



PRIORITIZATION OF INVESTMENT IN ACTIVITIES TO IMPROVE THE PROVISION OF WATER ECOSYSTEM SERVICES: FOUR CASE STUDIES IN BOYACÁ, COLOMBIA †

[PRIORIZACIÓN DE LA INVERSIÓN EN ACTIVIDADES PARA LA MEJORA EN LA PROVISIÓN DE SERVICIOS ECOSISTÉMICOS HÍDRICOS: CUATRO CASOS DE ESTUDIO EN BOYACÁ, COLOMBIA]

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SUMMARY

Background. State investments to improve the quality and quantity of water for human consumption require cost-effectiveness, especially in the Latin American and Colombian socioeconomic context. The conceptual framework of water ecosystem services allows decision makers to prioritize areas where monetary resources do generate a real impact on the water supplied to municipal aqueducts. **Objective.** Determine the areas and activities that should be invested as a priority, to promote two water ES in four municipalities of Boyacá. **Methodology.** The software RIOS was used in order to generate geographical explicit scenarios to indicate the areas where the municipal government must implement activities that in the short, medium and long term, will guarantee a baseflow at the dry season and the decrease of sediments by erosion. **Results.** It was identified that the higher altitude wooded areas in the basin, should be the object of agroforestry programs in its multiple expressions. **Implications.** In the specific case of Togüi, agroforestry does not seem to be the activity that contributes to flow control, possibly because of the natural slopes of the basin. **Conclusion.** This information can be used as a basis for the development of payment for water ecosystem services schemes (PWS). **Key words:** Water ecosystem service; state investment; RIOS; agroforestry; PWS.

RESUMEN

Antecedentes. Las inversiones estatales para la mejora de la calidad y cantidad de agua de consumo humano, requieren costo-efectividad, especialmente en el contexto socioeconómico Latinoamericano y Colombiano. El marco conceptual de los servicios ecosistémicos hídricos permite a los tomadores de decisiones, priorizar zonas donde los recursos monetarios generan un impacto real en el agua que surte a los acueductos municipales. **Objetivo.** Determinar las zonas y actividades en las que se debería invertir de manera prioritaria, para potenciar dos SE hídricos en cuatro municipios de Boyacá. **Metodología.** Se implementó el software RIOS para generar escenarios geográficamente explícitos, que señalen las zonas donde el gobierno municipal debe implementar actividades que, a corto, mediano y largo plazo, garanticen un caudal base en época seca y la disminución de sedimentos por erosión. **Resultados.** Se identificó que las zonas boscosas de mayor altitud en la cuenca, deberían ser objeto de programas de agroforestería en sus múltiples expresiones. **Implicaciones.** En el caso puntual de Togüi, la agroforestería parece no ser la actividad que contribuya al control del caudal, posiblemente por el efecto de las pendientes naturales de la cuenca. **Conclusión.** Se recomienda usar esta información como base para el desarrollo de esquemas de pago por servicios ambientales hídricos (PSAH). **Palabras clave:** Servicio ecosistémico hídrico; inversión estatal; RIOS, agroforestería; PSAH.

INTRODUCTION

Ecosystem services (ES) are those benefits, direct and indirect, that human populations receive from the processes of nature (Costanza *et al.*, 1997; Millennium

Ecosystem Assessment, 2005; Díaz *et al.*, 2015). Some of these benefits are socially recognized and relatively easy to conceptualize, for example, the water regulation exerted by forests (Calder, 2002; Brauman *et al.*, 2007). The conceptual framework of ES

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provides excellent support to decision makers (Liu *et al.*, 2013) as it shows the benefit of balancing human and ecological needs and translates it into determinants for land use planning and the budget agenda (de Groot *et al.*, 2012; Ministry of the Environment and Sustainable Development, 2012; Rincón-Ruiz *et al.*, 2014).

The implementation of forest cover maintenance programs (reforestation, restoration and similar) in the tropics from state money does not usually have a high success rate, mainly due to the lack of linking these activities with a specific water objective and the need for state compliance with short-term goals or targets (Le *et al.*, 2014), not related to a specific ecosystem service. This results in administrative and budget wastage and generates in the community a feeling of mistrust and doubt of the effectiveness of the activities, preventing the arrival of new projects (Jacobs *et al.*, 2016; Vadell *et al.*, 2016; Ota *et al.*, 2020). The ES approach can be a solution to the prioritization of investment areas and activities, in this way the sectors are identified where a change in land use and promotion of forest cover will have visible effects on all time scales (Rodríguez-Eraso *et al.*, 2013; Vogl *et al.*, 2016a), decision-making will be effective and easier, in addition to restoring the population's trust in ecosystem protection programs.

The quality, quantity and temporality of the water resource has been a constant topic on the political and economic agenda (ICWE, 1992; Borkey *et al.*, 2005; Brauman *et al.*, 2007; Ministry of Environment and Sustainable Development, 2012), likewise, the water guarantee provides arguments for the need of conservation and restoration of ecosystems (Grizzetti *et al.*, 2016), especially at the local and regional level, where public resources must be optimized to the maximum. At this scale, it is important to achieve effective communication between scientists and territory managers (Ota *et al.*, 2020), in such a way that changes in land use are calculated, thinking not only about the economic return, but also on the well-being of the population and ecosystem health (Clement and Amezcaga, 2008). In order to achieve this, multiple computer tools have been created, which combine ecological theories with financial and administrative planning, in a geographically explicit framework, these instruments provide maps that are used as a universal language on the management of natural resources (Vorstius and Spray, 2015; Jacobs *et al.*, 2016).

The Resource Investment Optimization System -RIOS (Vogl *et al.*, 2016b), is one of those tools created to help territory managers answer questions such as,

What are the areas where you should invest to guarantee the water ES? What are the activities that will generate the highest return on that investment? What will happen in a long term with these areas and the water ES? This free software identifies the places in the basin where conservation, restoration and similar activities can improve the ES at the lowest cost, based on the hydrological and forestry concepts established in the scientific literature (Vogl *et al.*, 2016b). RIOS produces maps that represent where and what activities to develop (within a short spectrum of possibilities entered by the user), as well as a projection of the success of those activities in the future (Vogl *et al.*, 2016a; Vogl *et al.*, 2016b; Vogl *et al.*, 2017). This tool is designed for those basins with minimal economic investment facilities on environmental or conservation issues, either due to scarce state funds or sporadic opportunities of private financing.

This is the case of the department of Boyacá (Colombia), where social and public order needs monopolize the public budget (Gobernación de Boyacá, 2016), leaving the investment for environmental issues in a minimal percentage (Mira Ponton, 2017; Decree 1007). This work seeks to determine the areas and activities that should be invested as a priority, to promote two water ES in four municipalities of Boyacá, specifically the regulation of the base flow in the dry season and the control of erosion to reduce sediments in the water: as basic information on the implementation of future payment schemes for water environmental services (PWS) or investment programs for the recovery of municipal microbasins. The proposed hypothesis suggests that the optimal areas are found in the middle to high areas of the evaluated basins, in accordance with the history of land use and the biophysical/topographic conditions of the municipalities studied.

MATERIALS AND METHODS

Study area

The department of Boyacá is located in the eastern center of Colombia, on the eastern mountain range of the Andes. For the present study, we prioritized four municipalities, according to the macroproject "Valuation of ecosystem services from essential components of Norandina biodiversity" following three basic criteria: altitudinal gradient, location within the two main basins of the region (Magdalena's river and the Orinoco's river) and previous relationship of the research group with local communities. Thus, the project was developed in the municipalities of San Mateo, Togüí, Pauna and Miraflores.

Social-technical approach

In order to know the investment needs or priorities in the studied microbasins, field visits were carried out in each municipality, there the aqueducts officials, both administrators and operators of the intakes were interviewed. Through a semi-structured dialogue (Geilfus, 2002) we investigate about the mechanisms of capture and purification, events of overflow, fire in the upper part of the basin and reforestation, restoration or similar programs, within five years ago.

During these visits, municipal administrations were consulted about the predominant economic activities in the upper and middle parts of the microbasins; from them, the average data of production and sale per hectare.

Input data collection

From the social information obtained, two objectives were selected to be executed within RIOS: base flow in the dry season and erosion control for drinking water

quality. The input data for each model were obtained from official national sources (Table 1).

The data obtained was converted to a raster type format, later it was run in the preprocessing toolbox of ArcGIS (ESRI, 2018); In this way, the final inputs were obtained to run RIOS, in the two selected objectives.

Opportunity Cost and Investment Portfolio Advisor

In Colombia, payments for water ecosystem services (hereinafter PWS) are regulated by Decree 953 of 2013, Decree Law 870 of 2017 and Decree 1007 of 2018; These regulations establish that payments made to property owners in strategic ecosystems for water service and other services, to execute preservation and restoration activities, must be calculated under the opportunity cost methodology (hereinafter OC). For the department of Boyacá, this methodology has been applied in the cases of the Chaina microbasin (Borda-Almanza *et al.*, 2010) and the Tota Lake (Talero and Salcedo, 2020).

Table 1. Input data for erosion control and base flow RIOS models.

Entrance	Source	Erosion	Base Flow
Table of Biophysical Coefficients of Land Use	Modified from the table of default values https://naturalcapitalproject.stanford.edu/software/rios	Yes	Yes
Land Use / Cover Map (LULC)	Metadata of the General Plan of Forest Management Corpoboyacá jurisdiction	Yes	Yes
Digital Elevation Model	https://earthexplorer.usgs.gov/	Yes	Yes
Erosivity due to rain (R)	Pérez-Arango and Mesa-Sánchez, 2001	Yes	Yes
Soil erosion (K)	Stone and Hilborn, 2012	Yes	Yes
Soil depth	IGAC, 2005	Yes	Yes
Soil texture	IGAC, 2005	Yes	Yes
Annual average rainfall	http://www.siac.gov.co/catalogo-de-mapas	No	Yes
Annual average evapotranspiration	http://www.siac.gov.co/catalogo-de-mapas	No	Yes
Location and # of beneficiaries by surface source of drinking water	Metadata of the General Plan of Forest Management Corpoboyacá jurisdiction	Yes	Yes

To run the model in RIOS Investment Portfolio Advisor, the introduction of economic parameters is required: the cost per unit area of each alternative activity to be projected:

- Agroforestry: understood as the systems and technologies of land use in which trees, shrubs, palms or bamboos are combined, with agricultural crops or animals on the same plot of land, with some type of spatial and chronological arrangement (FAO, 2018).
- Layers of grass or grasslands for bare soils: understood as an agroecological infrastructure formed by a linear cover of herbaceous plants, placed near the edge of a plot or property, perpendicular to the slope, which helps to limit soil erosion by slowing runoff and improve water infiltration (DNR, 2007).
- Management and recovery of riparian edges: activities that are carried out in the convergence zones between terrestrial and freshwater ecosystems, these zones form the boundaries of the riparian area and extend outwards, from the river bed or the lake shore; and upwards, in the vegetation canopy of the riverbank (Gregory and Ashkenas, 1990)
- Terrace construction: It refers to the construction of a mechanical structure of a canal, an earth ridge or a stone wall, to intercept surface runoff, encourage it to infiltrate, evaporate or divert to a predetermined and protected safe outlet, in a controlled speed to avoid soil erosion (Dorren and Rey, 2004).

These values were defined from the OC, which is nothing more than accounting all the income lost by not assigning these resources to other functions. In other words, the benefit that is no longer perceived in the traditional agricultural activity is measured, by dedicating itself to conservation, restoration and similar activities (Cristeche and Penna, 2008), since what is sought is to change the use of the current land, for one that guarantees the natural processes that will generate the desired water ecosystem service. In this way, 6 global budgets are proposed to be invested in the 4 alternative activities mentioned, according to the results from the OC calculation.

The estimation of the OC of the predominant agricultural productive sector in the municipality was carried out by collecting information on the yield of liters of milk per day per hectare and the tons of monthly sugarcane per hectare; based on data from the National Agricultural Census of 2014 (DANE, 2016). The statistical software used was R and the libraries used for data processing were library (tidyverse), library (dplyr), library (ggplot2), library (ggrepel),

library (reshape2). The calculation of the expected benefits is based on information gathered in the establishment of the agenda, specifically the unit prices and the unit costs of the products.

RESULTS

Particularities of each basin studied

The basin that supplies the municipality of San Mateo has a forest area of the high Andean type, which is located in the southeastern region, with an area of 198.2 hectares, in the Alfaro and Peñuela villages. The intakes of the main urban and rural aqueducts are located there, which have a total of 700 subscribers. The microbasin does not report lean seasons in the last 5 years. However, the amount of sediments controlled in the purification process increases considerably along with the flow in the precipitation peaks, over the months of April, May and October. The dominant productive activity in the upper and middle part of the Cifuentes and Dragú rivers is dairy cattle farming; 615 peasant producers are reported located mainly in the Alfaro, Palma and Peñuela villages, with an average of 16 heads of cattle per hectare per year.

In the municipality of Togüí, the Andean-type forest area is located in the southeastern region at the Carare and Hatillo villages, with an area of 455.6 hectares. The municipal aqueduct has its purification plant less than 1 km from the urban area; however, the intake of the main pipe is located in the lower area of Carare village, just where the most homogeneous forest mass ends. The company that supplies the public service has 310 subscribers. The Colorada River has not presented shortages during the dry season of December and January in the last 5 years, however, La Niña phenomenon has caused some overflows and sudden increases of water flow, causing damage to the water intake. The main economic activity is the cultivation of sugar cane for the production of panela (raw cane sugar), in the middle part of the basin, with 729 producers, mostly located in the Carare and Hatillo villages, with an average yield of 4.6 tons of sugar cane per hectare per year.

The vast extension of the municipality of Miraflores houses two Andean-type forest areas, the main one is located in the northwestern region, protected under the figure of the Cuchilla de Sucuncuca Protective Forest Reserve in the Estancia and Tablon and Suna Arriba villages; a smaller area in the southern part of the municipality, at the Morro Arriba village, with a total area of 81.1 hectares. The aqueduct company captures water for the urban area in the vicinity of Suna Arriba, from the El Ramo lagoon and the La Jordanera river;

the service is distributed to 2,609 subscribers. Historically, the basin registers shortages in the months of December and January, generating prolonged rationing, forcing the supply with the help of fire-fighting machinery. Likewise, periodic fires are reported that usually start in controlled pasture burning, according to popular belief of soil regeneration after the disturbance. Dairy cattle is the main source of income for the residents in the aforementioned villages. There are 1,227 producers, with an average of 15 heads of cattle per hectare per year.

In the municipality of Pauna, the wooded area is divided into two parts: a larger one in the northwestern zone as remnants of tropical humid forests and a smaller one to the southeast of the Andean forest type; the last one located in the Monte y Pinal village, with an area of 446.5 hectares. There the Manotera river is born, from where the aqueduct company is supplied to provide 715 subscribers. The geological conditions of the southeastern sector of the municipality, where the waters that are captured in the intake of the Manote village, cause constant phenomena of mass removal, which increase erosion problems and decrease the available surface for proper runoff and infiltration of precipitation. The predominant economic activity is dairy cattle, 794 producers, 167 of them in Monte and Pinal and 92 in Manote, with an average of 10 heads of cattle per hectare per year.

Opportunity cost

a. Cultivation of sugar cane

The net incomes from each farm were calculated, considering the difference between the average prices

of a ton of sugar cane (\$ 1,500,000) and its production cost (\$ 1,488,000). This is multiplied by the yield (ton / ha). Subsequently, the net present value of the opportunity cost (\$ / ha) was estimated taking into account the average inflation from the last five years (4%). Discount rates were considered for those who would participate in a payment contract for environmental services ($p = \text{inflation} + 1\%$) and for the financial operators of the scheme ($r = \text{inflation} + 2.5\%$) (Table 2).

b. Dairy farming

The net incomes from each farm were calculated, considering the difference between the prices per year of a liter of milk (\$ 325,000) and its cost of production (\$ 317,550); this is multiplied by the number of liters per day, per hectare. Subsequently, the net present value of the opportunity cost (\$ / ha) was estimated taking into account the average inflation from the last five years (4%). Discount rates were considered for those who would participate in a payment contract for environmental services ($p = \text{inflation} + 1\%$) and for the financial operators of the scheme ($r = \text{inflation} + 2.5\%$) (Table 3).

Scenarios of activities to improve the water supply

RIOS (Vogl *et al.*, 2016b) proposes 4 activities that contribute significantly to the selected objectives: agroforestry, layers of grass or grasslands for bare soils, management and recovery of riparian edges and construction of terraces. For the municipalities studied, the implementation of terraces was not an option to be modeled, since no map shows area in this activity. In contrast, agroforestry used much of the budget in each scenario.

Table 2. Opportunity cost (OC, minimum, medium and maximum) for the cultivation of sugarcane projected at 5 and 10 years.

Variable	Min.	1st Qu	Median	Mean	3rd Qu.	Max.
Yield (ton/ha)	3.99	4.96	4.96	4.90	4.96	5.38
OC 5 years	\$3.167.221	\$3.942.802	\$3.942.802	\$3.890.718	\$3.942.802	\$4.274.749
OC 10 years	\$2.950.372	\$3.672.852	\$3.672.852	\$3.624.334	\$3.672.852	\$3.982.071

Table 3. Opportunity cost (OC, minimum, medium and maximum) for milk production projected at 5 and 10 years.

Variable	Min.	1st Qu	Median	Mean	3rd Qu.	Max.
Yield (liter/day)	2.00	7.00	7.00	10.42	14.00	25.00
OC 5 years	\$965.628	\$3.379.697	\$3.379.697	\$5.029.191	\$6.759.393	\$12.070.345
OC 10 years	\$899.514	\$3.148.300	\$3.148.300	\$4.684.860	\$6.296.601	\$11.243.930

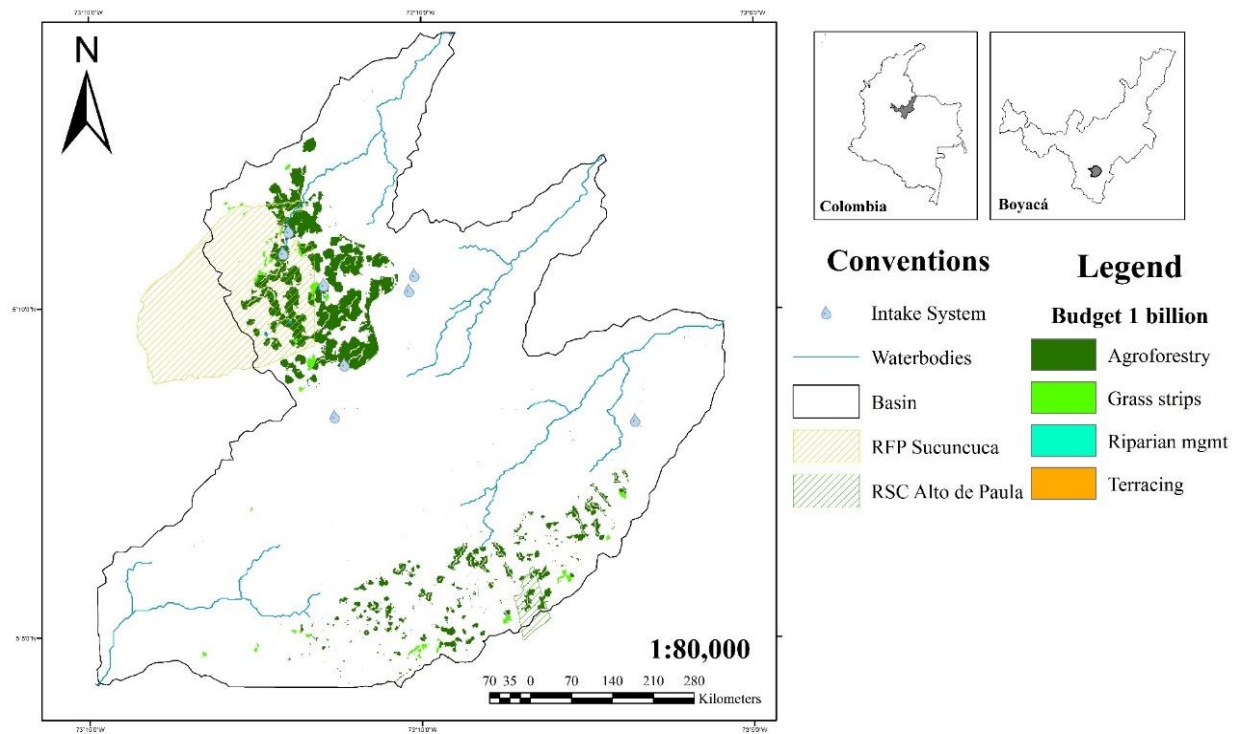


Figure 1. Activity scenarios for the improvement of base flow in the dry season and sediment retention, with a global budget of 1000 million pesos, in the municipality of Miraflores.

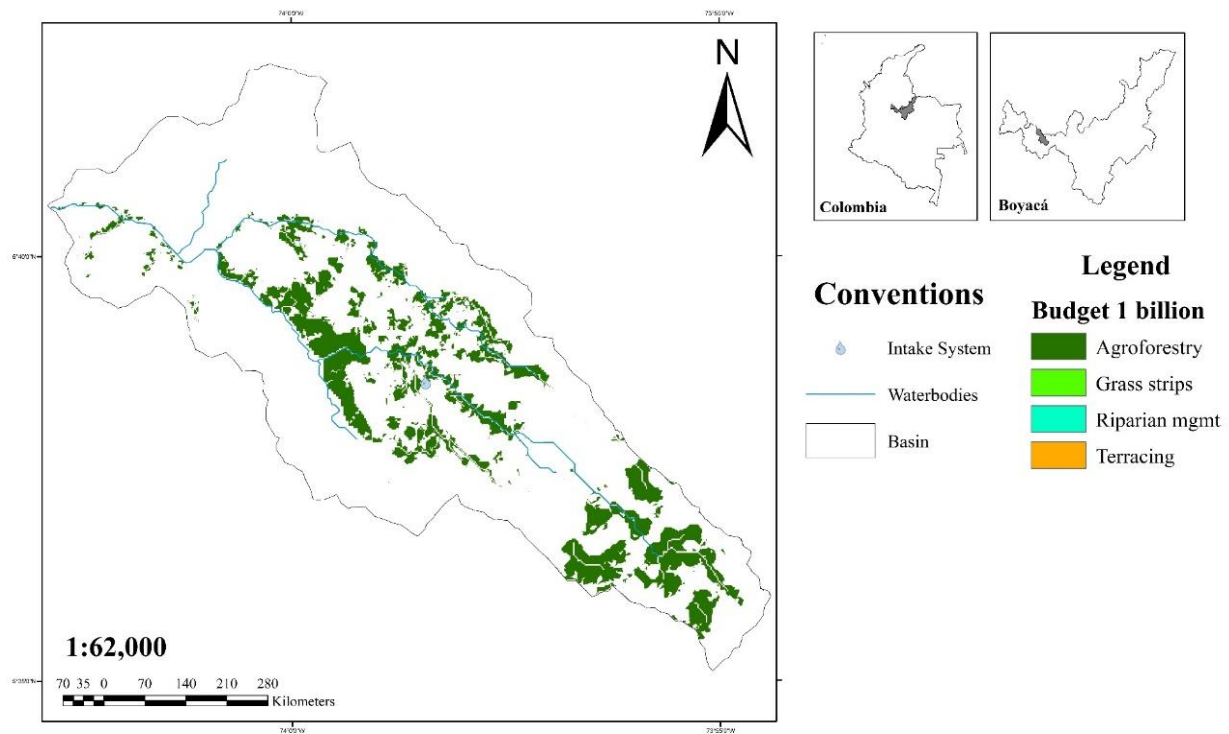


Figure 2. Activity scenarios for the improvement of base flow in the dry season and sediment retention, with a global budget of 1000 million pesos, in the municipality of Pauna.

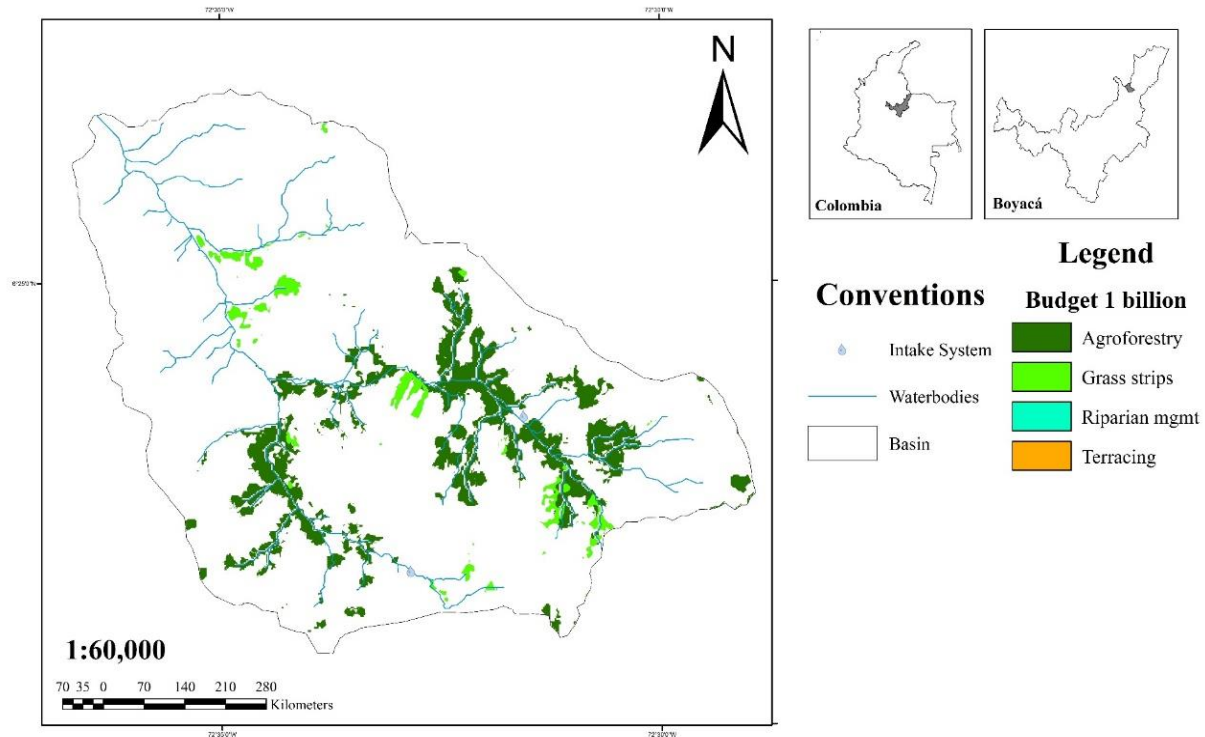


Figure 3. Activity scenarios for the improvement of base flow in the dry season and sediment retention, with a global budget of 1000 million pesos, in the municipality of San Mateo.

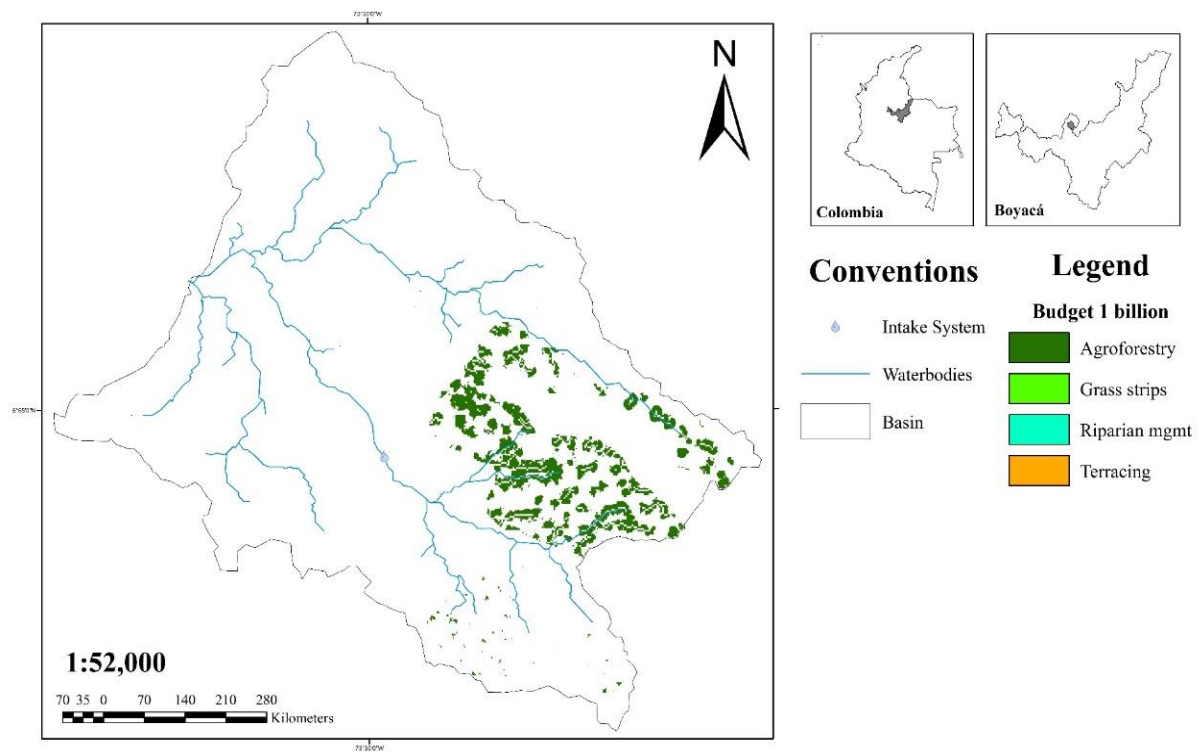


Figure 4. Activity scenarios for the improvement of base flow in the dry season and sediment retention, with a global budget of 1000 million pesos, in the municipality of Togüí.

From the economic results, 18 investment scenarios were obtained for the municipalities of Miraflores, Pauna and San Mateo, 12 scenarios for the municipality of Togüí. The results of the projections with the lowest opportunity cost and the highest overall budget for each location are shown below, following the recommendation given in section C of article 2.2.9.8.2.5. of the Decree 1076 of 2015; which seeks to apply the principle of cost effectiveness in PWS investments. To consult the remaining maps, you can go to sites.google.com/view/biologiaparalaconservacion

Figure 1 shows the scenario with the largest budget allocated to changing activities (1 billion COP per year) in the municipality of Miraflores. It is possible to detail that RIOS recommends the northwestern area that overlaps with the protected area of Sucuncuca, to carry out agroforestry actions and only some patches of grass layers. For the southeast sector, a similar scenario is projected, although with less area, including its application in the private protected area. In this municipality, RIOS does not recommend riparian recovery activities or terraces. Figure 2, for its part, shows the same budget scenario for the municipality of Pauna; although RIOS makes a projection for the entire study basin, it is important to focus the results obtained in the southeastern zone, since it is there where the catchment for the aqueduct service is carried out. Agroforestry is the only recommended activity and suggests several activity areas surrounding the river. Figure 3 explains the higher budget scenario for the municipality of San Mateo. Again, riparian recovery and terracing activities are not recommended. Agroforestry and grass layers create a “buffer” over the watershed at its two main tributaries. The scenario in figure 4 for Togüí projects agroforestry activities only in the southeastern zone and recommends uniform patches without a specific pattern of location, in the same way it does so with the largest possible budget.

Budget scenarios for the improvement of water provision

In addition to the geographically explicit information, RIOS (Vogl *et al.*, 2016b) communicates the expenditure per activity and the amount of area intervened with the investment, in such a way that decision-makers can evaluate the feasibility of implementing PWS according to science-based assumptions, in combination with the best monetary alternative. The area values are expressed in hectares and the investment money in Colombian pesos (COP), the global budget, in millions of Colombian pesos (COP).

These tables should be interpreted by a decision maker (or the reader) like this:

- What is the budget available to invest? This work projects from COP 50 million to COP 1 billion, so you should choose a value from the first column.
- Are we going to pay the minimum, medium or maximum opportunity cost? Then you need to scroll down to the preference column.
- So, how much area is this investment enough for? In the cell located from a and b, you will find a value in hectares and below this, the actual cost with the budget you chose.

Table 4. Budget scenario to improve water supply for the municipality of Pauna, Boyacá, Colombia.

Global Budget	Agroforestry		
	OC* Minimum	OC Medium	OC Maximum
50	51.78 \$49999.894	9.94 \$49991.973	4.14 \$49969.182
100	103.56 \$99999.789	19.88 \$99983.946	8.28 \$99986.320
200	207.12 \$199999.578	39.77 \$199987.873	16.57 \$199972.641
500	517.80 \$499998.946	99.42 \$499999.655	41.42 \$499979.557
800	828.47 \$799998.315	159.07 \$799991.456	66.28 \$799986.474
1000	1035.59 \$999997.893	198.84 \$999999.311	82.84 \$999959.115

*OC= opportunity cost

Table 5. Budget scenario to improve water supply for the municipality of Togüí, Boyacá, Colombia.

Global Budget	Agroforestry	
	OC Minimum	OC Maximum
50	15.78 \$49993.296	11.70 \$49999.224
100	31.57 \$99999.176	23.39 \$99998.449
200	63.15 \$199998.353	46.79 \$199996.898
500	157.87 \$499995.884	116.96 \$499992.245
800	252.59 \$799993.415	187.14 \$799987.593
1000	315.73 \$999991.769	233.93 \$999984.491

*OC= opportunity cost

Knowing the area, the expense/budget ratio and the OC, you should go to the generated maps (published in this work and the others at <https://cutt.ly/DLYhqHX>) and cross them with the cadastral information available in your government period to choose the properties that should be benefited in a PWS or similar program, applying the activity indicated by RIOS.

DISCUSSION

The four municipalities studied have similar characteristics in terms of the pressures exerted by human activity, taking into account the agricultural and livestock tradition of the department of Boyacá. Historically, the Andean region and its highlands have

Table 6. Budget scenario to improve water supply for the municipality of Miraflores, Boyacá, Colombia.

Global budget	Agroforestry			Grass Strips		
	OC* Minimum	OC Medium	OC Maximum	OC Minimum	OC Medium	OC Maximum
50	28.75	0.80	0.29	22.99	9.12	3.83
	\$27764.078	\$4036.122	\$3548.675	\$22197.451	\$45875.927	\$46276.642
100	76.18	4.12	0.42	27.34	15.74	7.85
	\$73559.271	\$20720.094	\$5035.282	\$26402.154	\$79163.948	\$94759.217
200	173.65	17.97	2.56	33.42	21.75	13.99
	\$167685.521	\$90393.160	\$30883.064	\$32275.693	\$109394.905	\$168897.755
500	478.58	72.37	19.51	39.15	27.01	21.88
	\$462133.608	\$363970.337	\$235459.392	\$37807.792	\$135829.510	\$264040.614
800	780.57	127.70	41.93	47.79	31.33	24.31
	\$753738.917	\$642223.023	\$506117.806	\$46144.305	\$157568.625	\$293389.117
1000	979.84	165.65	57.10	55.53	33.15	25.71
	\$946157.755	\$833079.669	\$689162.308	\$53617.626	\$166719.833	\$310317.256

*OC = opportunity cost

Table 7. Budget scenario to improve water supply for the municipality of San Mateo, Boyacá, Colombia.

Global budget	Agroforestry			Grass Strips		
	OC* Minimum	OC Medium	OC Maximum	OC Minimum	OC Medium	OC Maximum
50	19.72	7.56	3.69	31.92	2.32	0.44
	\$19043.925	\$38003.490	\$44598.214	\$30821.695	\$11668.789	\$5370.967
100	48.92	11.37	6.66	54.40	8.42	1.59
	\$47241.517	\$57165.082	\$80420.652	\$52528.087	\$42359.305	\$19229.982
200	142.18	16.59	10.35	64.61	23.07	6.14
	\$137293.503	\$83439.840	\$124875.001	\$62387.653	\$116028.532	\$74090.582
500	425.11	46.07	16.96	92.16	53.13	24.36
	\$410495.567	\$231697.410	\$204672.237	\$88993.137	\$267183.319	\$294060.488
800	699.44	97.72	25.26	128.05	61.04	40.83
	\$675403.319	\$491447.871	\$304898.333	\$123647.403	\$306985.082	\$492834.252
1000	886.21	134.45	35.12	148.20	64.06	47.53
	\$855745.147	\$676170.410	\$423922.817	\$143101.824	\$322190.474	\$573686.500

*OC = opportunity cost

had processes of deforestation and change in land use, promoted by methods of cultivation and bovine exploitation, which generally go hand in hand with controlled burns, use of machinery for the modification of the physical characteristics of the soil and even the intensive use of agrochemicals (Armenteras *et al.*, 2011; Armenteras *et al.*, 2013; Armenteras and Rodríguez, 2014; García-Romero, 2012; Muñoz-Gómez *et al.*, 2018).

The topography of the municipalities in Boyacá is usually comprised of two characteristic elements: a mountainous region with high slopes and a valley crossed by a river, where human settlement generally takes place. This tradition of urbanization seems to come from the Spanish ways of founding colonies in the 16th to 19th centuries, which required the proximity of a body of water for their supply and in many cases, transportation to other regions (Herrera *et al.*, 1976, pp. 127-128). This pattern of urbanization continues in force in the local political administrative division, directly influencing the way in which the aqueduct service is provided in the municipalities today. The intakes or water catchment points are usually installed at intermediate areas between the urban area and the sources of the tributaries, therefore, what happens at the ecosystem level from this point upwards altitudinally will impact the quality and quantity of the liquid. It is there where the economic activities that modify the original plant covers have the power to determine whether the provision of the ES is optimal or not. There is abundant literature that explains how the modification of the forest ecosystem structure directly and non-linearly influences the water supply (Rolando *et al.*, 2017; Guo *et al.*, 2019; Esquivel *et al.*, 2020; Mello *et al.*, 2020; Ni *et al.*, 2021).

The explicit geographic results support this idea since the polygons of suggested activities are in the upper and middle parts of the evaluated basins. Although not included in this publication, in the previous processing of the RIOS input, the layers showed that the areas most vulnerable to erosion were located just above (altitudinally) the aqueduct catchment points. Likewise, the land use shape showed large regions with fragmented forest or with total absence of forest in the upper part of the basins, except for Togüi. After processing, it is possible to confirm the postulated hypothesis.

Forest ecosystems are fundamental for the hydrological cycle (Bruijnzeel and Hamilton, 2000; Calder and Aylward, 2006; Brauman *et al.*, 2007), in the case of the tropical Andean forest, a greater amount of precipitation is intercepted (horizontal and vertical)

thanks to its abundant canopy and intermediate epiphytic strata (Obregon *et al.*, 2011; Levia *et al.*, 2011; Van Stan II and Pypker, 2015) gradually managing the drip, while slowing down erosion and allowing water infiltration into the soil (Neary *et al.*, 2009; Krishnaswamy *et al.*, 2013; Ramos-Franco and Armenteras-Pascual, 2019). The decrease and fragmentation of this type of vegetation has a direct impact on the hydrological service, since the downstream population receives the flow of water with major amount of sediment; in extreme climatic events, there may be a decrease or disappearance of the minimum flow, avalanches, or flash floods (Germer *et al.*, 2010). Bonnesoeur *et al.* (2019) recently reviewed the role of forest vegetation cover in hydrological services in the Andes. Using quantitative data from 291 publications, they state that increasing (non-exotic) forest on bare or degraded soils improved precipitation infiltration and increased erosion mitigation, even on very steep slopes. These authors ensure as well, that overgrazing and traditional farming systems increase surface runoff and water erosion. Likewise, in degraded soils, the presence of a vegetal layer, such as the one proposed with the “layers of grass” activity, can reduce surface runoff by up to 50%, giving time for the correct infiltration of precipitation.

The results obtained in this research suggest that agroforestry is the activity that, in the 4 cases of study, will guarantee a base flow in the dry season and a lower sediment load in the water flow. As mentioned earlier, this land use system can have many expressions, some of them are mentioned below:

- Forest agriculture: the use of the standing forest, cultivating under its canopy other species of commercial value (Kaba *et al.*, 2020), edible fungi (Franco-Maass *et al.*, 2016), native bees for honey production, pollen and propolis (Zocchi *et al.*, 2020), fruits and seeds for animal and human consumption (Steuer *et al.*, 2021).
- Silviculture: the combination of cattle grazing under the standing forest canopy, with bovine, goat, ovine and even buffalo species (Nahed-Toral *et al.*, 2013; Sánchez-Romero *et al.*, 2021).

Although it is not the objective of this work to talk about the operation of that system, it is important to mention that the change in the economic activity of the peasants in the studied municipalities can be facilitated through a transition; traditional intensive livestock farming in San Mateo, Pauna and Miraflores can migrate successfully to silviculture, preventing owners from having to abruptly sell their livestock and instead,

learn the techniques that allow animals to graze in the forest before they had to cut down to expand the foraging area (Mauricio *et al.*, 2019), at the same time that they undertake trades within the understory, which allows them to generate a new monetary income (FAO, 2018). For its part, the municipality of Togüí is being impacted by the changes in the market prices of panela, leaving the sugar mill owners bankrupt and the day laborers who cut and process sugarcane without jobs (Sánchez, 2021). This population urgently requires sustainability alternatives, in which the use of the Andean forest can contribute, thanks to the diversity of native bee species for the production of honey and derivatives, as highlighted by the results of phase 1 of this project (J. Leguizamón, personal communication, January 15, 2021), and the abundance of resident and migratory birds that would facilitate the opening of a market for avitourism and scientific or nature tourism, as highlighted by the results of phase 2 of this project (J. Gomez-Camargo, personal communication, January 15, 2021). In this way, it can be affirmed that the activities proposed by RIOS for the analyzed basins, can become the middle point of negotiation between local administrators and farmers, in such a way that the former achieve an efficient investment of the public treasury, and the latter are not forced to abruptly change their lifestyle, much less move to urban centers.

On the other hand, RIOS contemplates the installation of layers of grass in the municipalities of San Mateo and Miraflores, this may be due to the combination of very high slopes and the absence of a uniform vegetation cover (Ligdi and Morgan, 1995). The layers of grass seek to promote at the last moment, the retention of sediments that was not controlled in any way until reaching the edge of the bank, trying in turn to give stability to the riparian soil, which in events of flooding due to rain, can be detached generating mudslides and rocky material (Zhang *et al.*, 2018). The investment in this activity translates into a contingent value of damages avoided (Jónsson and Davíðsdóttir, 2016), which ideally should be contemplated in the Municipal Development Plans, regarding risk management (Law 1523 of 2012; Decree 2157 of 2017).

In the specific case of Togüí, which must deal with flash floods and flood damage, Bonnesoeur *et al.* (2019) observed that the increase in forest cover successfully softens the force of torrential rains and regulates the flows that these generate, however, the investment projection for this municipality does not have areas greater than 315 ha, so the form of mitigation should be focused on correctly managing

the urbanizable areas and the effect of the natural slopes of the basin on the magnitude of the flow.

Year after year, more case studies are published that demonstrate the urgency of intervention in the upper parts of the basins to stop phenomena such as erosion and sediment load to bodies of water, or the scarcity of liquid in the dry season due to lack of a correct infiltration in the soil and subsoil. However, this information seems to continue to be stored on the shelves of the scientific community, since decision makers in Boyacá continue to invest in reforestation in arbitrary places (Corpoboyacá, 2017; Gobernación de Boyacá, 2019) and carrying out PWS programs where the objective is the economic well-being of the population and not the activities that would have an impact on the improvement of the ES (Corpoboyacá, 2015; Primer Nombre, 2020). Although this research is understood as a first approach to the evaluation of water ES in the department of Boyacá, the approach that involved the social phase of it, showed that decision makers are not yet familiar with the conceptual framework and its benefits. tangible, and even worse, relate ES directly to economic valuation through instruments such as PWS, due to the diffusion that national policy has had (MinAmbiente, 2012), completely omitting the need for technical-scientific advice before than a budget; which results in the investment of public resources in programs that are not cost-effective (Ramos-Franco and Herrera-Carrascal, 2020).

Based on the information obtained, municipal administrations will be able to initiate a feasibility process for the implementation of PWS schemes, knowing the areas where their investment is guaranteed to generate a positive impact on the base flow and the sedimentary load of water bodies, that supply the local aqueducts; all this under the conceptual framework of ecosystem services, supported by the geographically explicit tools that the academy has made available for free.

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Author contribution statement (CRediT). A. Ramos-Franco, conceptualization, data curation, formal analysis, visualization, writing original draft and writing, review, and editing

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