Recovery of the Tambobamba Watershed after Environmental Zoning and Monitoring Using Vegetation Indices

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***Abstract*—Environmental zoning (EZ) in a watershed is intended to analyze the socioeconomic and biophysical parameters and design potential areas of intervention for the management and sustainability of natural resources, thereby improving people's quality of life. EZ is incomplete without soil and water conservation techniques and management (SW/mct) to remediate natural environments. In this study, the Tambobamba watershed—during and after EZ—was analyzed in terms of socioeconomics, biophysics, and SW/mct, and monitored according to vegetation indices (VIs). To determine the socioeconomic situation, a rapid rural survey was conducted. To design biophysical maps, each area of the watershed was evaluated. The EZ was designed in 2018, under the demands and basic needs of the population. For monitoring in 2017, 2019, and 2021, the VIs were applied. Population density and poverty levels were low, economic activity was high, there was no university education, and basic services and communication routes were scarce. The watershed presented four climates, two natural domains, a glacial surface, six life zones, eight physiographic zones, two taxonomic orders of soils, and twelve geological classifications. The land is dominated by unused areas, the dominant slope was steep and had four types of HLCUs. Watershed remediation after S-W/mct showed that SAVI increased by 0.01, MSI increased by 0.8, EVI remained constant, NDWI increased by 0.06, and NDVI increased by 0.02. After performing the EZ, we affirmed that the Tambobamba watershed is in a slow recovery.**

***Index Terms*—Socioeconomic status, environmental zoning, soil and water conservation techniques and management, vegetation indices, Tambobamba watershed**

I. Introduction

A watershed is considered a nucleus for the economic, social, and environmental development of its inhabitants [1–4]. It must be managed by participatory and integrated planning with the commitment of the population [2, 5]. Within a watershed, there is an endowment and variety of natural resources that contribute to the development [6], growth, and quality of life the residents [7], and it may be desirable to preserve them for future generations [1, 8]. The term "watershed management" is used to refer to the efficient conservation and management of these resources [2, 9, 10]. Watershed management has evolved through various stages of social development, starting with a local problem and extending to larger territorial issues [2, 10, 11]. Watershed management addresses anthropic problems [7], current land use [12], land use conflicts [13], excessive use of ecological resources [9], biological resources [14], water resources [15]. To solve these problems, watershed management employs multiple evaluation criteria, among them are the potential areas of intervention that can be addressed via environmental zoning (EZ) [9, 10, 16]. For zoning and management, it is necessary to start from the watershed concept using satellite monitoring and evaluation [1], as well as information on socioeconomic and biophysical characteristics [2, 4].

The most important thing in EZ is to design the potential areas of intervention with the protection, handling, management, and conservation of the environment (natural resources) [5, 9, 13] in mind, without overlooking the essential issue of the "basic needs of the population" [4, 17, 18]. EZ involves the integration, analysis, and planning with respect to controversial issues such as territorial planning [15, 16, 19], potential use of natural resources [6], evaluation of environmental impacts [3, 18], deterioration of natural resources [1], spatial distribution of the population and anthropic impacts [5, 16], efficient and productive industrial activities [9], demographic characterization, manipulation of current land use [8, 15], capacity of load that the soil resists in the formation of new resources (mentioned by institutions and governmental political norms) [20], edaphological and ecological characteristics [21, 22], land cover according to the natural cover (non-anthropic origin) [16, 21, 23], and natural areas protected by government institutions (foreign and/or local laws) [7, 17, 24, 25]. To implement EZ, it is necessary to start with socioeconomic and biophysical parameters [13, 21]. Most of the demographic development (health, basic services, education, communication system [1, 26–30]) is located at the bottom of the watershed, where the slope is less pronounced [7, 14, 27]. Wang [1] and Hall [24] discuss that socioeconomic development, along with accelerated growth, creates territorial conflicts that damage natural resources. The biophysical states within watersheds are those environmental parameters [1, 2, 21] that present a balanced dynamic for abiotic and biotic ecosystems [8, 21]. The biophysical environment is related to the development, conservation, and protection of wild native flora and fauna [21, 26, 29, 31]. Biophysical parameters also influence essential products, such as production [8, 9, 32], livestock,

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agroforestry systems, silviculture, and forest industries (afforestation and reforestation) [14, 17, 30].

Soil and water conservation techniques and management complement EZ [1, 7, 17, 27, 30]. A comprehensive vision for the watershed allows for a focus on the interrelationships in the system [7, 29], and projecting soil and water management and conservation practices [7, 17, 28, 29]. Biological, physical/mechanical, agronomic, and other types of activities are currently involved in watershed management [7, 28, 29], helping to diagnose, preserve, and protect areas for conservation purposes [8, 12, 24, 27].

To delimit the biophysical characteristics, socioeconomic states, and potential areas of intervention in EZ [5], the application of geographic information system (GIS) is useful [1, 3, 12, 33]. GIS facilitates areal planning within the watershed [1–3, 33], and monitoring the watershed's recovery is facilitated through satellite images [2, 12, 15, 21, 28]. Through a mathematical combination between bands of the same sensor, it is possible to study temporal patterns of natural resources, such as soil and plants [12]. The mathematical combination allows for the conceptualization of the vegetation indices (VIs) [21, 28]. The present study analyzed the following aspects of the Tambobamba watershed: its biophysical and socioeconomic parameters, the manageable and sustainable design of EZ, and watershed monitoring through VIs. These encompassed periods before, during, and after soil and water conservation techniques and management were applied.

II. Methodology

A. Description of the Watershed

The Tambobamba watershed is located in the province of Abancay, ~484.64 km from the capital Lima, Peru (Fig. 1). The watershed has an area of 424.74 km^2 and a perimeter of 104.94 km.

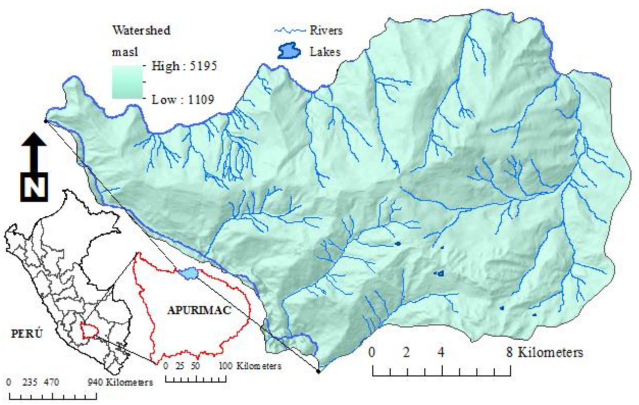

Fig. 1. Location of the Tambobamba watershed in Apurimac - Peru. (72°57'44.94" W, 13°28'50.92" S, altitude 3904 masl).

B. Data Analysis and Processing

The information was obtained through a rapid rural survey with semi-structured interviews with community leaders, collecting information on their socioeconomic situation (population density, communication routes, education, basic services and medical service). The watershed was delimited with the help of a GPS calibrated to WGS 84 zone 18L. The georeferenced points are imported into the QG is 3.24 software creating a shapefile. The biophysical parameters evaluated were altitudinal sector, soils, current use, capacity for greater use (through the "Regulation Classification of Lands for its Capacity for Greater Use: Supreme Decree N°. 017-2009-AG" [20]), life zones, and slope distribution. Based on the basic needs of the population, environmental zoning was designed (applying respective soil and water management and conservation techniques) and the monitoring process was carried out using the Vegetation Indices (NDVI [34], SAVI [35], MSI [36], EVI [37] and NDWI [38]) with images from Landsat 8 OLI/TIRS (years 2017, 2019, 2021 with 0% cloudiness, radiometric and geometric corrections).

$$\rho_\lambda = (M_\rho * Q_{cal} + A_\rho) / \cos[\theta_{ZE}] \quad (1)$$

$$MSI = (SWIR / NIR) \quad (2)$$

$$NDWI = (Green - NIR) / (Green + NIR) \quad (3)$$

$$SAVI = (NIR - Red) / (NIR + Red + L) \times (1 + L) \quad (4)$$

$$EVI = 2.5 \times [(NIR - Red) / (NIR + 6 \times Red - 7.5 \times Blue + 1)] \quad (5)$$

$$NDVI = (NIR - Red) / (NIR + Red) \quad (6)$$

where: ρ_λ: TOA reflectance of the sensor, with solar angle correction; Q_{cal}: quantified and calibrated standard product pixel value (ND); Mρ: Multiplicative scaling factor (Reflectance Mult Band X); Aρ: Additive specific band rescale factor from the metadata (Reflectance Add Band X); θ_{ZE}: Elevation angle of the local sun. Elevation angle in degrees, which is equivalent to $90-\theta_{ZE}$, and θ_{ZE} is the solar elevation; Multispectral bands: SWIR, NIR, Green, Red and Blue; L: correction value of 0.5. Bands: resolution 30m × 30m (LC08_L1TP_005069_20170715_20200903_02_T1), (LC08_L1TP_005069_20190806_20200827_02_T1) and (LC08_L1TP_005069_20210710_20210720_02_T1).

C. Environmental Zoning (EZ)

Research has suggested different types of environmental zoning [5, 12, 15, 16, 24, 27]. Designing EZ must be done according to the economic, social, environmental, political, and institutional needs of the inhabitants in the watershed. Here are different EZ zones that were used:

1) **Sustainable use zone, direct use, and productive:** They can be for direct use, agriculture, agroforestry, livestock, and protection of forest resources.
2) **Ecological protection and conservation zone:** Ecosystems with little or no intervention, minimal intervention, and natural resources.
3) **Recovery zone:** Protection zones that are degraded, in conflict, high risk, and low quality, with direct use of flora and fauna—a management category.
4) **Special use zone:** Areas occupied by human or industrial settlements and natural area with other purposes.
5) **Water protection zone:** Major rivers, lakes and springs.

D. Soil and Water Conservation Techniques and Management (S-W/mct)

Likewise, there are several soil and water conservation practices [14, 29, 30, 39–41]:

1) **Agronomic practices for soil management and conservation:** Choice of crops according to the

suitability of the soil, planting in contour and furrows, strip crops, crop rotation, and conservation tillage.

2) **Mechanical or physical practices:** barriers, terraces, infiltration ditches, runoff water evacuation works, and gully control.

3) **Biological practices:** Afforestation and reforestation (planting of trees and bushes with the help of infiltration trenches or narrow terraces), identifying limiting factors for forest plantations, and reinforcement of soil conservation works with the help of practices biological and biotraps.

III. Results and Discussions

A. Socioeconomic Situation

1) Population, communication routes, education and coverage of basic services

The watershed had six Populated Centers with 4,515 inhabitants [Occopata (354), San Ignacio (790), San José de Karqueque (1,550), Limanqui (890), Tambobamba (576), Siccllabamba (355)], and a total population density of the watershed of 11 inhabitants/km^2. The poverty level of the inhabitants was 76.80% Extremely Poor, 13.90% Not Extremely Poor, and 9.30% Not Poor. Economically active and employed persons are from the age of 23 to 60 years. Therefore, the economically active and employed population was 3,996 (dominated by livestock and agriculture) with the other 1.5% unemployed.

2) Education

The watershed had 35 educational institutions [initial education 17 (198 students), primary education 15 (800 students) and secondary education 3 (308 students)]. There was a school dropout rate that reaches 16.5% and a lack of coherence between the school calendar and the -livestock calendar required students to abandon their studies to help with work. Some educational institutions were located far from urbanized areas and the lack of mobile transportation was noted. The highest percentage of school dropouts was related to those who did housework or were in premature motherhood, which limited them to continue their studies.

3) Communication routes and coverage of basic services

The water was not purified or biochemically treated for human consumption. Throughout the watershed, residents consume untreated water in large tank reservoirs drawn from river and spring sources. Water services in some population centers were by schedule (that is, the population supplies water according to a schedule) from 9:00 a.m. to 1:00 p.m., representing 55% of the population. The rest of the population (45%) had 24-hour water service, located in the central part of the watershed. The watershed had two direct access roads (paved) connected with the capital Abancay. Within the watershed, there were five branches, two paved roads and three unpaved roads. The paved roads integrate the urbanized areas and the remaining three connected the other populated centers of the watershed. Fig. 2 shows the socio-economic parameters.

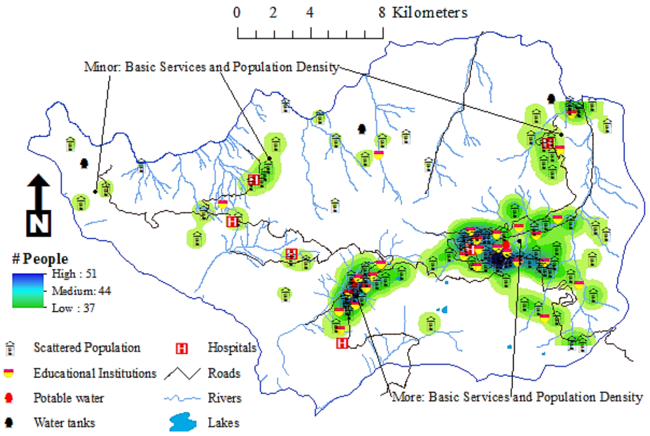

Fig. 2. Analysis of socioeconomic parameters within the Tambobamba watershed. (Note: the transition from blue to green indicates the demographic concentration of the inhabitants. Where the highest concentration of population is represented by the color blue and green with the lowest population.)

B. Biophysical Aspects

1) Slope distribution and current land use

According to the legal normative methodology of Peru "Supreme Decree N°. 017-2009-AG" the Tambobamba river watershed presented six types of soil slope as shown in Table I and Fig. 3D. Where the slope dominates (50–75), smaller slope (0–5). The current land use activities carried out by the inhabitants of the watershed remained constant during the years (2019, 2020 and 2021 due to the COVID-19 pandemic). The use is categorized into use, pastures (prairies), forestry, protection, areas occupied by rural areas, and bodies of water.

TABLE I: Current Land use and Pending Land Classification

Current use	Area	%	Slope	Slope	Area	%
Agricultural	35.82	8.43	0–5	Plane	1.63	0.39
Grasses	25.3	5.96	5–15	Moderately inclined	4.7	1.11
Urban	0.55	0.13	15–30	Inclined	28.98	6.87
Lake and rivers	2.6	0.61	30–50	Moderately steep	98.73	23.39
Forest	0.17	0.04	50–75	Steep	164.86	39.05
Without use	360.3	84.83	More than 75	Sheer	123.23	29.19
Total	**424.74**	**100**	**Total**		**422.14**	**100**

Note: To determine "current land", the surfaces of lakes and rivers were included. For the "pending land classification" the surfaces of lakes and rivers were not.

The current use of land was intended for the production of Andean crops (*Ullucus tuberosus* Caldas., *Solanum tuberosum* L., *Oxalis tuberosa* Molina., *Tropaeolum tuberosum* Ruiz & Pav., *Zea mays* L., *Vicia faba*, *Pisum sativum*, *Phaseolus vulgaris* L., etc.). The forest floor was made up of plantations and natural forests that are mostly located in the ravines and the lower part of the watershed (*Eucalyptus globulus* Labill., *Polylepis spp*., *Buddleja davidii* Franch., *Buddleja incana* Ruiz & Pav., *Pinus radiata* Don., *Baccharis latifolia* (Ruiz y Pavón) Pers The natural pasture soils were made up of high Andean grasslands (forage pastures, alfalfa, ryegrass and hay) intended for intensive grazing of herds, yoke, sheepfold, bovine, herd, etc. (Table I and Fig. 3B).

2) Natural domain, climatic classification and life zone

Peru has some of the most varied ecosystems in South

America, including coastal areas, mountains and tropical forests. The watershed Tambobamba had two Natural Domains: Andean-Patagonian [A-nd] [Name: Puneña Province (Ecoregion: Puna and High Andes) 158.47 km^2-37.31%] and Amazonian [A P-nd] [Name: Province of the Yungas (Ecoregion: High Jungle) 266.27 km^2-62.69%]. Four climates and one glacial surface were identified: [C(i)B' 160.41 km^2-37.77%]; [B(o,i)B' 51.75 km^2-12.18%]; B(o,i)C' [88.49 km^2-20.83%]; [C(o,i)B' 123.95 km^2-29.18%]. Six life zones were identified: moist-mountain forest [Bh m 139.53 km^2-32.85%], puna grassland [Pj pu 29.26 km^2-6.89%], snowy [Nv 1.63 km^2-0.38%], inter-Andean valley dry forest [Bs vi 50.78 km^2-11.96%], scrubland/ crops [Ma/Cuap 174 km^2-40.97%] and grassland/puna grass [Pj/Cp 29.54 km^2-6.95%] (Fig. 3, F, H and G, respectively).

TABLE II: GEOLOGICAL CLASSIFICATION WITHIN THE TAMBOBAMBA WATERSHED

Name	Year	Lithology	Area	%
Ollantaytambo Group	Cambrian [CaOi-o]	schists, micas, sericite, quartz, quartzites, green metavolcanic siltstones and marble levels, conglomerates	121.06	28.68
Lower Copacabana Group	Permico inferior [Pi-co_i]	gray to dark limestone in thick strata with good stratification and calcareous concretions	108.85	25.79
Mitu Group	Upper Permian Triassic [PsTi-mi/vo]	andesitic breccias and lavas, agglomerate interbedded with sandstones, siltstones and gypsum levels	47.43	11.24
Iscaybamba Complex	Neoproterozoic [Pe-i/mi]	micaesquistos	43.06	10.20
Colluvial deposits	Holocene Quaternary [Qh-co]	angular blocks and cobbles of variable size in a clay-sand matrix deposited on the flanks of the valleys	28.13	6.66
Soncco Formation	Paleogene Oligocene [Peo-so]	light gray sandstones of medium to coarse grain, with laminar stratification, interspersed with reddish pelitic levels, heterogeneous polymictic conglomerates	3.82	0.90
Munani Formation	Late Cretaceous Paleocene Eocene [Psp-mu]	subrounded conglomerates in clayey sand/sandstone matrix with conglomerate channels and thin levels of reddish-brown siltstones	2.51	0.59
Iscaybamba Complex	Neoproterozoic [Pe-i/mi,a,gn]	micaesquistos anfibolitas gneis	18.65	4.42
Upper Copacabana Group	Permico inferior [Pi-co_s]	gray shales and limestones, black and gray shales with abundant fossils, stratified with some levels of sandstones	14.51	3.44
Alluvial deposits	Holocene Quaternary [Qh-al]	sub-angular to sub-rounded blocks and gravels in sandy-silty matrix deposited along cones and terranes	14.39	3.41
Death deposits	Quaternary Pleistocene [Qpl-mo]	heterometric angular blocks, pebbles and gravels of different types of rocks in clayey sand matrix	11.98	2.84
Tarma Group	Carbonifero Superior [Cs-t]	silicified black shales	7.75	1.84
Total			**422.14**	**100**

Note: To determine "Geological classification", the surfaces of lakes and rivers were discounted.

3) *Geological, taxonomic and physiographic characteristics*

The physiography involves the water, atmospheric and biosphere systems. Watershed had steep relief, and this causes greater erosion due to lack of vegetation. The watershed had eight types of physiographic zones (Fig. 3E): High Terraces [Ta] a:0.24 km^2–0.06%; Low Terraces [Tb] a:2.67 km^2–0.63%; Structural Terraces [Te] a:0.7 km^2–0.17%; Slopes of Alta Alanada Mountain [Vmaa] a:11.78 km^2–2.79%; High Steep Mountain Slopes [Vmae] a:66.31 km^2–15.71%; High Steep Mountain Slopes [Vmas] a:158.98 km^2–37.66%; Very Steep High Mountain Slopes [Vmame] a:181.17 km^2–42.92%; and Low Mountain Slopes Allanada [Vmba] a:0.28 km^2–0.07%.

Thus, the watershed had different geological groups based on age and lithology (geographic surface Table II and Fig. 3I). The watershed had natural, resources including bodies of water, wildlife, native forests and plantations. This contributes to the high biodiversity and the formation of the soil. The watershed also had two types of soil taxonomy: Entisol and Inceptisol of four suborders and six groups. The KED taxonomy had a larger area and LDD is less extensive (Table III and Fig. 3C).

TABLE III: SOIL TAXONOMY WITHIN THE TAMBOBAMBA WATERSHED

Order	Suborder	Group	Symbol	Area	%
Intisol	Fluvents	Ustifluyents	LDD	1.23	0.29
	Orthents	Ustorhents	LEE	11.78	2.79
	Psamments	Ustipsamments	LCD	2.67	0.63
Inseptisol	Ustepts	Dystrustepts	KEC	66.31	15.71
		Eutrustepts	KEE	158.98	37.66
		Haplustepts	KED	181.17	42.92
Total				**422.14**	**100**

Note: To determine "Soil taxonomy," the surfaces of lakes and rivers were not included.

4) *Higher land use capacity (HLUC)*

The land classification for the watershed was obtained using the Land Classification Regulation for its Major Use Capacity: "Supreme Decree N°. 017-2009-AG". This analyzed load capacity, resistance, edaphological properties, and climatic properties. Therefore, four groups or classes of soils were found (A: crop zone, C: permanent cultivation zone, F: forest zone and X: protection zone) as summarized in Table IV and Fig. 3A.

TABLE IV: Higher Land Use Capacity within the Tambobamba Watershed

HLUC	Code	Observation	Area	%
Land Suitable for Clean Crops (A)	A2wi	Medium agricultural quality with drainage and flooding problems	7.86	1.85
	A3sec	Low agricultural quality with limitations of soil, topography, and climate	4.62	1.09
	A3swc	Low agricultural quality with limitations of soil, drainage, and climate	2.67	0.63
Land Suitable for Permanent Crops (C)	C2sw	Medium agricultural quality with soil and drainage limitations	0.24	0.06
Land Suitable for Forestry Production (F)	F2sew	Average agricultural quality with limitations of soil, topography, and drainage	0.28	0.07
	F3sec	Low agricultural quality with limitations of soil, topography, and climate	247.49	58.27
Protected Lands (X)	X	Without limits	158.98	37.43
Lakes		Water bodies	0.81	0.19
Rivers			1.79	0.42
Total			**424.24**	**100**

Note: In codes: The letters (A; C; F) are the soil groups. The numbers (2: medium agrological quality; 3: low agrological class) are agrological quality classes. The lowercase letters (w: for drainage; i: by flood irrigation; s: by floor; e: topography-erosion risk; c: by climate) are limitations of the capacity of the soil.

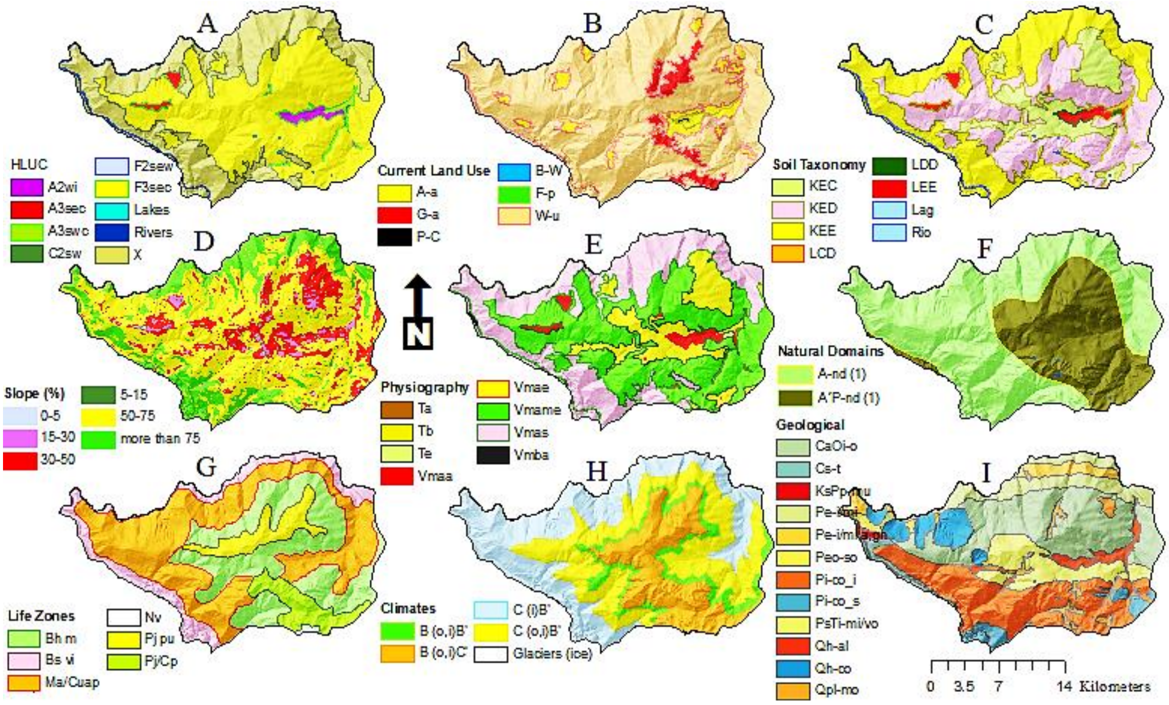

Fig. 3. Analysis of biophysical parameters within the Tambobamba watershed. Note: the parameters capacity for major land use and soil taxonomy consider lakes and rivers as biophysical parameters. The current use, slope, physiography, and geology parameters do not consider lakes and rivers as parameters. The symbol [B-W] in the current land use is interpreted as "water bodies".

C. *Environmental Zoning—Vegetation Index*

Ten environmental zonings were designed (Fig. 4) by applying soil and water conservation techniques and management. First, soil and water samples were collected; this analysis was important to observe the soil and water potential mentioned in the previous results in order to design the type of environmental zoning by applying soil and water conservation and management techniques (Fig. 5A-D). The first is the urbanized zoning Ua-z, which is intended to join the population in two zones. The Ua-z is designed to better take advantage of basic services, such as drinking water, sanitation, communication, health, education, etc. The Ua-z encourage the population to spread vertically and not horizontally (vertical growth via buildings, to not encroach on primary production areas, crops, forests and natural pastures) no (SW/mct) was applied.

In the Ss-z, S-W/mct:3 was carried out because the area is silvopastoral (interaction cultivation and livestock). The Ss-z is located in the upper parts of the watershed, and ranchers and farmers carry out this technique because there is a high demand for dairy products and beef. In 2018, the S-W/mct:3 reforestation activity was carried out with the help of infiltration ditches and narrow terraces. In this area, the slope is steep and this activity help reduce soil erosion from intensive silvopastoral activity. The planting of timber trees includes *Pinus radiata*, *Eucalyptus globulus* and *Polylepis spp* (Fig. 6A-F).

The watershed had various biophysical scenarios, which were well used to design different EZs. A single type of S-W/mct was applied for the Cc-z and Cpc-z zones, even though they had diverse crops based on the needs of the population. For these two zones, the SW/mct:1 was performed. The watershed has few areas of permanent crops, so it was suggested to choose a crop based on suitability (*Phaseolus vulgaris*, *Zea mays*, *Pisum sativum*, *Triticum spp* and *Hordeum vulgare*), crop rotation (*Hordeum vulgare* → *Triticum spp*, *Solanum spp* → *Zea mays*, *Medicago sativa* →

forage grasses, hay → rye grass), crops in strips (barley, wheat, corn, forage grasses, alfalfa, rye grass and hay) and planting in contours (corn, potato, barley, wheat → *Polylepis spp*) (Fig. 7C-F). This activity helps regenerate the soil without implementing agrochemicals that put the health of the soil and plants at risk.

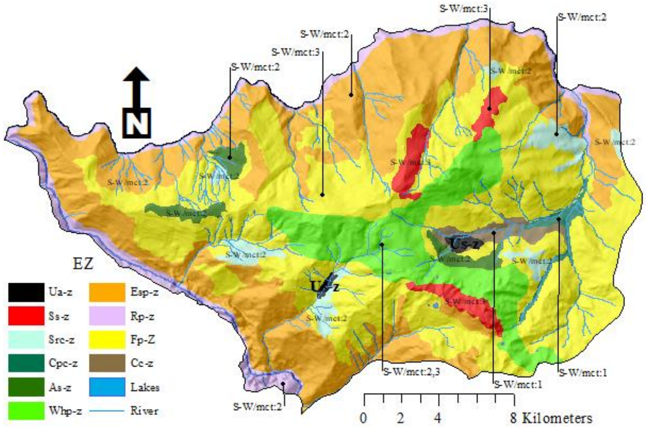

Fig. 4. Environmental zoning and techniques and management of soil and water conservation. The EZ was applied during the year 2018 and their respective zones were: Urbanized availability zone [Ua-z] a:1.73km^2 %:0.41, Silvopastoral system zone [Ss-z] a:9.78km^2 %:2.30, Soil recovery and conservation zone [Src-z] a:11.62km^2 %:2.73, Clean and permanent crop zone [Cpc-z] a:3.14km^2 %:0.74, Agroforestry systems zone [As-z] a:7.12km^2 %:1.68, Watershed headwater protection zone [Hwp-z] a:45.19km^2 %:10.64, Ecological protection zone and slopes [Esp-z] a:134.95km^2 %:31.77, Riparian protection zone [Rp-z] ha:27.46km^2 %:6.46, Forest production zone [Fp-z] a:178.13km^2 %:41.94, Clean crop zone [Cc-z] a:5.63km^2 %:1.33.

In the watershed, agroforestry systems are an effort to increase production and create microclimates to avoid extreme climatic variability. In As-z, S-W/mct:2 was carried out, where activities such as live barriers (*Zea mays* protection → *Polylepis spp* and *Eucalyptus globulus*), windbreaks (*Eucalyptus globulus*, *Polylepis spp*., *Buddleja davidii*, *Buddleja incana*, *Pinus radiata* and *Baccharis latifolia*) and live fences (*Buddleja spp*) were applied. The aim is to check the recovery of agroforestry systems through the vegetation indices described below.

In the Tambobamba watershed, there are high periods of rain from October to March. This increases the flow of the rivers, leading to overflow and erosion of the riverbank. That is why for the river protection zone Rp-z, works were carried out for the evaluation of runoff waters and control of gullies. River areas were reinforced by planting species such as (*Eucalyptus globulus*, *Polylepis spp*).

The inhabitants suggested creating eight environmental zones (7Src-z and 1Esp-z), where intensive grazing could damage these areas severely. Before, there were population centers, camps, and cattle settlements for intensive cattle raising. These places help avoid long and dangerous trips for the animals and the repeated departures and return that cost the ranchers a lot of time. In those camps, they help carry out activities such as grazing, sheep shearing, cheese making, milk extraction, and looms. An unaltered ecological environment is important for the balanced development of many species (endemic or native) due to the activities that many population centers and livestock settlements have initiated in an attempt to recover these areas. These areas were completely degraded, so the inhabitants suggested carrying out activities S-W/mct:2. For both areas, activities such as live barriers, infiltration ditches, and spreading natural fertilizer for the regeneration of natural pastures were applied, along with S-W/mct:3 techniques such as biotraps.

Fig. 5. A) pit profile 13°24'45.67” S, 72°59'2.56” W; B) soil sample collection 13°24'14.22”S, 72°56'21.39”W; C) description of the soil profile 13°27'28.55”S, 72°57'26.34”W; D) non-potable water 13°26'6.39”S, 73°0'19.18”W.

A special zone was designed, the “watershed head protection zone” labeled Whp-z. During the exploration of the watershed in 2018, it was observed that the development of urban and rural areas was increasing horizontally, reducing surfaces, pastures, and natural forests.

Fig. 6. A) tree and shrub seedling production nursery 13°30'1.98”S, 72°59'39.02”W; B) truck transporting pine seedlings 13°29'56.80”S, 72°59'24.48”W; C and D) control and measurement of pine trees 13°28'0.50”S, 73° 3'6.18”W; E) planting of pine trees 13°28'5.55”S, 73°3'29.05”W; F) pine tree irrigation 13°27'56.48”S, 73°3'32.24”W.

Population growth damaged many areas, and the lack of vegetation cover and intense rainfall accelerated landslides, damaging many homes. In the watershed, there is a lack of support from government institutions to stop these problems. Therefore, the inhabitants of the watershed proposed to carry out the S-W/mct:2 and 3. Activities included the evaluation of runoff water, control of gullies, reforestation (*Pinus radiata*, *Eucalyptus globulus*, *Polylepis spp* and *Buddleja spp*), planting of trees with the help of terraces (forage grasses, alfalfa, ryegrass, alcacer and hay) (Fig. 7A-B), and reinforcement of works with biotraps and infiltration ditches.

In the watershed, there are industrial forestry micro-enterprises that are dedicated to the extraction of trees such as eucalyptus, quinual, prunus, pine, alnus and cypress.

In the highlands of Peru (especially in Apurimac) quinual is especially common. This species is widely used for the recovery of degraded areas, agroforestry systems, and moisture retention. The species is not so abundant but its importance has led to study at an international level (since many investigations affirm that its regeneration helps to recharge rivers and lakes). Likewise, this species helps the growth of the native wild flora and fauna of Apurimac. The most abundant species in the watershed is eucalyptus, used for parquet, props, light poles, house construction, natural charcoal, etc. It has been observed that its density has been reduced by indiscriminate logging, the opening of new cultivation areas, and forest fires. That is why only one activity was carried out—reforestation.

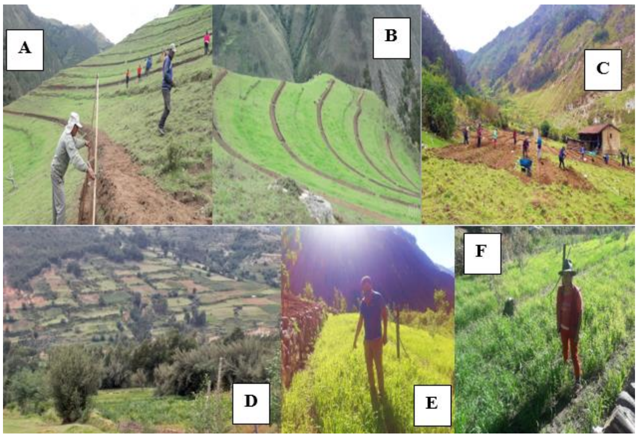

Fig. 7. A) workings for slow-forming terraces 13°30'20.17"S, 72°52'15.33"W; B) panoramic view of the slow-forming terraces planted with forage grasses; C) crops 13°26'56.18"S, 72°52'12.06"W; D) agroforestry systems with *Polylepis spp* 13°30'46.57"S, 72°52'40.23"W; E) control of forage grasses south side 13°26'49.78"S, 72°54'13.61"W; F) forage grass control north side 13°29'14.79"S, 73°4'29.07"W.

To analyze whether the management and conservation techniques for soil and water developed in 2018 benefit the recovery of natural resources, soil, water and plants, the watershed was monitored before and after the environmental zoning (years 2017, 2019 and 2021) through the Vegetation Indices (VI). Five vegetation indices were applied (SAVI, MSI, NDVI, NDWI and EVI); each has a range from −1 to +1, except the MSI which −3 to +3. SAVI analyzes the vegetation cover in relation to soil erosion. MSI affirms the hydric stress presented by the vegetation. NDVI is used to estimate the quantity, quality, and changes in plant health. NDWI shows the water content, especially for plants. EVI is used to quantify the greenness of the vegetation canopy.

Fig. 8 shows the temporal recovery before and after the S-W/mct. The Vis presented maximum (good indicator of soil and/or vegetation recovery) and minimum (bad indicator of soil and/or vegetation deterioration) digital levels. The analyzes of the IVs represented the dates: July 15, 2017, August 6, 2019, and July 10, 2021.

In 2017, the SAVI had a vegetative density of +0.59, in 2019 it maintained the same value, and in 2021 it was +0.60. As such, there was not a strong recovery in vegetation after S-W/mct. In 2017, the vegetation had water stress (MSI) of +2.64, in 2019 the stress increased to +3.30, and in 2021 it continued to increase to +3.44. Therefore, S-W/mct increased the water stress of the watershed. The NDVI in 2017 and 2019 was +0.84 and for 2021 it was +0.86. S-W/mct did not increase the quantity, quality and health of the vegetation. The watershed had high water content as evaluated by NDWI, +0.75 in 2017, in 2019 +0.76, and in 2021 it increased to +0.81. S-W/mct increased the water content in the watershed. In 2017, the greenness of the vegetation cover (EVI) was +0.77, in 2019 +0.76, and in 2021 it maintained the initial value of +0.77. The S-W/mct did not increase the greenness of the plant cover. Before the EZ, the VI values were >50% in their positive state. After the EZ plus the application of [SW/mct], there was little recovery of resources, although the trends are still being monitored.

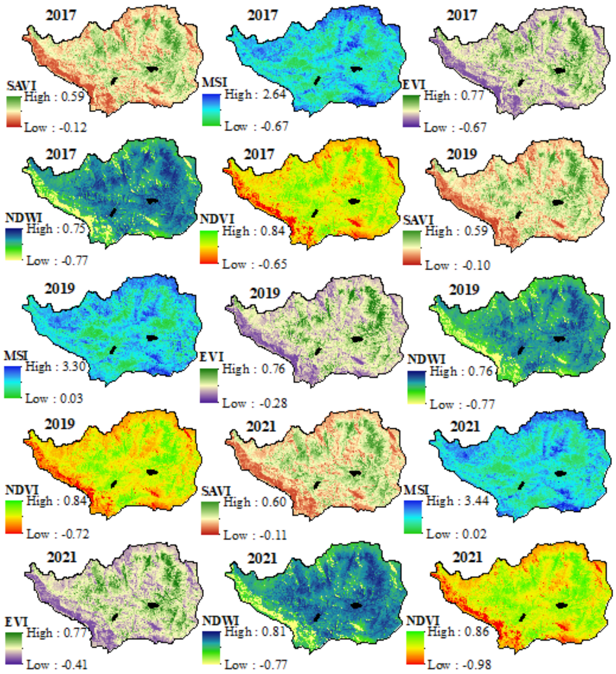

Fig. 8. Temporal analysis (2017→2021) of the Tambobamba watershed mathematical combinations of Landsat 8 OLI/TIRS images. Five vegetation indices (VI) were applied to determine if soil and water conservation techniques and management favored environmental zoning in the recovery of resources such as water, soil, and vegetation.

IV. Conclusion

It is important to analyze socioeconomic parameters to identify challenges of rural and urban development and improve the quality of life through sustainable development. The focal watershed has a low population density accompanied by a low level of poverty while its economically employed activity is high. Livestock production dominates economic activity. Education is essential to improve knowledge on economic, social, environmental and political-institutional issues. In the watershed, there is no higher educational institution (university) to improve personal knowledge. The basis for achieving a high economic position is often through university preparation. Communication routes and coverage of basic services are scarce or non-existent. Communication routes are not paved, which complicates the journey to the populated settlements. Tanks of water are not biochemically treated for human consumption.

Apurimac is located in the backbone of the Peruvian Andes and has diverse biophysical environments. Life zones are very important for the support of biodiversity. According to the "Regulations for the Classification of Lands by Their Major Use Capacity", this makes the use of life zones in a context for the best development of crops. The watershed has four HLUCs of six codes. The HLUCs is used to indicate the sustainable areas that will be used for the development of natural resources and population growth. The slope of the soil is steep, and this influences vegetation and soil erosion. Under the basic needs of the inhabitants of Tambobamba, certain crops remained stable in land use from 2019 to 2021. Some surfaces do not have any use due to their low soil fertility. Crops and pastures are the surfaces that dominate the watershed. That is why the inhabitants largely focus on livestock. Good geological, taxonomic, and physiographic soil stabilizes natural resources, such as water, soil, and plants. The analysis and recovery of the watershed before and after the environmental zoning was demonstrated using Vegetation Indices during the years 2017, 2019 and 2021. The watershed does not show a good recovery in these four years of evaluation. This is because there is no diffusion of the S-W/mct that is beneficial for recovering natural resources that are caused by intensive activities. The patience to allow these environmental zones to recover sufficiently can lead to sustainable development opportunities in the future.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The thinker of the research project was Zosimo Solano-Velarde (formulated, directed, developed and coordinated the research project with the respective authorities), Eng. Bimael Justo Quispe-Reymundo (performed the GIS and field work), Ronald Héctor Révolo-Acevedo (coordinated the technical work and management in the recovery of soil and water),Uriel Rigoberto Quispe-Quezada and Luthgardo Pastor Quispe-Quezada (carried out the collection of socioeconomic and biophysical data and coordinated with public and private institutions in their basic needs of the population) andHumberto Dax Bonilla-Mancilla (analyzed the surfaces of the environmental zoning and soil analysis); all teachers wrote and approved the manuscript.

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