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If Watersheds Spoke: A condition analysis of the Rio Tomebamba watershed in southern Ecuador using GIS analysis

Lenka G. Doskocil
SIT Study Abroad

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Doskocil, Lenka G.

Academic Director: Xavier Silva Ph.D.
Project Advisor: Lenin Villacis, M.S.

Colorado State University: Watershed Science
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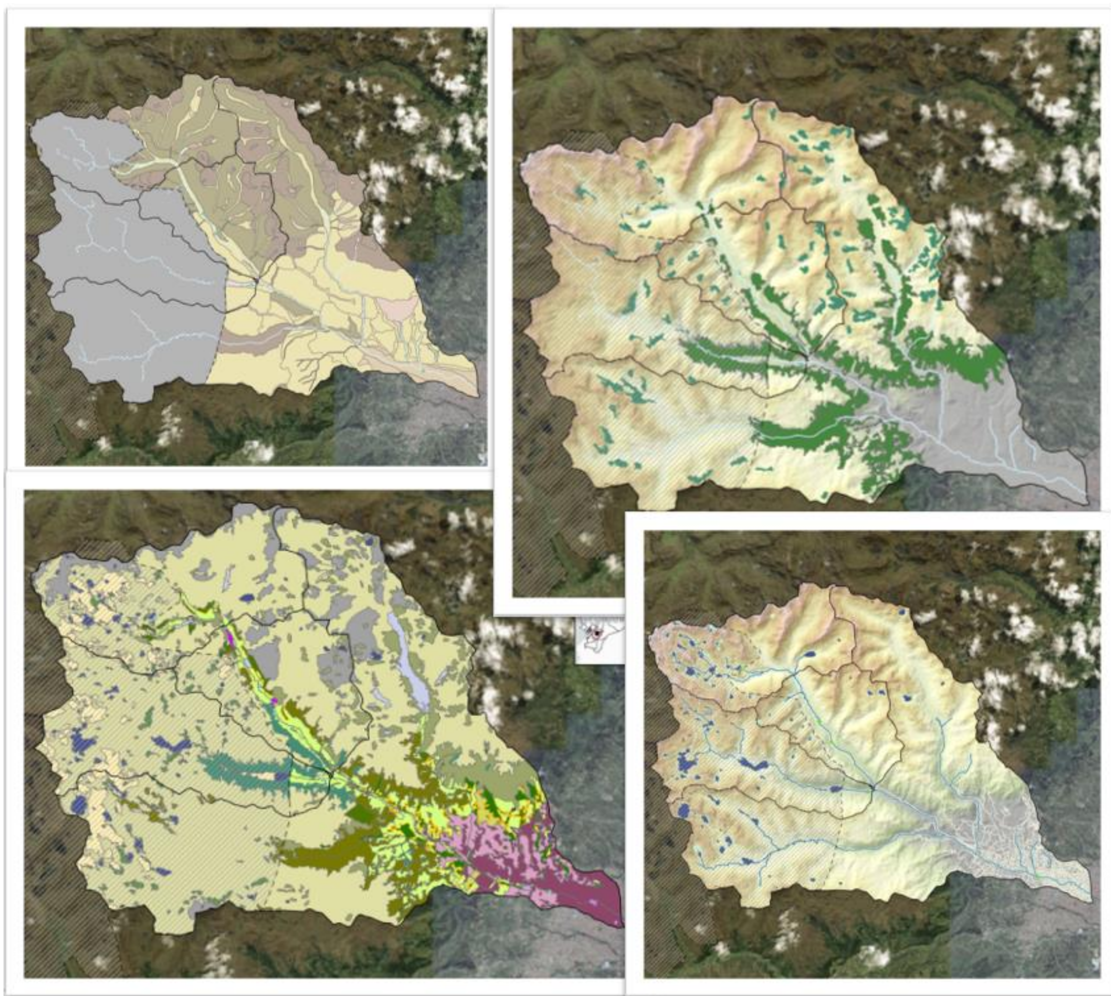

Erosion, habitat, land use, and riparian zone layers used in this analysis

Abstract

Understanding processes and ecological threats occurring at the watershed level scale composes a critical piece of water resource conservation and management. This proves doubly true in areas such as the Ecuadorian highlands where water resources depend heavily on the hydrologic regulation capacities of páramo soils. This study examined watershed condition of the Rio Tomebamba watershed and existing habitat for *Metallura baroni* and *Chibchanomys orcesi*, two highly endemic species, within its boundaries. Watershed condition was determined based on a simple index that considered nine indicators of watershed health—converted land, impacted riparian zones, impermeable surfaces, water quality, fluvial habitat condition, riparian vegetation condition, macroinvertebrate community composition, road density, and erosion potential—in four analysis regions of the Rio Tomebamba watershed. Data spanning a five-year period (2015-2019) were analyzed using ArcGIS Pro software. Cultivated pasture was the most common converted land type across all analysis regions, composing 5.8% of the entire Rio Tomebamba watershed. In general watershed condition was highest in the Llaviucu analysis region and lowest in the Lower Tomebamba analysis region. No analysis region, including the Llaviucu region which is protected almost entirely by the Cajas National Park boundary, received an "excellent" condition rating.

The Rio Tomebamba watershed as a whole was determined to be in "acceptable" condition. The results showed that riparian corridor degradation posed the most concern across all analysis regions within the watershed. Conservation and restoration of such areas would provide critical habitat for *Chibchanomys orcesi*, a highly endemic water mouse, and serve as an effective long-term management strategy for the area's water resources.

Key words: watershed condition assessment, habitat, Rio Tomebamba, watershed condition index, riparian corridors, land use, GIS analysis

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Resumen

El conocimiento de los procesos y amenazas ocurriendo al nivel de la cuenca es bastante importante para la gestión y conservación de los recursos de agua, especialmente en las regiones altas de Ecuador donde estos recursos dependen de la regulación hídrica de los suelos de páramo. Esta investigación consideró la condición de la cuenca de Rio Tomebamba y el hábitat que existe para *Metallura baroni* y *Chibchanomys orcesi*, dos especies endémicas, dentro de la cuenca. La condición de la cuenca se determinó por un índice simple, considerando nueve indicadores de la de una cuenca: tierra reconvertida, zonas de riberas impactadas, superficies impermeables, la calidad de agua, la condición de hábitat fluvial, la condición de vegetación ribereña, la composición de las comunidades de macroinvertebrados, la densidad de los caminos, y la potencia de erosión hídrica. Estos indicadores y el hábitat de las dos especies endémicas se analizaron sobre cuatro regiones dentro de la cuenca de Rio Tomebamba, usando ArcGIS Pro. Pasto cultivado fue el tipo de tierra reconvertida más común en todas las cuatro regiones y compuso 5.8% de la cuenca total. En general, la condición de la cuenca fue más alta en la región de Llaviucu y más baja en la región de Lower Tomebamba que en el resto de la cuenca. Ninguna de las regiones recibió una nota de condición "excelente". La cuenca de Rio Tomebamba se determinó en condición "aceptable." Los resultados demostraron que los corredores ribereños están en peor condición de los indicadores sobre todas las regiones de la cuenca. La conservación y restauración de estas áreas proveería hábitat importante para *Chibchanomys orcesi*, un ratón endémico de agua, y podría servir como una estrategia de gestión efectiva para los recursos de agua del área.

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Introduction

The very foundation of life on earth rests on the stability, productivity, and relative health of freshwater ecosystems. Unfortunately, they represent some of the most overused, under protected, and threatened systems in the world (Carpenter *et al.*, 2011). Areas of natural hydrologic regulation—wetlands, riparian zones, páramo soils---diminish daily due to human impact (Rojas, 2016; Condo-Carabajo & Julea-Palomeque, 2019; Buytaert, *et al.*, 2006; Carpenter *et al.*, 2011). Over exploitation and contamination of water resources, increases in agricultural land use, and human population growth have contributed to the continual decline in aquatic ecosystem condition and extent (Roldan, 1999; Acosta *et al.*, 2009; Rojas, 2016; Carrasco *et al.*, 2010). However, protection of such resources proves challenging as freshwater ecosystems exhibit high degrees of connectivity from headwaters to mouth and to the landscape processes occurring around them (Potyondy *et al.*, 2011). Impacts or deterioration in one area will carry over into the rest of the system.

Although Ecuador's borders contain an abundance of water resources, its freshwater ecosystems have been poorly studied and experience increasing pressure due to augmented demand for socio-economic and environmental services (Selvanayagam & Abril, 2015; Van Colen et al., 2017; Hampel *et al.* 2010). Although the country has instituted a number of water protection and management legislation, various ambiguities and deficiencies in application and management have severely impacted their effectiveness at the national level (Rojas, 2016; SENAGUA, 2015). In 2012, the Ecuadorian government began a process of decentralization created as part of the Buen Vivir program. This process has slowly been transferring more power to the 221 *cantones*, or municipalities over the past several years (United, 2016). Under the Ley Orgánica de Recursos Hídricos Usos y Aprovechamiento del Agua, the State has the responsibility both to manage water resources for multiple uses, including human consumption, ecosystem protection, and sustainability, and to protect watersheds' capacities to provide good quality water in sufficient quantities at appropriate times (SENAGUA, 2015). However, in the decentralization process, it has become unclear where this responsibility lies, contributing to the sporadic management at the national level. However, certain communities have developed voluntary, decentralized initiatives—such as the world's first environmental service payment program in the Pimampiro municipality, the Water Protection Fund (FONAG) in Quito, and ETAPA EP in Cuenca—which have proved successful in implementing monitoring and restoration programs to protect water resources (Kauffman, 2013).

In Cuenca, a southern Ecuadorian city located in the Azuay province and the western cordillera of the northern Andes, a local utility company (the Empresa Pública Municipal de Telecomunicaciones, Agua Potable, Alcantarillado, y Saneamiento de Cuenca (ETAPA-EP)) has set up a system of 36 stations monitoring climatic, hydrological, and ecological variables. These stations have locations across four sub-watersheds surrounding the city of Cuenca that serve as the primary sources of drinking water for the city: Rio Yanuncay, Rio Tomebamba, Rio Machangara, and, to a lesser extent, Rio Tarqui (ETAPA EP, 2019; Van Colen *et al.*, 2017). ETAPA EP and the city of Cuenca have designated two of these critical watersheds (Tomebamba and Yanuncay) as strict conservation areas and have chosen to manage the Machangara, Tarqui, Jadan, and Sidcay watersheds under an active conservation plan (Actualización, 2015). While Tomebamba and Yanuncay are the only two rivers with headwater regions inside Cajas National Park, all the rivers surrounding Cuenca are born in the páramo region, a unique grassland ecosystem found above 3,500 meters across the Andes known for both its incredible hydrologic regulation properties and its extreme climate (Buytaert *et al.*, 2006).

Unfortunately, rapid growth in tourism and land conversion from native vegetation to crop land and pasture land have placed water resources in this area at risk (González-Maldonado & Córdova-Vela, 2017; Tobón, 2009; Proano, 2004; Buytaert *et al.*, 2006; Carrasco, Pineda-Lopez, & Perez-Munguia, 2010; Van Colen *et al.* 2017). Soils altered by land conversion lose considerable water storage potential and regulation capacity, thereby reducing the total water yield potential of the area (Rojas, 2016; Buytaert *et al.*, 2006). In páramo regions, such impacts prove especially troubling. Páramo soils can hold up to twice their weight in water due to inherent structural characteristics and high organic matter content (Tobón, 2009; Van Colen *et al.*, 2017). Due in part to these characteristics, these soils possess considerable hydrologic regulation capacities and act as the primary avenue of water storage in the mountains of Ecuador. However, evidence exists that such soils have a very limited ability to recuperate natural retention characteristics once impacted, placing land conversion as one of the foremost threats to both the páramo ecosystem and the water resources they help provide (Condo-Carabajo & Juela-Palomeque, 2019; Tobón, 2009). Changes in land use also threaten riparian vegetation, an important distribution mechanism of matter and energy in freshwater ecosystems. This vegetation type regulates water temperature, algal growth, contaminants, organic matter content, and sediment inputs (Carrasco, Pineda-Lopez, & Perez-Munguia, 2010; Ceccon, 2003).

For water resource managers, accounting for the wide variety of threats impacting resource and ecosystem condition proves difficult. Geomorphologic, physical, hydrologic, and climatic characteristics of the surrounding landscape drive the natural conditions of freshwater ecosystems (Villamarin, 2013; Carvacho, 2012; Green Sweitlik, 2000; González-Maldonado & Córdova-Vela, 2017). As such, conducting management and analysis activities at the watershed level is paramount to understanding the complex ecological processes occurring within these systems (Potynondy *et. al*, 2011; Dieye *et al.*, 1999). Considering restoration, management, and community engagement at this scale also proves to be more effective, as local communities often already recognize basin boundaries, presenting a more logical framework for conducting and explaining ecosystem analysis (Potynondy *et. al*, 2011). Many governments and management agencies have integrated this approach into their general management plans. The United State Forest Service (USFS) employs the Watershed Condition Framework (WCF) as a vehicle to assess watersheds and develop management plans (Potyondy *et al.*, 2011). The United States Environmental Protection Agency (EPA) has developed the Integrated

Assessment of Healthy Watersheds (IAHW) to help provide national, regional, state, and local guidance for addressing and managing watershed health (United, 2018). The government of Ecuador has mandated that water resource management occur at the watershed level, although lack of readily available data, cooperation between various levels of government, and the relatively new concept of integrated adaptive watershed management have made implementation of this management strategy challenging (SENAGUA, 2015; Barrera *et al.*, 2012). Unfortunately, limited literature exists on assessing watershed condition and watershed level dynamics, especially when compared to the wealth of studies addressing specific ecosystems or habitats (Sadeghi *et al.*, 2019).

This could prove potentially disastrous if management actions executed at the watershed scale proceed without a comprehensive understanding of landscape level processes, interactions, and ecological pressures occurring within river basin boundaries. In order to support the movement toward watershed level management, site specific investigation of watershed condition must move with it. This study aims to present a relatively simple analysis of the condition of the Rio Tomebamba watershed in southwestern Ecuador to both provide water resource and land managers with a more complete understanding of the processes and various ecological pressures occurring within the basin and to identify processes that require more exploration. Although various studies have examined specific aspects of this watershed—aquatic habitat condition, hydrologic behavior, land use change impacts, macroinvertebrate community composition and variation, patch movement of avifauna, water quality—none have taken a landscape level approach accounting for multiple watershed-level processes. This study represents the first of its kind for this watershed.

Ethics

This study fully complies with the Research and Ethics in Field Work and Internship guidelines put forth by the School for International Training based on the Institutional Review Board and the American Anthropological Association guidelines. The author understands that she has a responsibility to the communities within the Rio Tomebamba watershed and to the City of Cuenca to avoid negatively impacting community members and to gear the study toward the needs of those communities. Due to the remote nature of this study, no human subjects or field data collection was involved, considerably reducing the possibility of negative impact to the field environment or to community members. Data use permissions were secured from both Empresa Pública Municipal de Telecomunicaciones, Agua Potable, Alcantarillado, y Saneamiento de Cuenca (ETAPA EP) and el Ministerio de Agricultura, Ganadería, Acuacultura, y Peces (MAGAP). Both were made aware that the author was a student conducting a watershed health analysis in the Rio Tomebamba watershed region.

Methods

1.1 Study area

This study focused on the Rio Tomebamba watershed (79.007905, -2.900507), whose headwaters lie partially within Cajas National Park northwest of the city of Cuenca in the Azuay province in southern Ecuador (Figure 1). Born in the páramo region, this river passes through both páramo grassland, páramo shrubland, and montane forest before joining the rivers Yanuncay and Machangara within Cuenca's city limits. The 328.91 km^2 study area includes 45.0% (132.54 km^2) of Cajas National Park, all of Bosque Proteger de Mazan—a private reserve dedicated to restoring the native montane forest ecosystem—and is dominated by herbaceous páramo vegetation (57.0% of the watershed's area). Rock outcroppings and cultivated pastures compete for the second most common landcover type (5.9% and 5.9% respectively) (Convenio MAG – IEE – SENPLADES, 2015). Andosols with glacial or periglacial genesis represent the dominant soil type (Consorcio TRACASA-NIPSA, 2015a. Well drained, low fertility soils with high organic matter content and moderate effective depth characterize the region (Consorcio TRACASA-NIPSA, 2015a; Van Colen *et al.*, 2017). Although the region has experienced recent and rapid growth in cattle ranching (both for dairy and meat) and fish farming, the main economic activities remain creation of artisan products for the city of Cuenca and small-scale farming (Rojas, 2016). Most landowners within the study site own property no larger than 3 hectares, although there exist a few large operations of 100 hectares or more (Rojas 2016). Of the various converted land types within the watershed boundaries, crops account for 40.5%, a land use type that composed 5.8% of the total study area. Monterey pine (*Pinus reticula)* and eucalyptus plantations, two species of trees introduced the late 1880s for lumber, compose 17.2% of total land use and 2.5% of the total watershed (Convenio MAG – IEE – SENPLADES, 2015). In 2015, Rio Tomebamba was yielding roughly 15.62 $l/s/km^2$ of water daily with a range of 0.13 $l/s/km^2$ to 151.69 $l/s/km^2$ (Condo & Juela, 2017). On average, the basin receives 1007.49 mm of precipitation and, in 2015, 337 days were reported to have seen rain (Condo & Juela, 2017). Above 3200 meters, this precipitation appears mainly as a light, constant drizzle or mist, although torrential rainstorms are not uncommon (Condo-Carabajo & Juela-Palomeque, 2019). Vegetation in this region has adapted to capture horizontal precipitation (mist) as droplets on its leaves, which then fall to the ground and are absorbed by the soil (Avendano, 2007).

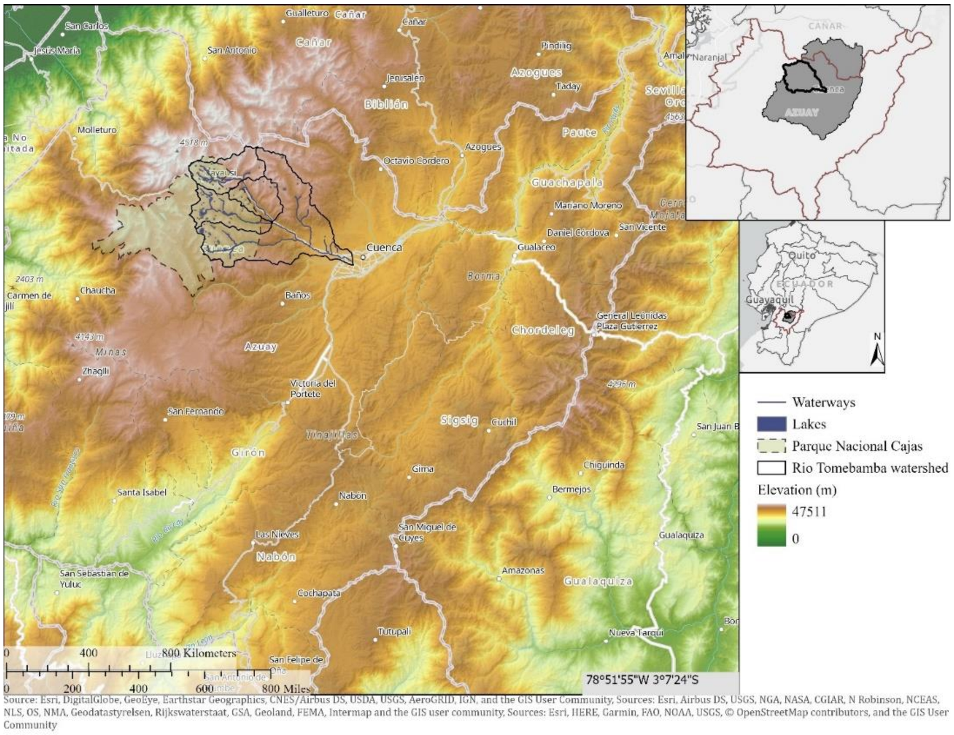

Figure 1. Location of Rio Tomebamba watershed study area. Elevation layer based on 30-meter DEM data from ASTER.

In order to better pinpoint areas of concern, the study area was divided into four regions according to existing water quality and ecological monitoring station locations and sub-watershed boundaries: Taquiurcu analysis region (referred to here after as TAR) located in the northwestern most area of the watershed and including a small piece of Cajas National Park, Quinuas analysis region (QAR) located directly below TAR along the main stem of the river, Llaviucu analysis region (LAR) encompassing the western most area of the watershed and almost entirely within Cajas National Park, and Lower Tomebamba analysis region (LTAR) located near the watershed's outlet (Figure 2). Due to data limitations, some regions contain more stations than others and vary in size. The Llaviucu region fell almost entirely within Cajas National Park while the lower Tomebamba region contained 6.87 km^2 of the city of Cuenca (Appendix B).

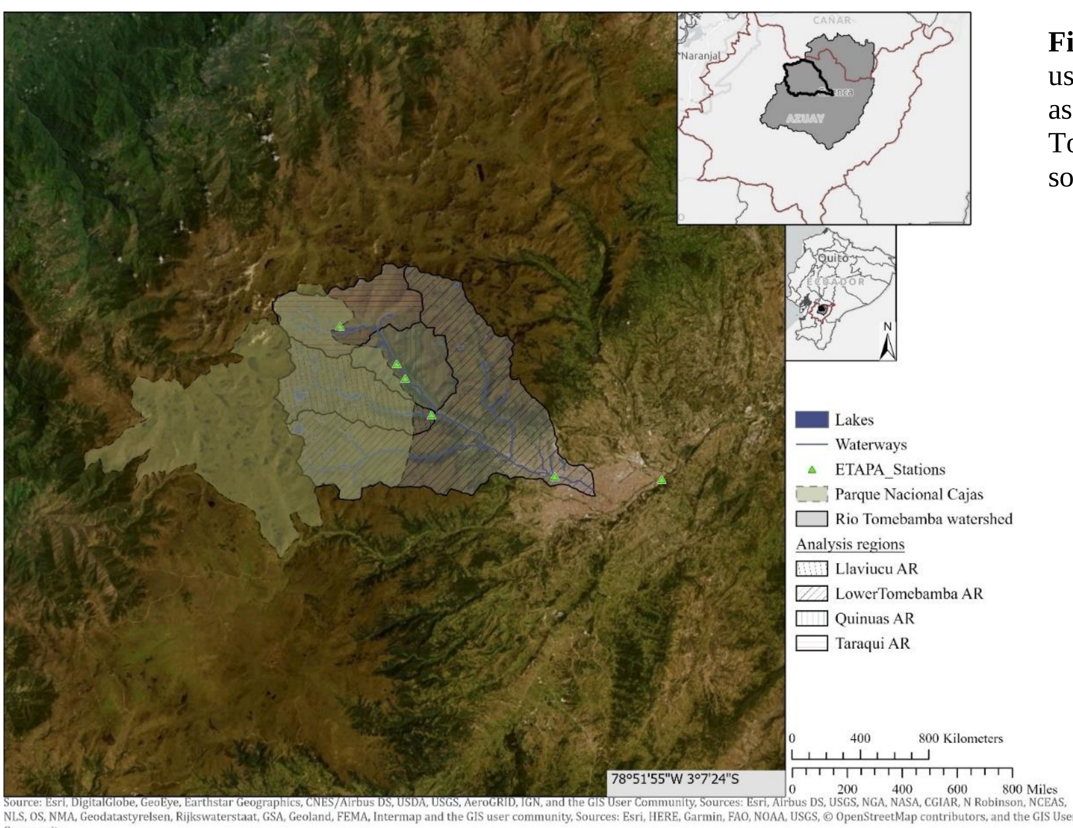

Figure 2. Analysis regions used for a watershed condition assessment of the Rio Tomebamba watershed in southern Ecuador

1.2 Assessment framework development

The method chosen to evaluate the current condition of the Rio Tomebamba watershed was based on watershed condition frameworks developed by the United States Forest Service (USFS) and the United States Environmental Protection Agency (EPA). The Integrated Assessment of Healthy Watersheds put forth by the EPA breaks watershed condition into six ecological attributes: landscape condition, habitat condition, water quality, hydrology, geomorphology, and biologic condition (United, 2018). The Watershed Condition Framework developed by the USFS echoes these ideas, utilizing twelve indicators divided into four categories: aquatic physical, aquatic biological, terrestrial physical, and terrestrial biological (Potyondy & Geier, 2011). This assessment uses nine indicators of watershed health chosen based on these recommendations and driven by available data and the expertise of the researcher. They included impermeable surfaces, converted land, road density, riparian zone impacted by roads, water quality, erosion potential, river habitat condition, quality of riparian vegetation, and macroinvertebrate community structure (Table 1).

Table 1. Watershed condition indicators, associated data sources, and relation to the United States Forest Service Watershed Condition Framework (WCF) and the United States Environmental Protection Agency Integrated Assessment of Healthy Watersheds (IAHW)

Indicator	Metric	IAHW	WCF	Data source
Impermeable surfaces	% impermeable surfaces	Landscape condition, geomorphology	Terrestrial physical	OpenStreetMap, Ministerio de Agricultura y Ganadería
Converted land	% converted land	Landscape condition	Terrestrial physical, terrestrial biological	Ministerio de Agricultura y Ganadería
Road density	Density	Landscape condition, habitat condition	Terrestrial physical	OpenStreetMap
Riparian zone impacted	% riparian zone impacted by roads	Habitat condition, hydrology, landscape condition	Aquatic biological	Ministerio de Agricultura y Ganadería, OpenStreetMap
Water quality	Water Quality Index (WQI)	Water quality	Aquatic physical	ETAPA EP
Erosion potential	Erosion potential	Geomorphology	Terrestrial physical	Ministerio de Agricultura y Ganadería
River habitat condition	Fluvial Habitat Index	Habitat condition, Hydrology	Aquatic physical	ETAPA EP
Riparian vegetation	Quality of riparian vegetation (QBR)	Habitat condition, landscape condition, hydrology	Aquatic biological	ETAPA EP
Macroinvertebrate community	BMWP/Col	Biological condition	Aquatic biological	ETAPA EP

Impermeable surfaces were restricted to those created by anthropogenic substances and classified as asphalt, concrete, urban areas, cobblestone, paved areas, paving stones, and industrial complexes. (For the purposes of analysis, roads were assumed to average 7 meters in width.) Such surfaces severely inhibit precipitation infiltration and are correlated with increased erosion and flood hazard (Shuster *et al.*, 2005; Chithra *et al.*, 2015). Water that the soil would have absorbed and retained runs off and into nearby water bodies, potentially carrying increased contaminant and sediment loads (National, 2011; Carpenter *et al.*, 2011). Sedimentation poses especially dangerous impacts to aquatic communities as it can produce profound negative effects on water temperatures, oxygen yield, spawning bed condition, and insect habitat (Akay *et al.*, 2008; Couceiro *et al.*, 2009). Road density was considered for a similar reason as higher densities play a dominant role in augmentation of erosion and associated sediment yield (Potyondy *et al.*, 2011; Reid & Dunne, 1984; Grace, 2002). Presence of such road density and converted land can also be considered surrogate indicators of habitat fragmentation (Heilman *et al.* 2002).

Changes in land use, particularly deforestation, pose a concern for a similar reason. Vegetative cover plays a significant role in reducing erosion hazard both by reducing the velocity of incoming precipitation droplets and stabilizing the soil (Ceccon, 2003; Avendano 2007). The shade provided also reduces evaporation, thereby improving the water storage capacity of the drainage basin. However, studies have shown that non-native vegetative species can impact or even reduce soil water storage capacity (Gibbons *et al.*, 2017; Farley *et al.*, 2004). In páramo soils, areas planted with

Monterey pine *(Pinus radiata*) lose 51% of their water storage potential while soil that has been worked for agriculture or altered by cattle grazing lose 12% and 27% respectively (Proano, 2004). Changes in vegetative cover alter soil characteristics. It was for this reason that percent converted land was included as an indicator of watershed health.

Riparian corridors play key roles as landscape connectivity agents and aquatic habitat regulators (Hawes *et al.*, 2008; Ceccon, 2003; Burneo & Gunkel, 2003; Crooks & Sanjayan, 2006). For the purposes of this analysis, the quality of the riparian vegetation was determined using QBR, the Fluvial Habitat Index, and proportion of the riparian area impacted by roads to quantify the condition of the riparian corridors in Rio Tomebamba. The riparian zone width was defined as a 30-meter buffer along all sides of freshwater bodies (Brazil, 2020; Zimbres *et al.*, 2017). The aquatic biological condition was determined based on the British Monitoring Working Party Columbia (BMWP/Col) index as calculated by ETAPA EP. This index uses the variation in macroinvertebrate family tolerances to water pollution to characterize water quality. Higher BMWP/Col scores reflect a higher abundance of tolerant families (Selvanayagam & Abril, 2015). For the purpose of this analysis, the presence of more tolerant macroinvertebrate families was assumed to correlate with higher stability at the base of the aquatic food chain. Climatic variables, such as precipitation, were intentionally excluded as indicators. Although such variables represent important metrics of watershed exposure (or vulnerability), they are considered background conditions to watershed health and are not altered by disturbances within the watershed area (Furniss *et al.* 2013).

Each indicator was divided into five numerical categories, each corresponding to a condition rating (Table 2). Mean indicator results were calculated for each year in each analysis region, for each region across the five-year period, and across all regions and years. Mean indicator results were also calculated for the Rio Tomebamba watershed, using mean values of WQI, BMWP/Col, IHF, and QBR across the four analysis regions for each year and raw data from the landcover, road, and erosion data sets (Appendix A).

Table 2. Indicator scoring matrix for a watershed condition assessment of the Rio Tomebamba watershed in southern Ecuador

		Poor				Excellent
Indicator	Metric	1	2	3	4	5
Impermeable surfaces	% impermeable surfaces	>25%	15-25%	5-14.9%	2.5-4.9%	<2.5%
Converted land	% converted land	>70%	40-69.9%	20-39.9%	10-19.9%	<10%
Road density	Density	<0.621	0.62 to 1.55	1.55 to 2.49	2.49 to 3.11	>3.11
Riparian zone impacted	% riparian zone impacted by roads	>20%	10-20%	5-9.9%	0-4.9%	0%
Water quality	Water Quality Index (WQI)	Very poor (0-25)	Poor (25-50)	OK (50-70)	Good (70-90)	Excellent (90-100)
Erosion potential	Erosion potential	Very high	High	--	Medium	Low
River habitat condition	Fluvial Habitat Index	Con limitacion (0-40)	--	Limitacion moderada (40-73)	--	Sin limitacion (73-100)
Riparian vegetation	Quality of riparian vegetation (QBR)	Con limitacion (0-51)	--	Limitacion moderada (51-97)	--	Sin limitacion (97-100)
Macroinvertebrate community	BMWP/Col	Very critical (<16)	Critical (16-35)	Problematic (36-60)	Acceptable (61-100)	Good (>100)

Although habitat connectivity was not included as part of the index scoring matrix, a separate, simple analysis of existing woodland habitat was conducted using the landcover data set from the Ministerio de Agricultura, Ganadería, Acuacultura, y Pesca (MAGAP). Páramo woodland habitat patches were characterized as any native forest or bushy vegetation occurring at elevations greater than 3,500 meters and in patches greater than 5 hectares. Montane woodland habitat patches included montane forest and montane shrubby vegetation occurring below 3,500 meters. Five-hectares was also used as the lower patch size limit. Should a patch occur with 150 meters of another in either habitat type, they were considered one patch as per the methods of Tinoco *et al.* 2003. Woodland habitat was chosen for three reasons. The

Violet-throated Metal-tail (*Metallura baroni)*, a critically endangered and hyper-endemic species of hummingbird, depends on *Polylepis* sp., shrubby páramo vegetation, and the upper elevation edge of montane forests for its habitat (Tinoco, 2009; Astudillo *et al.*, 2015). The Cajas water mouse (*Chibchanomys orcesi*), a second highly endemic species found near small, rapidly flowing streams and still lakes in shrubby and herbaceous páramo habitat, depends on the maintenance of this type of woodland, as do other bird and mammal species throughout the páramo region (Barnett, 1999; Boada & Vallejo, 2018). Managing for habitat conservation often proves more effective when targeting one or two species or when focusing on preventing further fragmentation in areas where connectivity is critically threatened. The two species *Metallura baroni* and *Chibchanomys orcesi* were chosen for this simple habitat assessment for their hyper endemism, critically endangered status at the national and global level, and their occupancy of fragmented páramo woodland and montane woodland habitat. Assessing existing habitat for these species helps to determine the watershed's biotic integrity, a critical aspect of a healthy watershed as the United States Forest Service defines it (Potyondy *et al.*, 2011).

1.3 Data sources

Data was compiled from OpenStreetMap, the Ministerio de Agricultura, Ganadería, Acuacultura, y Pesca of Ecuador (MAGAP), and la Empresa de Telecomunicaciones, Agua Potable, Alcantarillado, y Saneamiento de Cuenca (ETAPA EP). All spatial data were analyzed using ArcGIS Pro 10.7.1 software with UTM projection PSAD 58 Zone 17N (see Appendix A from data layer maps). Water quality data came from the five water quality monitoring stations maintained by ETAPA EP within the watershed boundaries (Table 3) and included the water quality index (WQI) rating, the Biological Monitoring Working Party Index (BMWP/Col), a fluvial habitat index (IHF), and an index quantifying the condition of the riparian vegetation (QBR) for the years 2015, 2016, 2017, 2018 and 2019. The riparian vegetation index scores streams based on the inclusion, limitations, and composition of substrates; rapid frequency; velocity and depth regimes; channel shading; habitat heterogeneity; and aquatic vegetation cover. QBR falls into two sub-indices based on ecosystem. QBR-B (*vegetación de ribera de bosque*) was developed for riparian habitats within montane forests and evaluates riparian habitat based on the quality, structure, and grade of vegetation within the riparian zone. QBR-P (*vegetación de ribera de páramo*) is used in páramo landscapes and assesses riparian areas based on the grade and quality of vegetation and the grade of the naturalness of the channel. Both QBR and IHF were proposed and developed by Acosta *et al.* 2009 and 2014 (see Appendix D for example score cards).

Table 3. Location of analysis regions and stations within the Rio Tomebamba watershed used during a watershed condition assessment

Name	Analysis area	Sub-watershed	Latitude	Longitude	UTM X	UTM Y
Taquiurcu (Salida Laguna)	Taquiurcu	Matadero alto	-2.7778	-79.1967	700457.948	9692814.279
Quinuas 1 despues de piscicolas Reina del Cisne	Quinuas	Matadero alto	-2.80386	-79.1569	704882.080	9689925.297
Quinuas 2 despues de Chirimachay	Quinuas	Matadero alto	-2.81518	-79.1497	705758.245	9688710.388
Llaviucu A.J. Quinuas	Llaviucu	Matadero bajo	-2.8433	-79.1257	708349.241	9685558.676
Tomebamba D.J. Q. Sacay	Lower Tomebamba	Tomebamba	-2.88976	-79.0362	718285.790	9680403.632

For the purposes of this analysis, only those summary indices recorded at ETAPA EP stations (WQI, BMWP/Col, IHF, and QBR) were used. Specific water quality data were not considered. Erosion and soil data originated from a data set detailing soil properties, classifications, and erosion potential developed by SIGTIERRAS and downloaded from the MAGAP geoportal (Appendix A, Figure 1). The erosion potential classifications within this data set were determined by SIGTIERRAS based on slope, landcover, effective depth, texture, rainfall intensity, and land use (Consorcio, 2015b). The data set also included information on soil type, soil origin, fertility, salinity, toxicity, cation exchange capacity, drainage characteristics, organic matter content, effective depth, humidity and temperature regimes, base saturation, and infiltration speed. The landcover data was also obtained from MAGAP and developed by SENPLADES over a six-year period (2006 to 2015) (Appendix A, Figure 3). Landscape imagery made public more recently than 2015 that was sufficiently detailed for landcover type analysis could not be found. Therefore, the 2015 data set was considered sufficient. Road and waterway data were downloaded as vector shapefiles from the Humanitarian OpenStreetMap Team website.

Results

2.1 Analysis regions

2.1.1 Taquiurcu Analysis Region (TAR)

The Taquiurcu analysis region (53.46 km^2) was dominated by herbaceous páramo vegetation and rock outcroppings (66.3% and 13.3% respectively). The dominant converted land cover type was cultivated pasture closely followed by *Pinus reticula* (Monterey pine) plantations. Each made up 1.9% and 1.4% of total landcover respectively, contributing to 1.75 km^2 of converted land (3.3% of the total area). The only impermeable surface introduced by human activity was asphalt, attributed to 13.62 km of road that covered 0.2% of the region. Road density appeared to be relatively low with 52.90 km of roads occurring in the region, corresponding to a density of 0.98 km/km^2. The area contained roughly 28 lakes and 7 moderately sized streams, 5.4% of whose riparian area was impacted by road development (Table 4). Water quality as measured by WQI appears to have generally declined over the past 5 years, although not until 2019 did the rating drop from "excellent" to "good." The British Monitoring Working Party Columbia index (BMWP/Col) follows a similar pattern, although only in 2018 did it drop below an "acceptable" rating to a "problematic" rating. In 2019, BMWP/Col increased to "acceptable" with a value comparable to 2016. The condition of the fluvial habitat appears to have increased over the five-year period, with the lowest score occurring in 2015. QBR-P appears to have generally decreased, with a significant low point occurring in 2016 (Appendix C). Areas with no data characterizing erosion potential composed 43.2% of the region, followed by areas with high erosion potential covering 35.2% of the total area. No part of the analysis region was considered to have a low or very high erosion potential.

Table 4. Index results for the Taquiurcu analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment based on data from el Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador and OpenStreetMap

Indicator	2015	2016	2017	2018	2019
% converted land	3.28%	3.28%	3.28%	3.28%	3.28%
% riparian zone impacted by roads	5%	5%	5%	5%	5%
WQI	97.159	91.851	95.688	95.62	89.683
BMWP/Col	132	123	105	93	122
IHF	49	70	68	71	73
QBR	75	30	60	60	60
Erosion potential	Alta	Alta	Alta	Alta	Alta
Road density (km/km^2)	0.989	0.989	0.989	0.989	0.989
% anthropogenic impermeable surfaces	0.18%	0.18%	0.18%	0.18%	0.18%

The mean index value for TAR across the five-year period was 3.8 (s=0.10), placing it in the upper region of an "acceptable" condition rating. Only the index value for 2016 (3.7) differed from the mean by more than one standard deviation. All index values within the five-year period fell within the "acceptable" rating, although the maximum condition rating occurred in 2015 and 2017 (Table 5). The TAR mean was within one standard deviation of the population mean across all analysis regions and all years (μ=3.4, σ=0.4). Index values for 2015 and 2017 varied from the population mean by more than one standard deviation, both with an index value of 3.9.

Table 5. Index rating results for the Taquiurcu analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment

Indicator	2015	2016	2017	2018	2019
% converted land	5	5	5	5	5
% riparian zone impacted by roads	3	3	3	3	3
WQI	5	5	5	5	4
BMWP/Col	5	5	5	4	5
IHF	3	3	3	3	3
QBR	3	1	3	3	3
Erosion potential	2	2	2	2	2

Road density (km/km^2)	4	4	4	4	4
% anthropogenic impermeable surfaces	5	5	5	5	5
Mean	3.9	3.7	3.9	3.8	3.8
Median	4	4	4	4	4

2.1.2 Quinuas Analysis Region (QAR)

The Quinuas analysis region (39.56 km^2) was the smallest of the four regions and was dominated by the same two land cover types found to be abundant in TAR: herbaceous páramo vegetation (59.5% of the area) and rock outcroppings (11.3%). The most common converted land type was cultivated pasture (8.9% of the total watershed area) followed by *Pinus reticula* plantations (2.3%) and pisciculture areas (0.5%), contributing to 4.78 km^2 (12.1%) of converted land. Impermeable surfaces accounted for 0.07 km^2 or 0.2% of the total region area, comparable to TAR, and were composed primarily by asphalt with some contribution from a small town. Road density was the lowest of the four regions at 0.34 km/km^2 (13.64 km of road). Impacted riparian areas were also lowest in QAR with 3.8% of the zone impacted (Table 6). Water quality did not appear to change significantly over the five-year period, remaining between 85.4 and 87.3, a range that fits comfortably within the "good" rating. BMWP/Col decreased greatly between 2015 and 2018, dropping to a lower category each year before increasing to a maximum for the five-year period in 2019. The fluvial habitat condition decreased from 2015 to 2017 before increasing to a maximum in 2018, although it remained within the "limitacion moderada" category. Excepting 2016, QBR generally increased over the five-year period from a "con limitacion" rating to a "limitacion moderada" rating (Appendix C). Just over 21.0% of the erosion potential in the area was unknown, dominated by a high erosion potential in 36.4% of the region. Medium erosion potential followed closely at 20.6%. No areas were reported to have very high erosion potential.

Table 6. Index results for the Quinuas analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment based on data from el Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador and OpenStreetMap

Indicator	2015	2016	2017	2018	2019
% converted land	12.07%	12.07%	12.07%	12.07%	12.07%
% riparian zone impacted by roads	4%	4%	4%	4%	4%
WQI	86.6145	87.443	85.3515	86.563	87.368
BMWP/Col	106.5	99.5	51.5	75.5	114.5
IHF	61	57.5	57	69.5	67.75
QBR	30	10	30	37.5	52.5
Erosion potential	Alta	Alta	Alta	Alta	Alta
Road density (km/km^2)	0.345	0.345	0.345	0.345	0.345
% anthropogenic impermeable surfaces	0.18%	0.18%	0.18%	0.18%	0.18%

The mean index value for QAR was 3.6 (s=0.2) across the five-year study period, equating to an "acceptable" watershed condition rating. Index values for both 2017 and 2019 varied from the mean by more than one standard deviation (3.4 and 3.9 respectively). Index values across all years fell within the "acceptable" rating. The maximum and minimum watershed condition ratings occurred in 2019 and 2017 respectively (Table 7). The QAR mean was within one standard deviation of the mean across all analysis regions and all years ($\mu=3.4$, $\sigma=0.4$). The index value for 2019 (3.9) varied by more than one standard deviation from the population mean.

Table 7. Index rating results for the Quinuas analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment

Indicator	2015	2016	2017	2018	2019
% converted land	4	4	4	4	4
% riparian zone impacted by roads	4	4	4	4	4
WQI	4	4	4	4	4
BMWP/Col	5	4	3	4	5
IHF	3	3	3	3	3
QBR	1	1	1	1	3
Erosion potential	2	2	2	2	2
Road density (km/km^2)	5	5	5	5	5

% anthropogenic impermeable surfaces	5	5	5	5	5
Mean	3.7	3.6	3.4	3.6	3.9
Median	4	4	4	4	4

2.1.3 Llaviucu Analysis Region (LAR)

The 51.83 km^2 Llaviucu analysis region lay nearly entirely within Cajas National Park and was dominated by herbaceous páramo vegetation (72.6% of total area) followed by wasteland (9.4%) and montane forest (9.1%). The only converted land type appears to be cultivated pasture, composing 1.5% of the total area. No impermeable surfaces introduced by human activity were found. However, 49 km of dirt roads were present, impacting 7.7% of the riparian zone and resulting in a density of 0.95 km/km^2 (Table 8). Water quality appeared to generally increase over the five-year period, although it oscillated between higher and lower values within the "good" rating category before arriving at a "excellent" rating in 2019. BMWP/Col appears to generally decrease from a maximum in 2015 to a minimum in 2017 and 2018 before increasing again. However, only scores reported in 2015 and 2016 were high enough to warrant a "good" rating. All other years were labeled "acceptable." In general, the fluvial habitat condition remained constant and within the "sin limitacion" category, excepting a minimum in 2016 that dropped into the "limitacion moderada" category. QBR experienced the opposite effect, remaining constant excepting a spike in 2016. All years retained a "limitacion moderada" rating (Appendix C). Over 93.0% of LAR was reported to have unknown erosion potential. In this instance, a medium erosion potential was assigned for a variety of reasons. Firstly, converted land made up a small portion of the region's area, suggesting that native vegetation dominated LAR land cover. Such vegetation decreases erosion potential (Consorcio, 2015b), decreasing the likelihood that high erosion potential would dominate the area. However, the average slope was comparable to slope angles in TAR that reported a high erosion potential, severely diminishing the likely likelihood that LAR was characterized by low erosion potential. As such, the region was assigned a medium erosion potential, the same rating that characterized 7.0% of the region.

Table 8. Index results for the Llaviucu analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment based on data from el Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador and OpenStreetMap

Indicator	2015	2016	2017	2018	2019
% converted land	1.45%	1.45%	1.45%	1.45%	1.45%
% riparian zone impacted by roads	8%	8%	8%	8%	8%
WQI	88.824	85.089	87.242	86.288	90.95
BMWP/Col	105	105	70	71	99
IHF	75	58	75	77	75
QBR	60	80	60	60	60
Erosion potential	Media	Media	Media	Media	Media
Road density (km/km^2)	0.946	0.946	0.946	0.946	0.946
% anthropogenic impermeable surfaces	0%	0%	0%	0%	0%

The mean index value for LAR across the five-year study period was 4.1 (s=0.1), corresponding to a "good" rating. One index value varied from the mean by more than one standard deviation (2015, 4.2). All years achieved "good" condition ratings. The maximum condition rating was achieved in 2015 before dropping slightly for three years and then increasing slightly in 2019 (Table 9). The mean for LAR varied from the population mean (μ=3.4, σ=0.4) by more than one standard deviation, as did all index values across all years.

Table 9. Index rating results for the Llaviucu analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment

Indicator	2015	2016	2017	2018	2019
% converted land	5	5	5	5	5
% riparian zone impacted by roads	3	3	3	3	3
WQI	4	4	4	4	5
BMWP/Col	5	5	4	4	4
IHF	5	3	4	4	4
QBR	3	3	3	3	3
Erosion potential	4	4	4	4	4

Road density (km/km^2)	4	4	4	4	4
% anthropogenic impermeable surfaces	5	5	5	5	5
Mean	4.2	4.0	4.0	4.0	4.1
Median	4	4	4	4	4

2.1.4 Lower Tomebamba Analysis Region (LTAR)

The Lower Tomebamba analysis region was the largest of the four at 184.06 km^2 and composing 56.0% of the total watershed. Herbaceous páramo vegetation dominated here as well and although the boundaries contained the largest amount of this landcover type by area, it made up the smallest percentage of any analysis region at 49.6%. The second most dominant cover type was cultivated pasture, also the dominant converted land type, at 7.5% followed by montane shrub vegetation and páramo bushy vegetation at 5.5% and 5.3% respectively. This analysis region contained the only eucalyptus plantations in the watershed at a total area of 5.19 km^2 and composing 2.8% of LTAR and 1.6% of the Rio Tomebamba watershed. The largest area of *Pinus reticula* plantations was found in this analysis region (1.30 km^2) although they composed barely 0.7% of the total area of the region. The dominant converted land cover types were cultivated pasture, suburban areas, and urban areas at 7.5%, 4.3% and 3.7% respectively. Road density here was the highest across all four analysis regions and higher than the watershed value (2.51 km/km^2 compared to 1.56 km/km^2). Riparian areas impacted by roads were also more abundant in LTAR at 9.0% (Table 10). Water quality generally increased through 2017, after which it decreased to a minimum for the five-year period in 2019. Excepting the minimum in 2019, all years received a “good” quality rating. BMWP/Col decreased drastically from a rating of “excellent” in 2015 to “critical” in 2018. In 2019, the score rose to “acceptable.” After an initial decrease from 2015 to 2016, the fluvial habitat condition increased to a maximum in 2019. Excepting a “con limitacion” rating in 2016, all years received a “limitacion moderada” rating. QBR followed the opposite pattern. After an initial increase to a maximum in 2016, scores dropped considerably to a minimum. However, all years remained with the “con limitacion” category (Appendix C). Medium erosion potential characterized 40.7% of the watershed. Impermeable surface introduced by human activity were highest in both area and percentage within LTAR, making up 11.0% of the watershed and were due mainly to suburban and urban areas.

Table 10. Index results for the Lower Tomebamba analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment based on data from el Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador and OpenStreetMap

Indicator	2015	2016	2017	2018	2019
% converted land	21.72%	21.72%	21.72%	21.72%	21.72%
% riparian zone impacted by roads	9%	9%	9%	9%	9%
WQI	73.548	71.6405	78.6655	76.632	65.389
BMWP/Col	166.5	45	48	38.5	65
IHF	41	36	49.5	52	56.5
QBR	25	45	17.5	17.5	17.5
Erosion potential	Media	Media	Media	Media	Media
Road density (km/km^2)	2.157	2.157	2.157	2.157	2.157
% anthropogenic impermeable surfaces	10.96%	10.96%	10.96%	10.96%	10.96%

The mean index value for LTAR for the five-year period was 3.0 (s=0.2), corresponding to the lowest numerical rating across all four analysis regions, although LTAR was still within the “acceptable” range. Index values for 2015 and 2016 varied from the sample mean by more than one standard deviation (3.2 and 2.8 respectively). The year 2016 was the only year in the study period to dip down to a “problematic” rating. Maximum and minimum watershed condition ratings occurred in 2015 and 2016 respectively (Table 11). The mean LTAR condition rating varied by more than one standard deviation from the population mean (μ=3.4, σ=0.4) as did index values for 2016, 2017, 2018, and 2019.

Table 11. Index rating results for the Lower Tomebamba analysis region of the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment

Indicator	2015	2016	2017	2018	2019
% converted land	3	3	3	3	3
% riparian zone impacted by roads	3	3	3	3	3
WQI	4	4	4	4	3

BMWP/Col	5	3	3	3	4
IHF	3	1	3	3	3
QBR	1	1	1	1	1
Erosion potential	4	4	4	4	4
Road density (km/km^2)	3	3	3	3	3
% anthropogenic impermeable surfaces	3	3	3	3	3
Mean	3.2	2.8	3.0	3.0	3.0
Median	3	3	3	3	3

2.2 Rio Tomebamba watershed condition

Across all five years, LTAR and LAR represented the minimum and maximum watershed condition ratings. In all years except 2019, TAR had the second highest condition rating. QAR was the only analysis region to have a maximum at the end of the five-year study period (2019). LTAR and LAR reached maximums in 2015 while TAR reached its maximum twice, once in 2015 and again in 2017. TAR and LTAR reached their respective minimum ratings in 2016, followed QAR in 2017. The minimum value for LAR occurred in 2016, 2017, and 2018 (Figure 3).

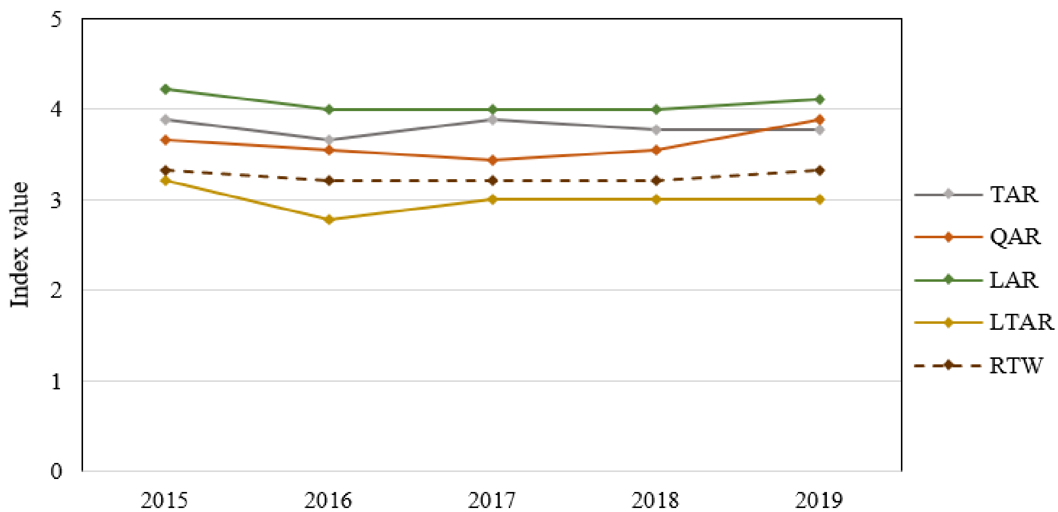

Figure 3. Watershed condition index results for four analysis regions—Taquiurcu analysis region (TAR), Quinuas analysis region (QAR), Llaviucu analysis region (LAR), and Lower Tomebamba analysis region—and the Rio Tomebamba watershed (RTW) in southern Ecuador based on data from the Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador, OpenStreetMap, and ETAPA EP

The mean value for the Rio Tomebamba watershed across the five-year study period was 3.3 (s=0.1), equating to an "acceptable" condition rating. Index values for 2015 and 2019 varied from the sample mean by more than one standard deviation, both with values of 3.3. The watershed across all five years was in "acceptable" condition. Index values reached a slight maximum in 2015 and 2019 (Table 13).

Table 12. Index results for the Rio Tomebamba watershed in southern Ecuador as part of a watershed condition assessment based on data from el Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador, OpenStreetMap, and ETAPA EP

Indicator	2015	2016	2017	2018	2019
% converted land	14.37%	14.37%	14.37%	14.37%	14.37%
% riparian zone impacted by roads	7.46%	7.46%	7.46%	7.46%	7.46%
WQI	86.536375	84.005875	86.73675	86.27575	83.3475
BMWP/Col	127.5	93.125	68.625	69.5	100.125
IHF	56.5	55.375	62.375	67.375	68.0625
QBR	47.5	41.25	41.875	43.75	47.5
Erosion potential	Media	Media	Media	Media	Media
Road density (km/km^2)	1.558	1.558	1.558	1.558	1.558

% anthropogenic impermeable surfaces	6.19%	6.19%	6.19%	6.19%	6.19%

Table 13. Watershed condition index rating results for the Rio Tomebamba watershed in southern Ecuador

Indicator	2015	2016	2017	2018	2019
% converted land	4	4	4	4	4
% riparian zone impacted by roads	3	3	3	3	3
WQI	4	4	4	4	4
BMWP/Col	5	4	4	4	5
IHF	3	3	3	3	3
QBR	1	1	1	1	1
Erosion potential	4	4	4	4	4
Road density (km/km^2)	3	3	3	3	3
% anthropogenic impermeable surfaces	3	3	3	3	3
Mean	3.3	3.2	3.2	3.2	3.3
Median	3	3	3	3	3

2.3 Woodland habitat

In the Rio Tomebamba watershed, 62 existing páramo woodland patches were identified with a total area of 902.0 hectares (9.020 km^2). LTAR contained 30 of those patches and 542.2 hectares (5.422 km^2), followed by QAR with 14 patches and 180.8 hectares (1.808 km^2) and TAR with 11 patches and 98.1 hectares (0.981 km^2). The Llaviucu analysis region had the least at 7 patches and 80.9 hectares (0.809 km^2). Patch number was less significant than area for lower elevation woodland habitat as the 150-meter consideration combined 3350.5 hectares of habitat into just 9 patches across the Rio Tomebamba watershed. Of the analysis regions, QAR had the highest number of patches (5) but the second lowest area (342.8 hectares). LTAR had the highest area of low elevation woodland habitat (2516.1 hectares) distributed across 3 distinct patches. Llaviucu analysis region had 477.7 hectares of montane woodland habitat, although that area was part of a large patch in LTAR that crossed the sub-watershed boundary. TAR had the lowest area at 13.9 hectares (0.130 km^2) (Figure 4).

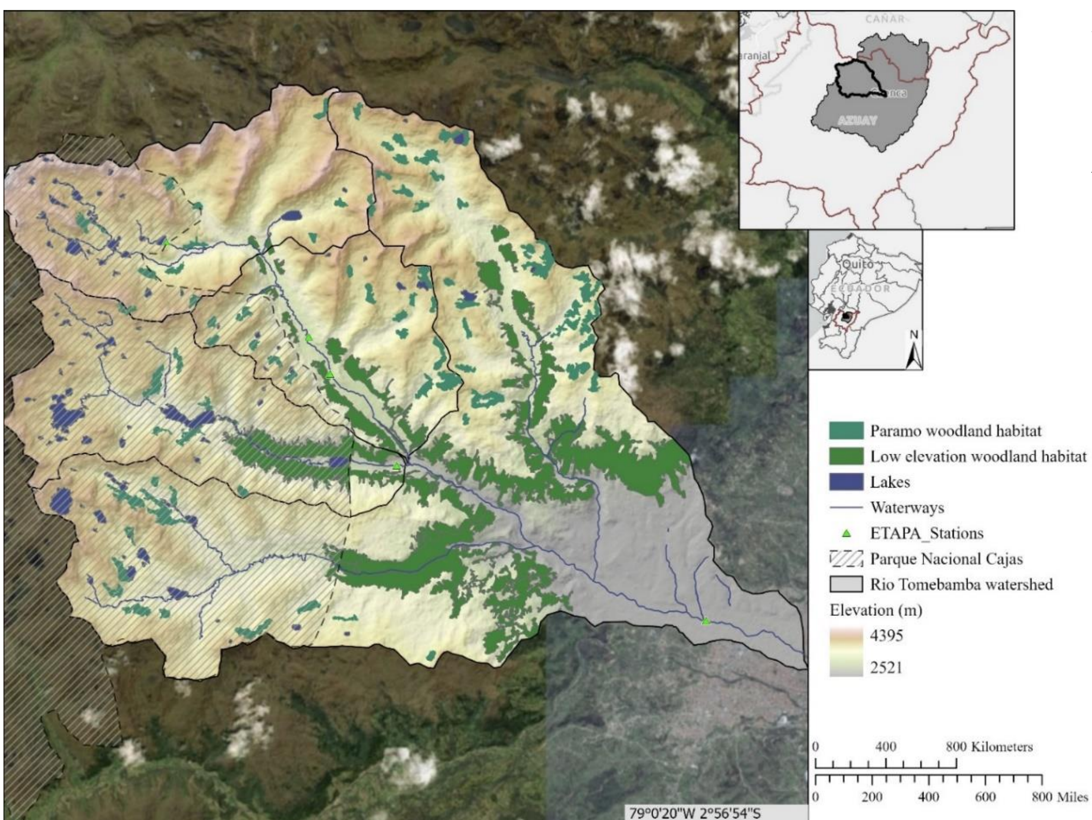

Figure 4. Existing páramo and lower elevation (montane) woodland habitat in the Rio Tomebamba watershed based on landcover data from el Ministerio de Agricultura, Ganaderia, Acuacultura, y Peces de Ecuador and methodology based on methodology from Tinoco *et al.* 2013.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Discussion

The Rio Tomebamba watershed provides vital water resources, cultural services, and ecological benefits to members of the surrounding population. Part of the traditional cultural practices of communities in the Quinuas region involves rituals associated with Rio Tomebamba (Rojas, 2016). Cuenca, too, depends on the discharge from this watershed—it is the city's oldest water source and provides over 60% of the urban area's water supply (Carrasco *et al.*, 2010). Rio Tomebamba also lies inside one of the most economically important watersheds in the country—the Paute river watershed, which contains the Daniel Palacios hydroelectric plant which supplies roughly 40% of the country's energy supply (CONELEC,2011; Carrasco *et al*., 2010; Padron-Pesantez, 2019). The watershed also contains 132.5 km^2 (45%) of Cajas National Park, a RAMSAR site significant as a repository for highly endangered or endemic species, one of two formal conservation sites protecting south-western Ecuadorian high-elevation ecosystems, and as an area of hydrologic regulation (Astudillo *et al*., 2014; Van Colen *et al.*, 2017). Although the Llaviucu analysis region demonstrated the highest rating for watershed condition and the Lower Tomebamba region the lowest, few clear trends emerged regarding either individual indicators or analysis regions.

3.1 Riparian corridors

Although Cajas National Park protects 93.0% of the Llaviucu analysis region, that area still only achieved a "good" condition rating based on the indicators used. The riparian zones within this area, as well as across the watershed, seem to be the most prominent point of concern. In all analysis regions, indicators related to riparian corridor condition—riparian zones impacted by roads, quality of riparian vegetation, and fluvial habitat condition—appear impaired. As is common in mountainous regions, human settlement, roads, and cultivated land occur in or near riparian areas, impacting both system health and water quality. Riparian corridors and the vegetation that compose them act as the principal source of organic matter and energy in freshwater systems, there-by driving both biological and physical interactions within them (Ceccon, 2003; Zimbres *et al*., 2017). Fish, macroinvertebrates, and other aquatic species depend on intact and highly functioning riparian ecosystems to maintain health and community structure (Burneo & Gunkel, 2003; Carrasco, 2010). This type of vegetation also serves as a filter for sediment and water contaminates, slowing or halting their entrance into the freshwater system (Carrasco, 2010; Ceccon, 2003). In short, riparian zones act as the interface between in-channel freshwater aquatic ecosystems and the landscape in which they reside, serving vital roles in the maintenance of water quality and habitat condition. Water contaminates rarely originate within the stream or river channel itself; rather, they are produced in the surrounding landscape and transported to stream channels (Anbumozhi *et al*., 2005). As such, riparian buffer zones prove vital for reducing contaminant input and maintaining water quality and ecosystem health.

Riparian corridors also play essential roles in maintaining both biodiversity and landscape connectivity, even in cases where they fail to completely connect forest patches (Hawes *et al*., 2006; Crooks & Sanjayan, 2006; Hilty *et al.*, 2006). In highly deforested landscapes, such as those common throughout Ecuador and to some extent within the Rio Tomebamba watershed, they present the best available opportunity for preserving terrestrial mammal diversity (Zimbres *et al*., 2017). The quality of riparian vegetation within the four regions of the Rio Tomebamba watershed, the degree of road impact within riparian zones, and poor fluvial habitat condition in some areas all indicate severely impacted riparian areas. Indeed, in 2010, Carrasco *et al.* 2010 reported that riparian corridor widths in the Rio Tomebamba watershed were no greater than six meters in any of the sampled areas. No indication in either the data gathered for this investigation or in the literature surrounding the Rio Tomebamba watershed suggests that this statistic has improved. On the contrary, increases in landscape conversion for pastures and crops as well as increases in cattle ranching have most likely led to the continued decline of such areas (González-Maldonado & Córdova-Vela, 2017). As far back as 1991, Armour *et al.* identified significant impacts to riparian areas produced by cattle activity near waterways. Understory structure and geomorphology were altered by overgrazing below the browse line and bank collapse caused by excessive trampling of stream banks (Armour *et al*., 1991).

Riparian corridor maintenance has been a widespread landscape management strategy and could prove particularly effective within the Rio Tomebamba watershed (Bier & Noss 1998). Restoring sections of the riparian corridor and potentially rerouting lesser used dirt roads away from the riparian zone could prove effective in improving the overall health of the watershed as well as the water resources and habitat condition within it.

3.2 Converted land

Converted land within the watershed amounted to just over 14.0% with a greater extent in the Lower Tomebamba watershed region and minimal extent within the Llaviucu analysis region. This relatively positive result suggests that a vast majority of the watershed retains intact native vegetation. However, this assumption represents a heavily simplified rendering of a much more complex reality. Historically, the páramo region was considered communal land and community members shared responsibility for maintenance of the area (moving livestock frequently, keeping development to a minimum, etc.). However, when property rights were transferred to non-family members, rights to this vast communal area did not accompany them. Over time, the páramo areas that utilized this management strategy became areas *sin propietario conocido*, or areas with no known owner, and were appropriated by others. The practice of maintaining small beef cattle herds on this landscape became common as a demonstration of that claim to land ownership (Rojas, 2016). Consequently, there exist a rather large number of unrestrained livestock in the páramo areas. This ecosystem evolved without large mammals and the presence of cattle has a profound impact on the water retention and regulation capacities of this ecosystem's soil and vegetation (Hofstede, 1995; Buytaert *et al.*, 2006). Although quantifying and assessing this metric was outside the scope of this study due to the lack of data and available methodology, future analyses of watershed health in these areas ought to consider livestock management and impact on páramo hydrology when addressing terrestrial ecosystem components.

3.3 Water quality

Across all regions, BMWP/Col (British Monitoring Working Party Columbia index) appeared to decrease from 2015 to 2018 before increasing, in some cases considerably, in 2019. The water quality index did not follow the same trend, suggesting that the changes in macroinvertebrate community structure were driven by factors other than those included within WQI (water quality index). One study has shown that macroinvertebrate community structure in the Andean páramo changes drastically depending on the season (rainy vs. dry), suggesting the importance of maintaining consistent sampling timing from year to year (Jerves-Cobo *et al.*, 2020). However, BMWP/Col data from ETAPA-EP stations was collected within the same two-week period year to year. One potential explanation is that changes in land use impacted the taxa present, as seen in the Pesquieria River in Mexico, although this variable would not account for the increase in 2019 (Castro-López *et al.*, 2019). Oxygen saturation and dissolved oxygen content drive macroinvertebrate presence in the Ecuadorian Andes, but those variables do not depict either an upward or downward trend during the study period (Jacobsen & Marin, 2004; ETAPA EP, 2020). Another possibility is that BMWP/Col does not characterize the water quality of the region as well as other macroinvertebrates indices might. In a 2017 study developing a multi-metric index assessing the ecological state of southern Ecuadorian Andean rivers, González-Maldonado and Córdova-Vela compared the water quality results reported by the British Monitoring Working Party Columbia index, the Andean Biotic Index, the IMEERA index, and the index developed in the study (IMRASE). The study found that, of the four, BMWP/Col was the least reliable descriptor of actual ecological status (González -Maldonado & Cordova-Vela, 2017). Although BMWP/Col was adapted for Columbian ecosystems, it may not completely represent the sensitivity of some taxa in the Andean region of Ecuador (Rios-Touma et al., 2014). While this does not entirely explain the observed trend, it presents one potential component. A change in climatic or geomorphologic characteristics that fell outside the scope of this study may also explain the sudden shift from decline to increase.

The Quinuas analysis region fell directly downstream of the Taquiurcu analysis region, but contrary to what was expected, did not follow stream channel related trends depicted by WQI, IHF, and QBR. In most cases, it experienced the inverse of what was occurring in its upstream counterpart. Where both QBR (quality of riparian vegetation) and WQI (water quality index) declined slightly over the five-year period in TAR, those two variables increased in QAR. Where the IHF (Fluvial Habitat Index) increased over time in TAR, it decreased in QAR. The relationship between IHF and QBR showed a similar pattern across all analysis regions. In the case that IHF showed an increase over the five-year period, QBR declined over the study period in that same analysis region. Although the fluvial habitat index focuses primarily on physical aspects of the river channel (velocity regimes, substrate composition, etc.), it also addresses channel shading and leaf litter contributions. Under this index, complete channel shading represents an undesirable condition while shade with some windows appears to contribute to a preferred situation. It is possible that, in montane forest areas, some removal of woody riparian vegetation may have reduced channel shading and improved the fluvial habitat. However, this does not explain the same trend in páramo areas such as the Taquiurcu analysis region. A more likely explanation is that the aspects of the QBR index that do not overlap with aspects of the IHF index, such as introduced species and naturalness of the channel grade, drove the decline in riparian vegetation quality. A study targeting the relationship, if any, between these two indices could prove insightful and may further explain the ecological dynamics of riparian ecosystems in Ecuadorian páramo and montane forest areas.

3.4 Habitat

In a study addressing the avifauna response to different patch characteristics in Polylepis forests, *Metallura baroni* was the third most abundant species in the sites sampled (Tinoco *et al.*, 2013). Their primary diet appears to be composed of arthropods and nectar from a variety of native flowers found within páramo woodlands (Tonoco *et al.*, 2009). Results from the 2013 study suggest that this species prefers smaller, more connected patches of mature Polylepis stands and páramo bushy vegetation (Tinoco *et al.*, 2013 & 2009). Although the scope of this study did not include páramo woodland patch connectivity, the patches distributed in the Rio Tomebamba watershed appear to fit the needs of the Violet-throated Metal-tail quite well. The watershed contained 902.0 hectares occurring in 62 patches distributed across the páramo area of the watershed, 7 of which (80.9 hectares) occurred within Cajas National Park. Many of the patches appear close to the montane forest edge, a habitat the hummingbird in known to frequent during the latter half of the year (Tinoco *et al.*, 2009). This habitat matrix may reflect good habitat conservation potential for this species within the Rio Tomebamba watershed, so long as efforts to prevent further fragmentation continue. Tourism may pose a helpful mechanism to promote habitat for *Metallura baroni,* as Cajas National Park and the surrounding area are popular with birders, particularly those interested in endemic species.

Although *Chibchanomys orcesi* does not exhibit the same dependency on páramo woodland as *M. baroni*, conservation of this habitat type invariably benefits this species (Boada & Vallejo, 2018). When the species was identified in 1997, it was found at only four lakes, at least two of which fall within the Rio Tomebamba watershed boundaries (Jenkins & Banett, 1997). More recently, studies and land managers have found the species near other páramo aquatic areas in the Cajas National Park region and in central Peru (Boada & Vallejo, 2018). Its diet appears to be entirely composed of aquatic insects and the occasional small fish, making it particularly susceptible to changes in water quality that may impact the specie's food source (Barnett, 1999). Such a dependence on aquatic invertebrates may make *C. orcesi* a candidate as an indicator species for aquatic and riparian ecosystem health in the páramo, should more information about its distribution, habitats, and detectability come to light. As this species frequents rapidly flowing streams and still lakes, maintaining and restoring riparian areas within the Rio Tomebamba watershed could prove an important step in its conservation (Jenkins & Barnett, 1997; Barnett, 1999). The results of this study pinpoint riparian corridor deterioration as a critical issue in the context of this watershed's health. Managing those corridors as a conservation method for *Chibchanomys orcesi* could prove an effective approach.

3.5 Index and analysis regions

The area with the lowest reported condition within the watershed was the Lower Tomebamba analysis region. In general, water quality and erosion potential were the only indicators registered to reflect "good" condition and only BMWP/Col in 2015 reflected an excellent condition. This analysis region contained the bulk of urban and suburban development as well as a greater quantity of roads. Cultivated lands were more common in this region as well. However, due to the size of this analysis region compared to the other three (LTAR accounted for 56.0% of the total watershed area), it was difficult to pinpoint areas or indicators of concern. The greatest quantity (by area) of páramo ecosystem was found within LTAR's boundaries but made up a lower percentage of the region's area than in other analysis regions. Evaluating condition of the two sub-watersheds contained within LTAR's boundaries would likely have proved more informative. However, due to the location of the water quality monitoring stations, this proved impossible. An on-the-ground study could distribute water quality and riparian habitat sampling efforts more evenly across the watershed, specifically targeting the sub-watersheds within LTAR, the upper regions of the Llaviucu analysis region, and the sub-watershed located within Taquiurcu analysis region.

Although the limits of a remote study prevented this, assessment of areas currently experiencing erosion could be combined with potential erosion hazard to develop a better understanding of where that indicator proves most problematic. Sediment introduced by erosion into stream and river channels has a profound negative impact on the aquatic habitat as well as the water quality (Akay *et al*., 2008; Couceiro *et al*., 2009). Erosion itself is also detrimental to the terrestrial habitat and landscape in which it occurs. Although the erosion data set used for this analysis was sufficient, future analyses of watershed or resource condition should consider more detailed erosion information. It may also prove informative to examine changes to the Rio Tomebamba watershed area fire regime. More frequent fire, wood extraction, and cattle grazing can all impact páramo vegetation as well as the spatial distribution of *Polylepis* sp. stands, thereby affected both habitat and hydrologic regulation properties (Renison *et al*., 2006; Cierjacks *et al*., 2008).

Conclusion

Although the Rio Tomebamba watershed appears to exhibit generally acceptable condition, this study represents only the first step in developing a full understanding of the watershed's vulnerability and resiliency capabilities. Riparian corridors within its boundaries exhibit poor health and continue to experience considerable pressure from land use changes and road impacts. Maintaining and restoring these corridors would not only improve the overall watershed condition, but would also increase landscape connectivity, water quality, and refuge areas for fauna (Ceccon, 2003; Zimbres *et al*., 2017; Burneo and Gunkel, 2003; Carrasco, 2010; Anbumozhi *et al*., 2005). Such action could also prove an effective conservation strategy for *Chibchanomys orcesi*, a highly endemic water mouse considered endangered by the country of Ecuador. The Rio Tomebamba watershed also exhibited potential for *Metallura baroni* habitat conservation. Although the connectivity of woodland habitat within the watershed needs further investigation, the number and distribution of patches within its boundaries appears promising.

Thus, this study presents two potential avenues for improving watershed health: managing the area for *M. baroni* and *C. orcesi* habitat, thereby protecting the native ecosystem and the hydrologic regulation that it provides and/or focusing on riparian area restoration. Both benefit the watershed and the water resources it provides. However, a more developed understanding of the various processes occurring within high elevation freshwater ecosystems in this region is necessary to ensure that such actions are informed and will produce effective results. The relationship between the quality of riparian vegetation as reported by QBR and fluvial habitat condition reported by the Index of Fluvial Habitat could prove especially interesting. Results from this study appear to suggest an inverse relationship exists between the two, but finer-scale research should investigate the finding.

Although this study established that the Rio Tomebamba watershed provides for moderate biotic integrity, exhibits moderate connectivity between stream channels and to the surrounding landscape, and can produce most ecosystem services, the watershed's resiliency and recovery abilities still need assessment. Often this information proves the more useful, as it helps inform future management decisions. The United States Forest Service has developed a Watershed Vulnerability Framework that targets watershed exposure and resiliency. A modified version of this framework should be applied to the Rio Tomebamba watershed to complete the findings of this study.

Remote watershed assessments depend on current available data and so seldom completely reflect the actual on the ground condition. Therefore, more site-specific field-based assessments ought to be conducted to plan for future management actions and restoration projects.

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Appendices (A-D) included as a separate document