Páramo to Pasture Conversion in a Mountain Watershed: Effects on Water Quality and Quantity

Author: Matovelle, Carlos

Source: Mountain Research and Development, 41(4)

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-21-00026.1

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

MountainResearch
Systems knowledge

Páramo to Pasture Conversion in a Mountain Watershed: Effects on Water Quality and Quantity

Carlos Matovelle
cmmatovelleb@ucacue.edu.ec

Catholic University of Cuenca, Research Group on Environment, Science and Energy, HYDROLAB, Cuenca, Ecuador

The typical vegetation cover of the Andes in southern Ecuador is composed of grassland wetland ecosystems. These form the basis of the area's hydrology, regulating water flows and supplying water to the lower regions of the basins. This study focuses on the Rircay River subbasin, where the dynamics of human activities have transformed natural ecosystems to alternative land uses, particularly cattle pastures. My study examines the change from native wet grasslands to introduced grasslands for livestock grazing. The research uses cartographic land use and land cover change data from 1990 to 2015. Subsequently, I evaluate the effect of these changes on river flow. Flow is measured at a control point at the exit of the total area. At this point, specific water quality parameters resulting from livestock contamination are measured and related using nonlinear models. The results are conclusive and indicate a marked decrease in river flows and an increase in the concentration of pollutants due to the increased area occupied by livestock pastures.

Keywords: *hydrological regulation; Andean grassland; livestock grassland; water quality; streamflow; land use and land cover change.*

Received: *21 March 2021* ***Accepted:*** *30 November 2021*

Introduction

By the year 2055, it is projected that 64% of the world's population will live in watersheds with water stress and 33% in areas with absolute water scarcity (FAO 2007). Most of these areas will be used for livestock production. In many cases, the impact of livestock on the water sector is not well understood, since water management varies according to location. Depending on how it is managed, the highest water consumption could be for pasture irrigation, cleaning, or direct consumption by animals (Schlink et al 2010). The type of livestock also plays a fundamental role in how the resources are used. Inadequate management techniques have led to decreased resources, including a loss of quality and quantity of water, soil compaction, and degradation of ecosystems (Walker and Salt 2006).

Water quality, resource availability, and habitat are adversely affected in many areas because of the need for water for livestock and space for pastures. Conversions of native ecosystems for livestock production affect the availability of water in Andean basins and represent additional consumption of water. This directly affects public health management because of pollution problems that put water security at risk, especially in downstream areas (Mateo-Sagasta et al 2009).

Proper water management within areas where it is used for irrigation and maintenance of pasture for livestock reduces shortages at times of the year when there is not enough rainfall. Drought has adverse effects on agriculture and aggravates management problems since more water is used than can be replenished, thus disrupting the ecological balance (Ortega-Gaucin et al 2008).

Concern for the adequate maintenance of these water systems is the focus of several studies (eg Niyonzima et al 2013). These prioritize access to water for livestock, while giving less consideration to the impact on the resource. It is important to analyze both water quality and water quantity resulting from the loss of native ecosystems or from high extraction. Nyachieo (2016) describes specific cases from Kenya where strategic management of water together with community training achieved sustainable maintenance of livestock pastures.

The transformation of forest cover into pastures, cropland, or urban areas is a global problem (Kareiva and Marvier 2015). Land use change is driven by combinations of resource depletion, changes in economic dynamics, political intervention, and changes in organizations (Lambin et al 2003). Change is not linear but associated with various environmental and social dynamics (Lambin and Meyfroidt 2010).

In order to propose adequate strategies to address the problem of changes from native vegetation to other land uses, we need to understand the dynamics of land use change (Quintero-Gallego et al 2018). Land use change is a phenomenon that occurs within a complex system that affects ecosystem services within a territory (Berrio-Giraldo et al 2021). The transition to pasture is the main trigger for the loss of landscape in Andean areas (Cocca et al 2012).

In Ecuador, land use has evolved since the time of the *haciendas*. Back then, most people engaged in agricultural activities within organized territories with private owners.

There were fewer landowners, the work was more homogeneous, and there was no excessive pressure on resources. Over the years, the territories split up into smaller landholdings and the number of landowners and thus stakeholders increased. People practiced agropastoralism based on family agriculture; pasture use was limited and considered a capital reserve, and the primary source of income was crops, grown in rotation on the agricultural frontier of the *páramo*.

In the 1990s, livestock production was intensified and *páramo* lands were used exclusively for grazing. Agrarian reforms encouraged this activity (López-Sandoval and Maldonado 2019). This change in land use was economically beneficial and was promoted without adequate planning and, above all, without considering the environmental consequences.

Research is needed on ways to address global and local changes and their effects on the loss of natural resources and the reduction of ecosystem services. This is particularly important in unique ecosystems, such as the *páramo*, wet grasslands, and native forests of the Andes.

Recent studies on human water security reveal global threats to the population and economic growth, misuse of water, climatic extremes, and a general failure to protect landscapes effectively. Approximately 85% of humanity depends on freshwater sources that are moderately to severely threatened as a byproduct of unplanned development (Vörösmarty et al 2021).

Alternatives that are showing results include integrating the main actors in the conservation and proper management of these resources, analyzing the drivers of change and response variables from the local to the national scale, and emphasizing the importance of monitoring. Llambí et al (2019) suggest integrating monitoring of land use change drivers and their effects along environmental (eg elevation) and land use gradients (eg mosaics of productive systems, ecosystems with different levels of degradation).

Assessing vulnerability in socioecological systems can serve to identify the degree to which environmental change affects ecology, functioning, and social wellbeing. This type of evaluation provides valuable information for the design and implementation of land use planning policies. The approach shows that society is threatened when the integrity of the biophysical system changes and it cannot maintain a given level of ecosystem services (Berrouet et al 2020). Therefore, knowing these changes gives us a fundamental basis for land use planning that contributes to the sustainable development of high mountain basins under heavy human intervention.

At the same time, this intimate connection between water, space, and the identity of social groups has caused struggles over the material control of the use of water, systems, and territories. Both scientific and local communities need to know the true impact of changes in the quality and quantity of this resource (Boelens 2014).

This study aims to verify land use change from natural cover to agricultural use and to link these changes with water flow and quality over the period of 1990–2015.

The aim of achieving universal water security under the Sustainable Development Goals motivates a serious consideration of strategies for analyzing the impact of land use changes on water and the implementation of new alternatives as nature-based solutions (High Level Panel on Water 2018). A coupled framework is required to realize the global potential of linking these studies with the application of viable options. This research analyzes past land uses to determine the impact they have on the quality and quantity of water (Celleri et al 2017).

Methods and study area

This study analyzed the subbasin of the Rircay River in the province of Azuay in southern Ecuador (Figure 1). Its territory occupies an area of 830 km^2 within the Jubones River basin. The Rircay subbasin has particular characteristics typical of high Andean basins, such as maximum elevations over 4000 masl. However, having Pacific slopes, it has a very marked hypsometry, presenting minimum heights of 960 masl.

In the Rircay subbasin, natural pastures constitute a large part of the *páramo* vegetation, especially the grasslands (*Stipa ichu*) that, in this analysis, I have considered simply as *páramo* or *páramo* vegetation. In addition, other herbaceous plants are generally present in the more humid parts, such as rabbit foot (*Geranium* sp), sigse (*Cortederia* sp), and horned deer (*Halenia weddelliana*), among others. For the purposes of this analysis, these species are considered herbaceous vegetation that forms high-elevation natural pastures.

The Rircay River subbasin is an area of great importance because of the dynamics of land use changes that have occurred over the last 3 decades. These changes have been marked by variables such as the region's productive activity, local development, migration, and mining. In addition, the area has agrarian importance because of livestock production, supply of drinking water for various populations, and its contribution to hydropower production.

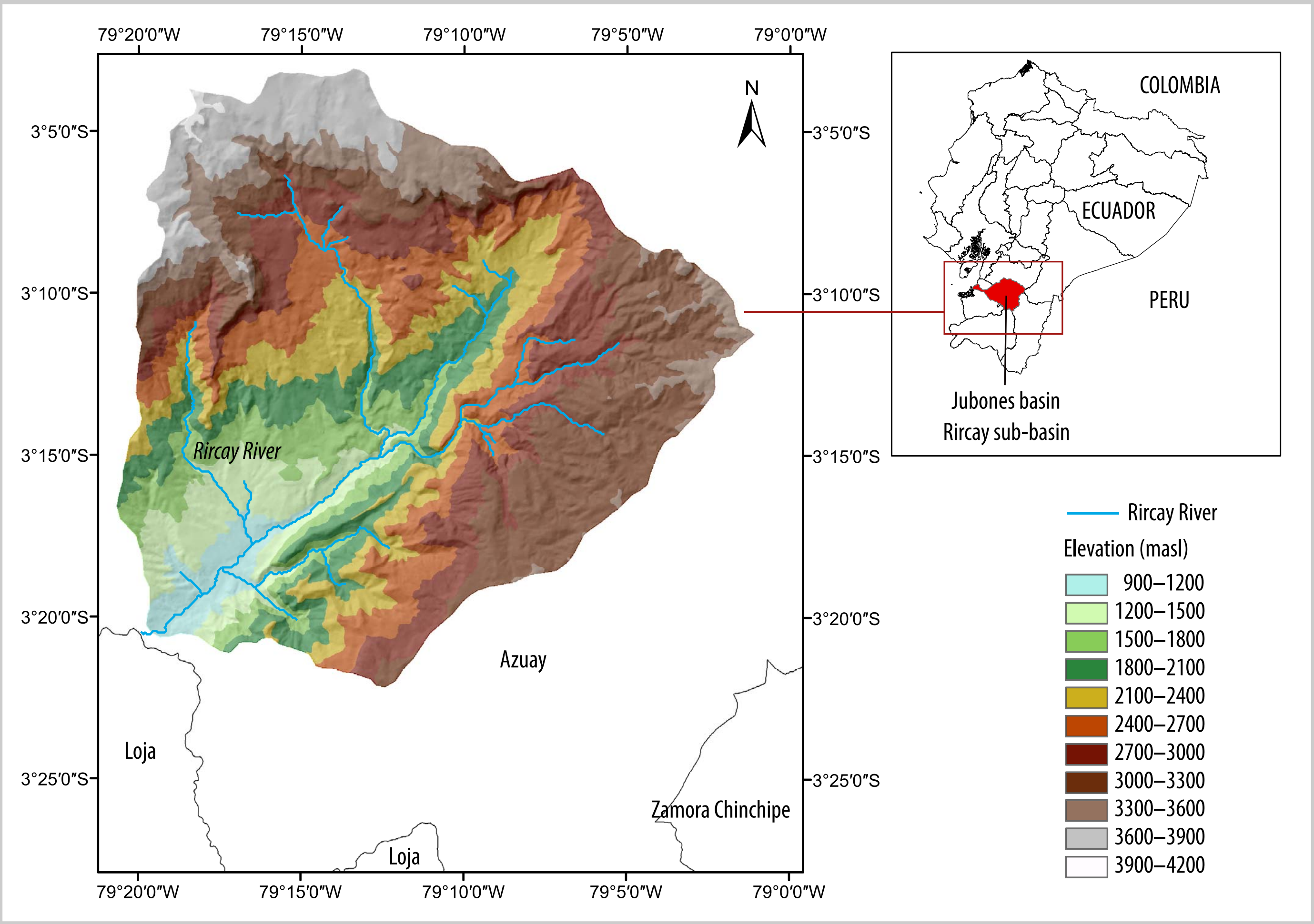
In this area, water is mainly used for grazing activities (Valladares and Boelens 2019). The water is supplied through a series of diversions, channels, and infiltration ditches that have been built for years and that allow the cattle pastures to be constantly irrigated. For the water to reach the entire pasture area, an adaptation of pre-Inca systems is used that improves infiltration into the soil, keeping the grasslands in good condition, especially during the dry period (Grainger et al 2019).

Within the subbasin, the area of land used for livestock production has grown year on year. Several authors relate these behavioral dynamics to variables such as migration, which has changed the patterns of productive systems in the region (Vasco et al 2016). Local producers see livestock production as an activity with better economic returns and requiring less physical effort than agriculture.

These changing dynamics are affecting the environment, causing loss of the amount of water available in the basin and a decrease in water quality. There is also a loss of ground vegetation cover typical of the area, such as wetland and *páramo* grasslands. These are characterized as having excellent water retention capacity, being flow regulators, and guaranteeing water security in both quantity and quality for the populations living in the lower basin.

The change in land use in the basin was evaluated over time using official maps for the years 1990, 2000, 2008, 2011, and 2015. Common land uses were identified so that the change over the years of study could be verified. This allows

FIGURE 1 Location of the study area.



comparisons with global changes and quantification of the effects of change in land use in ecosystem services under different scenarios (Sun et al 2021).

Classification of land use and land cover types

Land cover and land use are 2 different, but linked, criteria. Land cover reflects the area's surface characteristics, and land use refers to anthropic activities over the area (Khamchiangta and Dhakal 2020). For this study, I considered natural covers, such as grassland wetland ecosystems that were replaced by livestock grazing land. This intensive change is causing issues with water resources. Further, degraded wasteland is replacing cultivated grasslands.

In this study, I classified land use and land cover into 11 classes (Figure 2). The increase in livestock grassland areas and the decrease in vegetation cover of grassland wetland and *páramo* ecosystems were correlated. I also show temporal changes in coverage and varying land uses to illustrate the dynamics of land use change across the area.

I used satellite data from official sources in Ecuador: the Ministry of Agriculture, the Secretary of Territorial Planning, and the Ministry of the Environment. These were combined with historical data available from 1990 to 2015.

Data analysis, water quantity, and water quality

The percentages of the area according to the classifications of land use and the monthly mean flows measured at the station at the basin's outlet were correlated (Li et al 2021).

The water quality was measured at the same monitoring point at the outlet of the basin. Monthly data were collected from January 2000 to December 2015. Five water quality parameters associated with contamination from livestock activities were analyzed: chemical oxygen demand (COD), biochemical oxygen demand (BOD), nitrates (NO_3^-), suspended solids (SS), and total coliforms. Normality tests were applied to the data for each parameter. Then the data were analyzed using the Pearson correlation coefficient and the Spearman rank correlation test to evaluate the relationship between land use and the concentration of pollutants (Helsel et al 2020).

Nonlinear models that included exponential regressions, potential regressions, second-order polynomial regressions, and logarithmic regressions were used to identify the relationships between different percentages of livestock pasture use with the water quality data. Models were used to find the best-fit relationship between land use and pollutant concentration (Bates et al 2015).

Before the nonlinear models were obtained, an initial descriptive analysis of water quality and flow data was

 https://doi.org/10.1659/MRD-JOURNAL-D-21-00026.1

FIGURE 2 Land cover patterns in 5 selected years within the study period. (A) 1990; (B) 2000; (C) 2008; (D) 2011; (E) 2015.

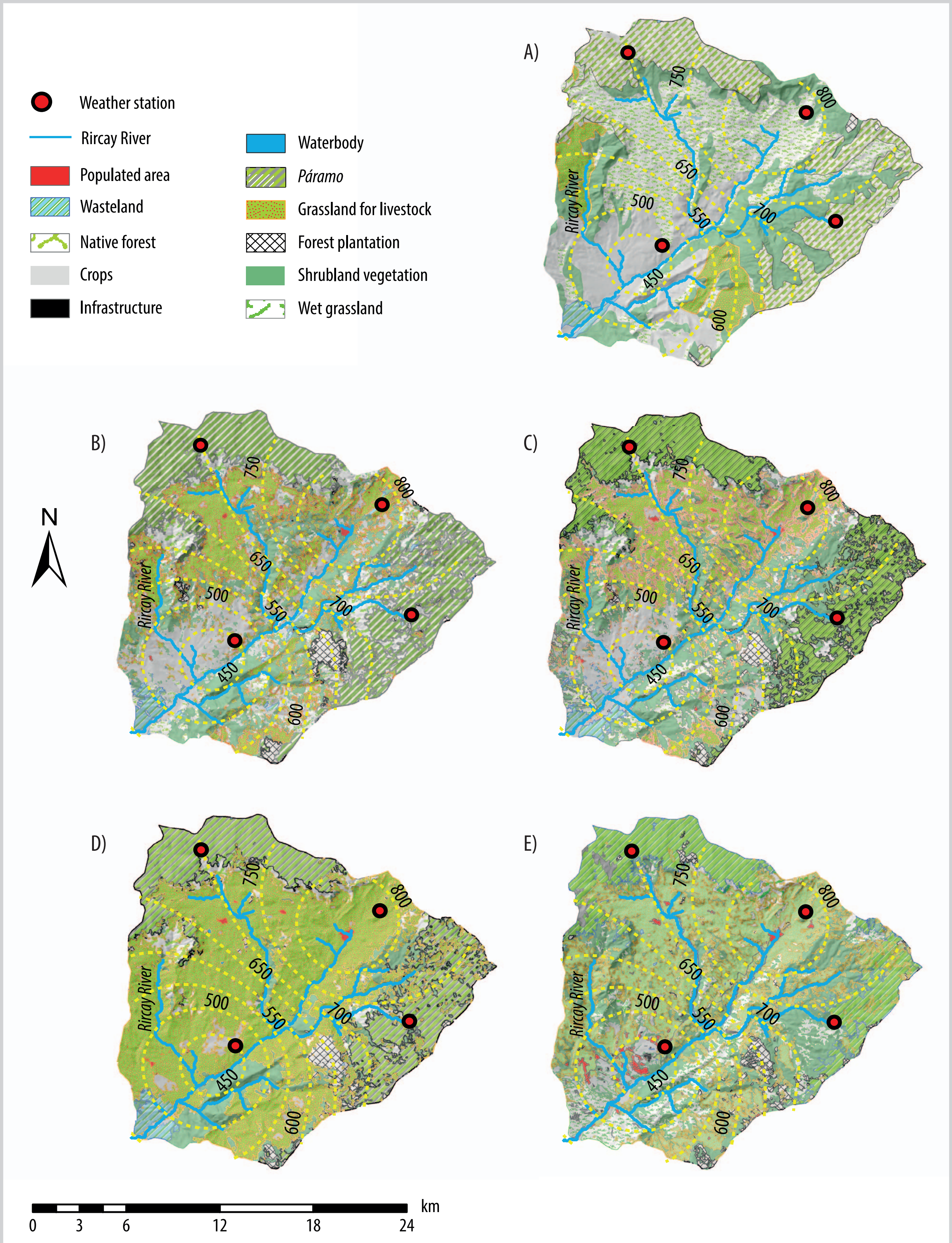


TABLE 1 Information on nonlinear model fits.

Parameter	Mean	Median	Maximum	Minimum	SD	SE
Livestock grassland area (km^2)	231.65	196.34	437.48	50.21	142.63	63.79
Water demand	4379.0	4805.4	7689.8	451.4	2944.92	1317.01
Mean flow stream	11.41	11.54	18.48	4.70	5.20	2.32
COD (mg/L)	14.34	15.30	20.00	8.10	5.36	2.40
BOD (mg/L)	10.88	11.20	17.50	5.50	5.00	2.23
SS (mg/L)	95	110	125	30	37.57	16.80
NO_3^- (mg/L)	2.96	2.50	5.47	1.46	1.55	0.69
Total coliforms (MPN/100 mL)	576.6	80.0	1450.0	13.0	731.15	326.98

Note: MPN, most probable number.

conducted to see how they varied. Table 1 shows the statistical values of central tendency (mean and median), maximum and minimum values, the standard deviation of the sample (SD), and the standard error (SE) that allows the data to be extrapolated since it represents the variability of the samples.

Results

During the analysis period of 25 years (1990–2015), several changes in land use were observed, with increases and decreases in the same use for different periods. Reasons for this include public policies or even social dynamics in the study area. These results highlight the issues caused by livestock, tourism, urbanization, and even mining.

Figure 2 shows land cover patterns for the period analyzed. The maps show how land use has changed over this period. Figure 3 shows how the percentage area of each land use has changed over the period considered. The changes reflect the implementation of support policies for livestock.

This analysis shows that there is undoubtedly a substantial decrease in native vegetation. In 1990, native forest covered 11.3% of the basin's total area; by 2015, it comprised only 2.6%. *Páramo* decreased from 21.2% to 15.9%, and wet grassland decreased from 29% to 12.9%. Most of this land was converted to livestock grasslands, which in 1990 only covered 6% of the basin's total area, but by 2015 had increased to 34.5%.

FIGURE 3 Shares of land uses in total area by year.

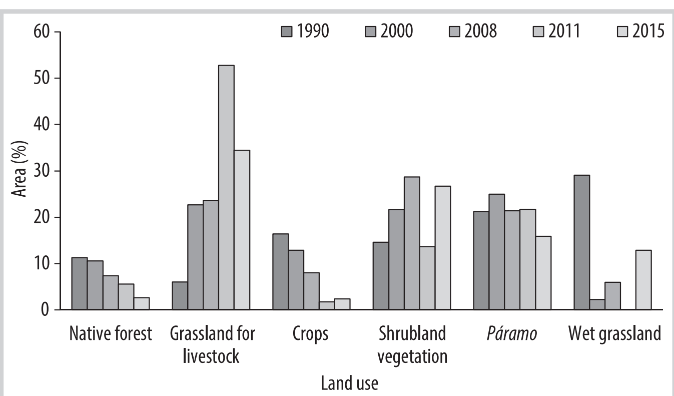


Table 2 shows the percentage area for each land use type and how this changed over the years of analysis. The marked decrease in agricultural land illustrates the trend in social and production dynamics toward livestock production in the area, partly caused by incentives for livestock production.

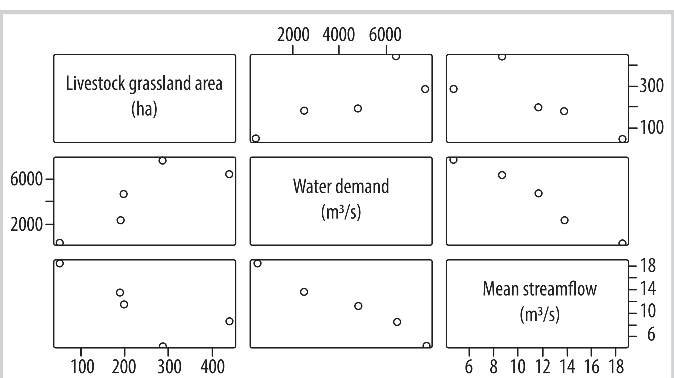
These changes have had a significant impact on resources, especially water. First, Pearson and Spearman tests were used to examine the correlation between the increase in livestock pastures, water use, and flow measured at the outlet of the basin for the period of analysis. There is a significant correlation (Figure 4) between the 3 variables, indicating water consumption increases with an increase in livestock area.

The research results were validated according to the monotonic relationships that were found. The Spearman correlation does not necessarily measure linear relationships, but rather those between the data in each year of land use change analysis.

For the relationship between livestock grassland area and water demand, there is a relationship of 0.83. For streamflow, the relationship is –0.78. That is, consumption is directly related to the change in land use and the presence of pasture for livestock.

As land use area for cattle pasture increased, the concentration of all the pollutants monitored also increased (Figure 5). A similar trend was found for all land uses that altered native cover to specific anthropic uses, including agricultural use.

FIGURE 4 Correlation analysis for land use, water demands, and streamflow.



 https://doi.org/10.1659/MRD-JOURNAL-D-21-00026.1

TABLE 2 Land uses for the analysis period.

Land use	Area (%)				
	1990	2000	2008	2011	2015
Native forest	11.3	10.6	7.4	5.6	2.6
Grassland for livestock	6.1	22.7	23.7	52.7	34.5
Crops	16.4	12.9	8.0	1.8	2.4
Shrubland vegetation	14.6	21.6	28.7	13.6	26.7
Páramo	21.2	25.0	21.4	21.7	15.9
Wet grassland	29.0	2.3	6.0	0.1	12.9
Wasteland	1.4	5.0	4.9	4.5	5.0
Total area	100.0	100.0	100.0	100.0	100.0

The adjusted R^2 values for the exponential models were 0.69 and 0.82 for the relationships for COD and total coliforms, respectively. The potential models were adjusted for BOD and NO_3^- with R^2 of 0.66 and 0.62, respectively. Finally, for SS, the best-fit model was logarithmic, with R^2 of 0.87 as the best-fit nonlinear model for all the data analyzed (Table 2).

Table 3 gives the Spearman correlation value to verify the correlation between the analyzed water quality data.

Discussion

The results show an apparent decrease in water flow related to the change in land use in the study years. Unlike similar studies that project future land use changes, such as Avilés et al (2020), this research analyzes past changes in the study area along with their causes, making it possible to consider potential effects of unplanned or controlled changes when planning future land use in the area. For the years of analysis, a marked trend has been evidenced in the increase in area of cattle pastures; this goes hand in hand with the decrease in flow. This can be attributed, in the first instance, to the reduction of water retention capacity of the soil occupied by livestock pasture (Mosquera et al 2022).

In basins without such marked changes in land use, water flow responds to other global changes, as shown by Kim et al (2013). The results of another study conducted by Balthazar et al (2015) show the impact of land use change on all ecosystem services in the basin. The loss of water retention observed, especially the shift from *páramo* grasslands to forest plantations, was scored. The storage of water in the soil of native forests cannot be recovered through afforestation. The benefits in terms of hydrological regulation are at the expense of a reduction in total water from supply, as forest cover is associated with increased water use in most Andean countries (Bonnesoeur et al 2019).

FIGURE 5 Nonlinear models for relationships between livestock grassland and water quality parameters: (A) COD; (B) total coliforms; (C) BOD; (D) NO_3^-; (E) SS. MPN, most probable number.

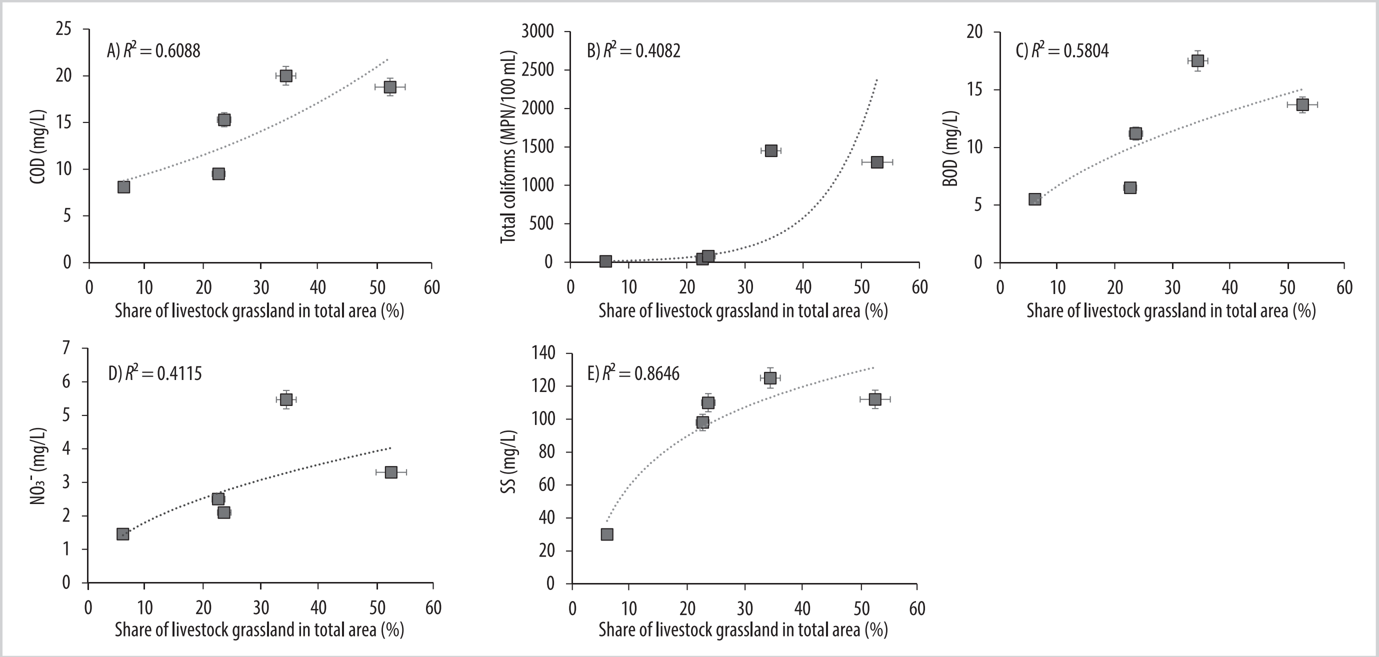


TABLE 3 Models fitted.

Water quality parameter	Model	Adjusted R^2	Spearman
COD (mg/L)	Exponential	0.69	0.83
BOD (mg/L)	Potential	0.66	0.73
SS (mg/L)	Log	0.87	0.76
NO_3^- (mg/L)	Potential	0.62	0.60
Total coliforms (MPN/100 mL)	Exponential	0.82	0.81

Note: MPN, most probable number.

In the Andean *páramos*, Patiño et al (2021) conducted a systematic search on the effects on hydro-physical soil properties due to the change in land use. They found a relationship similar to that established in the current study but viewed this from the perspective of soil characteristics and their direct relationship with water storage and conservation of water flows.

A similar investigation was conducted by Ochoa-Tocachi et al (2016), analyzing the impact of land use change on hydrological response in Andean basins. They found variations ranging from extremely high discharges to highly seasonal base flows. The effects of land use are equally diverse, and their magnitudes are a function of watershed properties, original and replacement vegetation, and type of management. The impacts of grazing are more variable but have the greatest effect on hydrological regulation of the basin.

In the studies conducted by Heerspink et al (2020), the entire Amazon basin was analyzed. The analysis indicated significant variations in streamflow that were due to changes in land use and variability in precipitation, which is similar to the findings of Haghtalab et al (2020), but they also included daily changes and extreme events. These studies all support the link between changes in land use and the global changes in rainfall patterns and evapotranspiration. This allows a precise forecast of the variability of the flows within a basin to be obtained. Land use and land cover change emerge from the interaction between biophysical, social, economic, and institutional factors (Geist and Lambin 2002).

In terms of water quality, there is clear evidence that livestock activities are directly related to a decrease in water quality and quantity, as analyzed by Strauch et al (2009). In this case, the different types of livestock are evaluated. I did not analyze different livestock production techniques, but rather examined the direct effect of these activities on water quality. Taniwaki et al (2017) found a direct relationship between pasture crops for livestock and the increase in organic matter in water flows, especially in the wet season. This is related to the increase in runoff caused by rainfall carrying pollutants from pasture soils to water courses. This effect is not observed in humid grasslands and *páramo* areas, since these are not grazed and thus have no major input of organic matter from livestock. Their soils have a great capacity to retain, in addition to water, organic matter.

This research points to ways to increase the sustainability of mountain areas, including improving the quality of life of local populations that depend on livestock and agricultural activities. However, agricultural activities are increasing to a lesser extent. In a study conducted by Blackmore et al (2021) in the central highlands of the Ecuadorian Andes, land degradation and activities of local populations were analyzed, showing the relationship between eroded and nonproductive lands and the vulnerability of livelihoods. Properly managing land could significantly reduce the exposure of the livelihoods of populations and contribute to sustainable development.

Addressing the hydro-social territorial issues highlighted here requires that the populations inhabiting and farming livestock in these areas be involved in participatory practices to develop public policies to manage and conserve resources (Mills-Novoa et al 2020), such as soil and water, and the benefits they provide.

Conclusions

Land cover and use in the Rircay river subbasin have changed dramatically over the last 3 decades. These dynamics do not have a linear trend but are due to social behavior that the area's productive activity has influenced. A loss of 116 km^2 of native forest and *páramo* and 134 km^2 of natural pastures is observed. Almost all this loss of vegetation cover has been due to cattle pastures that, by 2015, occupied 286.1 km^2, 34.5% of the total area. These changes in land use mean a difference not only in the hydrological behavior of the site but also in water demands. By 2020, the average daily water use for pasture irrigation was 7.7 m^3/s, compared to the provision for human consumption, which was 0.13 m^3/s. This high increase in water consumption for irrigation is observed as a directly proportional relationship with water extracted from the river channel.

In addition to the pressure on water consumption, the problem worsens when the quality of the remaining river water is reduced. There is an increase in the concentration of the 5 pollutants analyzed in this research. The nonlinear models of percentage land use (such as cattle pasture) and contaminants have different adjustments and different growth rates, but all indicate an increase in pollutant concentration. If the quantity of water decreases and the quality is impoverished, we face an imminent risk to the water security of the area.

The dynamics of land use change from native vegetation to cultivated grassland is a common problem within the high mountain basins in Ecuador. There are issues of water regulation, pollutants in water flows, and loss of ecosystem services

This research contributes to and complements other studies. Above all, it serves as a base study on the combined effects of the quality and quantity of water. Further analyses are needed that include climate variables, which play a fundamental role in the variability of the flows in a specific area.

It is necessary to evaluate the tangible impacts of the changes and land cover on the quality and quantity of water, and land management alternatives to reduce these impacts. Managing the territory to obtain the greatest advantages without accelerating degradation is one way toward sustainable development in mountain areas.

ACKNOWLEDGMENTS

The author thanks SENAGUA and the Ministry of Agriculture and Livestock for the data on water use and vegetation cover. The research was developed by the

Financing of the V Call for Funds for the development of Research Projects of the Catholic University of Cuenca.

REFERENCES

Avilés A, Palacios K, Pacheco J, Jiménez S, Zhiña D, Delgado O. 2020. Sensitivity exploration of water balance in scenarios of future changes: A case study in an Andean regulated river basin. *Theoretical and Applied Climatology* 141(3–4):921–934. https://doi.org/10.1007/s00704-020-03219-y.
Balthazar V, Vanacker V, Molina A, Lambin EF. 2015. Impacts of forest cover change on ecosystem services in high Andean mountains. *Ecological Indicators* 48:63–75. https://doi.org/10.1016/j.ecolind.2014.07.043.
Bates D, Mächler M, Bolker BM, Walker SC. 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 67(1):1–48. https://doi.org/10.18637/jss.v067.i01.
Berrio-Giraldo L, Villegas-Palacio C, Arango-Aramburo S. 2021. Understating complex interactions in socio-ecological systems using system dynamics: A case in the tropical Andes. *Journal of Environmental Management* 291:112675. https://doi.org/10.1016/j.jenvman.2021.112675.
Berrouet L, Villegas-Palacio C, Botero V. 2020. Vulnerability of rural communities to change in an ecosystem service provision: Surface water supply. A case study in the northern Andes, Colombia. *Land Use Policy* 97:104737. https://doi.org/10.1016/j.landusepol.2020.104737.
Blackmore I, Iannotti L, Rivera C, Waters WF, Lesorogol C. 2021. Land degradation and the link to increased livelihood vulnerabilities among indigenous populations in the Andes of Ecuador. *Land Use Policy* 107:105522. https://doi.org/10.1016/j.landusepol.2021.105522.
Boelens R. 2014. Cultural politics and the hydrosocial cycle: Water, power and identity in the Andean highlands. *Geoforum* 57:234–247. https://doi.org/10.1016/j.geoforum.2013.02.008.
Bonnesoeur V, Locatelli B, Guariguata MR, Ochoa-Tocachi BF, Vanacker V, Mao Z, Stokes A, Mathez-Stiefel S-L. 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.
Celleri R, Campozano L, Avilés Á. 2017. Integrated water resources management in an Andean mountain basin: The case of the Machángara River. *In:* Al-Saidi M, Ribbe L, editors. *Nexus Outlook Assessing International Challenges*. Cologne, Germany: University of Applied Sciences, pp 80–86.
Cocca G, Sturaro E, Gallo L, Ramanzin M. 2012. Is the abandonment of traditional livestock farming systems the main driver of mountain landscape change in Alpine areas? *Land Use Policy* 29(4):878–886. https://doi.org/10.1016/j.landusepol.2012.01.005.
FAO [Food and Agriculture Organization of the United Nations]. 2007. *Livestock's Long Shadow*. Rome, Italy: FAO. https://www.fao.org/3/a0701e/a0701e00.htm; accessed on 14 December 2021.
Geist HJ, Lambin EF. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52(2):143–150. https://doi.org/10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2.
Grainger S, Hommes L, Karpouzoglou T, Perez K, Buytaert W, Dewulf A. 2019. The development and intersection of highland-coastal scale frames: A case study of water governance in central Peru. *Journal of Environmental Policy and Planning* 21(4):373–390. https://doi.org/10.1080/1523908X.2019.1566057.
Haghtalab N, Moore N, Heerspink BP, Hyndman DW. 2020. Evaluating spatial patterns in precipitation trends across the Amazon basin driven by land cover and global scale forcings. *Theoretical and Applied Climatology* 140(1–2):411–427. https://doi.org/10.1007/s00704-019-03085-3.
Heerspink BP, Kendall AD, Coe MT, Hyndman DW. 2020. Trends in streamflow, evapotranspiration, and groundwater storage across the Amazon basin linked to changing precipitation and land cover. *Journal of Hydrology: Regional Studies* 32:100755. https://doi.org/10.1016/j.ejrh.2020.100755.
Helsel DR, Hirsch RM, Ryberg KR, Archfield SA, Gilroy EJ. 2020. *Statistical Methods in Water Resources*. U.S. Geological Survey Techniques and Methods, Book 4, Chapter A3. https://doi.org/10.3133/tm4a3.
High Level Panel on Water. 2018. *Making Every Drop Count: An Agenda for Water Action*. New York, NY: United Nations. https://sustainabledevelopment.un.org/content/documents/17825HLPW_Outcome.pdf; accessed on 14 December 2021.
Kareiva P, Marvier M. 2015. *Conservation Science: Balancing the Needs of People and Nature*. Greenwood Village, CO: Roberts.
Khamchiangta D, Dhakal S. 2020. Time series analysis of land use and land cover changes related to urban heat island intensity: Case of Bangkok metropolitan area in Thailand. *Journal of Urban Management* 9(4):383–395. https://doi.org/10.1016/j.jum.2020.09.001.
Kim J, Choi J, Choi C, Park S. 2013. Impacts of changes in climate and land use/land cover under IPCC RCP scenarios on streamflow in the Hoeya River basin, Korea. *Science of the Total Environment* 452–453:181–195. https://doi.org/10.1016/j.scitotenv.2013.02.005.
Lambin EF, Geist HJ, Lepers E. 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources* 28:205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459.
Lambin EF, Meyfroidt P. 2010. Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Policy* 27(2):108–118. https://doi.org/10.1016/j.landusepol.2009.09.003.
Li Y, Boswell E, Thompson A. 2021. Correlations between land use and stream nitrate-nitrite concentrations in the Yahara River watershed in south-central Wisconsin. *Journal of Environmental Management* 278(2):111535. https://doi.org/10.1016/j.jenvman.2020.111535.
Llambí LD, Becerra MT, Peralvo M, Avella A, Baruffol M, Díaz LJ. 2019. Monitoring biodiversity and ecosystem services in Colombia's high Andean ecosystems: Toward an integrated strategy. *Mountain Research and Development* 39(3):A8–A20. https://doi.org/10.1659/MRD-JOURNAL-D-19-00020.1.
López-Sandoval M, Maldonado P. 2019. Change, collective action, and cultural resilience in *páramo* management in Ecuador. *Mountain Research and Development* 39(4):R1–R9. https://doi.org/10.1659/MRD-JOURNAL-D-19-00007.1.
Mateo-Sagasta J, Marjani Zadeh S, Tural H, Burke J. 2017. *Water Pollution From Agriculture: A Global Review. Executive Summary*. Rome, Italy: Food and Agriculture Organization of the United Nations; Colombo, Sri Lanka: International Water Management Institute. https://www.fao.org/documents/card/en/c/a9598c47-0ca1-4c77-8d9d-1c2708050ba0/; accessed on 15 December 2021.
Mills-Novoa M, Boelens R, Hoogesteger J, Vos J. 2020. Governmentalities, hydrosocial territories & recognition politics: The making of objects and subjects for climate change adaptation in Ecuador. *Geoforum* 115:90–101. https://doi.org/10.1016/j.geoforum.2020.06.024.
Mosquera GM, Marín F, Stern M, Bonnesoeur V, Ochoa-Tocachi BF, Román-Dañobeytia F, Crespo P. 2022. Progress in understanding the hydrology of high-elevation Andean grasslands under changing land use. *Science of the Total Environment* 804:150112. https://doi.org/10.1016/j.scitotenv.2021.150112.
Niyonzima T, Stage J, Uwera C. 2013. The value of access to water: Livestock farming in the Nyagatare district, Rwanda. *SpringerPlus* 2(1):644. https://doi.org/10.1186/2193-1801-2-644.
Nyachieo J. 2016. *Promising Practices in Supporting Management of Water Resources in Pastoral Areas*. Bern, Switzerland: Swiss Agency for Development and Cooperation. https://www.shareweb.ch/site/Agriculture-and-Food-Security/aboutus/Documents/pastoralism/pastoralism_brief_water_management_e.pdf; accessed on 14 December 2021.
Ochoa-Tocachi BF, Buytaert W, De Bièvre B, Célleri R, Crespo P, Villacís M, Llerena CA, Acosta L, Villazón M, Guallpa M, et al. 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.
Ortega-Gaucin D, Mejía Sáenz E, Palacios Vélez E, Rendón Pimentel L, Exebio García A. 2008. Model for the optimization of resources for an irrigation district [in Spanish with English abstract]. *Terra Latinoamericana* 27(3):219–226. http://www.scielo.org.mx/pdf/tl/v27n3/v27n3a6.pdf.
Patiño S, Hernández Y, Plata C, Domínguez I, Daza M, Ovideo-Ocaña R, Ochoa-Tocachi BF, Buytaert W. 2021. Influence of land use on hydro-physical properties of Andean *páramos* and its linkages to hydrological regulation. *Catena* 202:105227.
Quintero-Gallego ME, Quintero-Angel M, Vila-Ortega J-J. 2018. Exploring land use/land cover change and drivers in Andean mountains in Colombia: A case in rural Quindío. *Science of the Total Environment* 634:1288–1299. https://doi.org/10.1016/j.scitotenv.2018.03.359.
Schlink AC, Nguyen ML, Viljoen GJ. 2010. Water requirements for livestock production: A global perspective. *OIE Revue Scientifique et Technique* 29(3):603–619. https://doi.org/10.20506/rst.29.3.1999.
Strauch AM, Kapust AR, Jost CC. 2009. Impact of livestock management on water quality and streambank structure in a semi-arid, African ecosystem. *Journal of Arid Environments* 73(9):795–803. https://doi.org/10.1016/j.jaridenv.2009.03.012.
Sun Q, Qi W, Yu X. 2021. Impacts of land use change on ecosystem services in the intensive agricultural area of north China based on multi-scenario analysis. *Alexandria Engineering Journal* 60(1):1703–1716. https://doi.org/10.1016/j.aej.2020.11.020.
Taniwaki RH, Cassiano CC, Filoso S, Frosini de Barros Ferraz S, Barbosa de Camargo P, Martinelli LA. 2017. Impacts of converting low-intensity pastureland to high-intensity bioenergy cropland on the water quality of tropical streams in Brazil. *Science of the Total Environment* 584–585:339–347. https://doi.org/10.1016/j.scitotenv.2016.12.150.
Valladares C, Boelens R. 2019. Mining for mother earth: Governmentalities, sacred waters and nature's rights in Ecuador. *Geoforum* 100:68–79. https://doi.org/10.1016/j.geoforum.2019.02.009.
Vasco C, Salazar D, Borja J, Limaico K. 2016. The impact of international migration and remittances on agricultural production patterns: The case of rural Ecuador [in Spanish with English abstract]. *Siembra* 3:1–6. https://doi.org/10.29166/siembra.v3i1.180
Vörösmarty CJ, Stewart-Koster B, Green PA, Boone EL, Flörke M, Fischer G, Wiberg DA, et al. 2021. A green-gray path to global water security and sustainable infrastructure. *Global Environmental Change* 70:102344. https://doi.org/10.1016/j.gloenvcha.2021.102344.
Walker B, Salt D. 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Washington, DC: Island Press.