagoon), P (precipitation), E (evaporation) $\Delta V/\Delta t$ (change in storage)

Month	h (m)	Q_{in} (m^3)	Q_{out} (m^3)	P (m^3)	E (m^3)	$\Delta V/\Delta t$ (m^3)	Q^{Res} (m^3)
May	2.3	97,146	166,436	2,070	8,850	30 000.0	106,070
June	2.5	80,430	15,033	1,650	9,750	-36,000.0	6,703
July	2.26	70,040	118,867	1,440	10,800	18,000.0	76,187
August	2.38	60,813	118,867	4,200	11,550	-63,000.0	2404
September	1.96	52,021	115,033	2,400	10,800	21,000.0	92,412
October	2.1	74,674	113,966	7,920	11,100	84,000.0	126,472
November	2.66	87,273	142,690	7,830	10,050	-19,500.0	38,137
December	2.53	103,842	246,279	37,830	8,250	25,500.0	138,357
January	2.7	281,902	506,084	40,500	6,750	0.0	190,432
February	2.7	285,137	588,315	31,380	5,550	0.0	277,348
March	2.7	277,750	635,316	28,050	6,300	-45,000.0	290,816
April	2.4	167,184	396,965	6,690	7,200	-60,000.0	170,291
							1,516 000

4 Conclusion

Research has shown how high-altitude ecosystems above 3,900 meters contribute to ecosystem services for water regulation. Therefore, the regulation of the three evaluated ecosystems (Pagona, Bofedal, and Polilepis forests) did not show greater differences per unit area. However, at the watershed level, it is recognized that the Andes mountain range is the ecosystem that contributes the most to water management (80%) due to its wide coverage in the territory. In this sense, this study helps to understand the importance of these ecosystems in water supply, and in this sense, it also provides elements for improving investment policies and priorities related to planting water and strengthening water.

Acknowledgments

Special thanks to FONDECYT, an initiative of CONCYTEC Peru, for financing this research within the framework of the Doctorate in Economics of Natural Resources and Sustainable Development of the National Agrarian University La Molina (Agreement No. 200-2015-FONDECYT).

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Bellot J. & Chirino E. 2013. Hydrobal: An eco-hydrological modelling approach for assessing water balances in different vegetation types in semi-arid areas. Ecological Modelling, 266: 30-41. https://doi.org/10.1016/j.ecolmodel.2013.07.002.

[2] Billings W.D. 1974. Adaptations and origins of alpine plants. Arctic and Alpine Research, 6(2): 129-142. https://www.tandfonline.com/doi/abs/10.1080/00040851.1974.12003769

[3] Bonnesoeur V., Locatelli B., Ochoa-Tocachi B., Vanacker V., Mao Z., Stokes A. & Mathez-Stiefel S. 2019. Impacts of forests and forestation on hydrological services in the Andes: a systematic review. Forest Ecology and Management, 433: 569-584. https://doi.org/10.1016/j.foreco.2018.11.033.

[4] Brown C., Reyers B., Ingwall-King L., Mapendembe A., Nel J., O'Farrell P., Dixon M. & Bowles-Newark N. 2014. Measuring ecosystem services: guidance developing ecosystem services indicators. Cambridge, UK: UNEP-WCMC.

[5] Buytaert W., Célleri R., De Bièvre B., Cisneros F., Wyseure G., Deckers J. & Hofstede R. 2006. Human impact on the hydrology of the Andean páramos. Earth-Science Reviews, 79(1-2): 53-72. https://doi.org/10.1016/j.earscirev.2006.06.002.

[6] Cohen-Shacham E., Walters G., Janzen C. & Maginnis S. 2016. Nature-based Solutions to address global societal challenges. Gland, Switzerland: UICN. https://doi.org/10.2305/IUCN.CH.2016.13.en.

[7] ESA. 2018. Copernicus open access hub. ESA (The European Space Agency) Consultado en junio de 2019 de: https://scihub.copernicus.eu/.

[8] GRA. 2010. Zonificación ecológica y económica de la región Apurímac-ZEE. GRA (Gobierno Regional de Apurímac). Abancay, Apurímac, Perú.

[9] GRA. 2013. Hidrología de la cuenca del río Mariño. Un estudio definitivo del proyecto de gestión integral de la microcuenca Mariño-Apurímac. U.E. Pro Desarrollo Apurímac. GRA (Gobierno Regional de Apurímac). Abancay, Perú.

[10] Hasan H. & Khan A. 2019. Groundwater and Surface Water Interaction (Chapter 14). In: Venkatramanan S., Prasanna M.V. & Chung S.-Y. (eds). GIS and Geostatistical Techniques for Groundwater Science. 197-207. Amsterdam, Netherlands. https://doi.org/10.1016/B978-0-12-815413-7.00014-6.

[11] Hayashi M. & Van der Kamp G. 2000. Simple equation to present the volume-area-depth relations of shallow wetlands in small topographic depressions. Journal of Hydrology, 237(1-2): 74-85. https://doi.org/10.1016/S0022-1694(00)00300-0.

[12] Körner C., Neumayer M., Pelaez S. & Smeets-Scheel A. 1989. Functional Morphology of Mountain Plants. Flora, 182(5-6): 353-383. https://doi.org/10.1016/S0367-2530(17)30426-7.

[13] Körner C. 2003. Alpine Plant Life. Functional Plant Ecology of High Mountain Ecosystems. 2 ed. Springer. Basilea, Suiza. https://doi.org/10.1007/978-3-642-18970-8.

[14] León F. 2016. Inversión en infraestructura natural: haciendo sostenibles las inversiones en infraestructura física. Cooperación Alemana al Desarrollo – Agencia de la GIZ en el Perú. Lima.

[15] Llambí L., Soto A., Célleri R., De Bievre B., Ochoa B. & Borja P. 2012. Páramos Andinos: Ecología, hidrología y suelos de páramos. Proyecto Páramo Andino: CONDESAN, Instituto Humboldt (Colombia), EcoCiencia, Instituto de Montaña, ICAE (Instituto de Ciencias Ambientales y Ecológicas), GEF, UNEP, etc.). https://www.portalces.org/sites/default/files/references/040_LLamb%C3%AD%20et%20al.%202012.PP-Ecologia%20Hidrologia%20y%20Suelos%20de%20Paramos_0.pdf.

[16] Lynn Hood J., W Roy J. & Hayashi M. 2006. Importance of ground water in the water balance of alpine headwater lake. Geophysical Research Letters, 33(13): 1-5. https://doi.org/10.1029/2006GL026611.

[17] MINAM. 2019. RM N° 178-2019-MINAM: Lineamientos para la formulación de proyectos de inversión en las tipologías de ecosistemas, especies y apoyo al uso sostenible de la biodiversidad. El Peruano (Normas Legales), 36(14969): 7-8. Domingo 9 de Junio de 2019. MINAM (Ministerio del Ambiente). Lima/ Perú. https://busquedas.elperuano.pe/download/url/aprueban-los-lineamientos-para-la-formulacion-de-proyectos-resolucion-ministerial-n-178-2019-minam-1777515-1.

https://cdn.www.gob.pe/uploads/document/file/319848/RM_N__178-2019.pdf.

[18] Ochoa-Tocachi B., Buytaert W., De Bièbre B., Célleri R., Crespo P., Villacís M., Llerena CA., Acosta L., Villazón M., Guallpa M., Gil-Ríos J., Fuente P., Olaya D., Viñas P., Rojas G. & Arias S. 2016. Impacts of land use on the hydrological response of tropical Andean catchments. Hydrological Processes, 30(22): 4074-4089. https://doi.org/10.1002/hyp.10980.

[19] Somers L. & McKenzie J. 2020. A review of groundwater in high mountain environments. Wires Water, 7(6): e1475. https://doi.org/10.1002/wat2.1475.

[20] Sprenger F. 1978. Determination of direct runoff with the curve number method in the coastal area of Tanzania/East Africa. Wasser Boden, I: 13-16.

[21] Touhami I. 2014. Estimación del balance hídrico y de la recarga en el acuífero Ventós - Castellar (SE España). Efectos del cambio climático. Tesis Ph.D. España, Alicante, Universidad de Alicante. URI: http://hdl.handle.net/10045/41923.

[22] Tranquillini W. 1964. The physiology of plants at high altitudes. Annual Review of Plant Physioogyl, 15: 345-362. https://doi.org/10.1146/annurev.pp.15.060164.002021.

[23] USGS. 2016. Natural Processes of ground-water and surface-water interaction. In: Winter T.C., Harvey J.W., Franke O.L. & Alley W.M. Ground Water and Surface Water a Single Resource (https://pubs.usgs.gov/circ/circ1139/). USGS (United States Geological Survey), Circular 1139. Consultado en enero de 2020 de: https://pubs.usgs.gov/circ/circ1139/htdocs/natural_processes_of_ground.htm.

[24] USDA. 2016. Natural Resources Conservation Service. Soil Water Characteristics. USDA (United States Department of Agriculture). Consultado en abril de 2020 de: https://www.nrcs.usda.gov/.

[25] Valencia-Leguizamón J. & Tobón C. 2017. Influencia de la vegetación en el funcionamiento hidrológico de cuencas de humedales de alta montaña tropical. Ecosistemas, 26(2): 10-17. DOI: 10.7818/ECOS.2017.26-2.02.

[26] Vallet A., Locatelli B., Levrel H., Dendoncker N., Barnaud C. & Quispe Y. 2019. Linking equity, power and stakeholders' roles in relation to ecosystem services. Ecology and Society, 24(2): Art. 14. https://doi.org/10.5751/ES-10904-240214.

[27] Vallet A. Locatelli B. & Pramova E. 2020. Servicios ecosistémicos y equidad social: ¿quién controla, quién se beneficia y quién pierde? Infobrief, (311): 1-8. Traducción del No. 307 de November 2020. https://doi.org/10.17528/cifor/007850.

[28] Viviroli D., Durr H., Messerli B., Meybeck M. & Weingartner R. 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resource Research, 43(7): 1-13. https://doi.org/10.1029/2006WR005653