Natural Resources Conservation and Research (2020) Volume 3 Issue 2
doi:10.24294/nrcr.v3i2.1546

ORIGINAL RESEARCH ARTICLE

Interception and runoff of the high Andean forest in the “El Malmo” Protective Forest Reserve

Albaluz Ramos Franco[1*], Dolors Armenteras Pascual[2]

[1] *School of science, Universidad Pedagógica y Tecnológica de Colombia, Tunja, Colombia. E-mail: albaluz.ramos@uptc.edu.co*

[2] *School of science, Universidad Nacional de Colombia, Bogotá, Colombia.*

ABSTRACT

Tropical forests are globally important for their biodiversity and the ecosystem services, and they are key to the global water cycle. Anthropogenic changes and pressures affecting tropical forests affect the fundamental role of tropical forests in water supply. This study evaluates the relationship between the vegetation coverage in the high Andean forest of the “El Malmo” Protected Forest Reserve and the quality and quantity of intercepted runoff; the life zone analyzed comprises four types of cover: dense high Andean forest, low secondary vegetation, broadleaf plantation and mosaic of pasture with natural spaces. Eight setups (two per cover) were installed, each composed of a runoff plot and a precipitation meter under the canopy; data collection was carried out every eight days for 24 weeks. The results indicate that precipitation interception does not vary in each canopy, while surface runoff and its quality with respect to sediment are affected, which is mainly due to differences in soil physical conditions. The cover that allows the best dimensions of water quality and quantity is the dense high Andean forest. The influence of anthropic intervention in the area and the presence of invasive species negatively affect these variables. This work provides knowledge on the hydrological behavior of the reserve for forest management. It also generates information on the interception/runoff relationship in the forests of the Cundiboyacense region, which has not been available until now, becoming an starting point of comparison for further research in high Andean ecosystems.

Keywords: Water Quality; Water Quantity; Vegetation Cover; Soil

ARTICLE INFO

Received: 23 June 2020
Accepted: 21 August 2020
Available online: 10 September 2020

1. Introduction

Water has been considered a natural resource with economic value since the Earth Summit in Rio de Janeiro in 1992[1], and it is valued as a finite, vulnerable and essential resource that must be managed in an integrated manner[2]. The provision of freshwater for human consumption, crop irrigation, industrial and hydropower production is a priority factor in the world economy. Nevertheless, approximately 60% of the ecosystems analyzed in the Millennium Ecosystem Assessment[3] are being degraded or used in an unsustainable manner, increasing the probability of non-linear changes in the supply of services and therefore in the human well-being of those who receive them. Impacts on these ecosystems are often evident at some distance from where they occur, i.e. in the supply of freshwater from high mountain systems, changes occurring in the upper watersheds are magnified in the lower watershed areas[4].

Tropical forests are important ecosystems due to their high biodiversity and the ecosystem services they provide. They play a key role in the global water cycle, including promoting infiltration, increasing soil moisture, supplementing aquifers, and promoting the gradual release of water in ecosystems[5,6]. Water supply is an ecosystem supply service in terms of quantity, quality, as well as seasonality. These arise from site-specific ecological processes, and they represent more than the sum of their parts; the hydrological attributes generated from these processes will characterize the services provided by the ecosystem[7].

Interception is a highly relevant factor in understanding water-related ecosystem services in forested areas. The vegetation cover is impacted by precipitation in the form of rain, which may remain on the foliage, run down the trunk, fall from the leaves by dripping, or not hit any plant element until it touches the ground[8,9]. When precipitation manifests itself in the form of dew, it forms clusters that pass through the canopy; the microscopic droplets adhere to leaf and woody surfaces and join with others to form a droplet large enough to slide to the ground[10]. Once there, it will penetrate the deciduous layer and reach the soil surface. Droplets can be retained in the pores of the substrate and when the substrate reaches maximum saturation, the excess water will be carried away by the sloping terrain. The rate at which this saturation is released through surface runoff depends on the characteristics of the soil[11].

Forest structure, such as canopy distribution and density, the water balance of species and their growth rate, will also influence the water balance in an ecosystem. In general, deciduous tree species intercept lower amounts of water than evergreen species, interception being around 18% and 31% of total precipitation respectively[6]. There is also an effect of canopy density on precipitation interception[12]; the higher leaf area indices is associated with a 45% reduction in the volume of water reaching the soil surface, thus minimizing liquid erosivity. In tropical forests, abundant epiphytes also increase the interception of water in the form of fog, otherwise the fog would not be recovered[10].

The type of vegetation cover associated with soil use influences soil texture and determines soil structure which in turn changes its water properties[13]; the physical, chemical, and biological characteristics of soils under forest canopies are particularly suitable for providing high quality water to rivers, easing watershed hydrology, and providing various aquatic habitats; their high organic contents contribute to abundant and diverse microfauna; root systems under forests are extensive and relatively deep compared to croplands and grasslands; all together, these biological conditions create soils with high macroporosity, low bulk density, highly saturated hydraulic conductivities, and high infiltration rates[14]. A change in such cover could result in organic matter losses, increased soil density and erosion, decreased water flow continuity, and increased surface runoff. This type of increase not only threatens the change in water quality downstream, contributing sediments and leached nutrients[15], but also increases the risk of flooding in the surrounding populations[16].

El Malmo Protected Forest Reserve, categorized within the National System of Protected Areas[17], is one of the few remnants of high Andean forest near the city of Tunja, where the Barón and Verbenal rivers originate and supply the rural aqueducts of the Barón, Runta, and Chorro Blanco villages. This reserve is highly impacted by human intervention, with a large number of pastures and Chusquea scandens Kunth. This species can reduce the natural regeneration of the forest and even halt plant succession[18-20]. Likewise, within the declared area, the undocumented plantation of Acacia melanoxylon R.Br. and Acacia mearnsii De Wild. were found, the latter species is listed among the 100 most invasive species in the world[21]. Acacia melanoxylon can affect the survival and growth of native species and become a strong competitor, reducing the areas occupied by native species[22]. The hypothesis proposed is that the area may present significant changes in the original coverage of the high Andean forest, negatively affecting the retention and interception rates of precipitation, and therefore, altering some aspects of hydrological services.

The objective of this work was to evaluate the quantity and quality of interception and runoff water and its relationship with the different vegetation covers present in the high Andean forest of the El

Malmo Protected Forest Reserve; it is expected to contribute valuable information to the scarce records that cross precipitation/runoff variables, as well as to make comparisons between intermediate covers, which are not found in the literature. This research intends to set a comparable precedent on the phenomena that may occur but has not yet been explored in the forests of the Cundiboyacense highlands.

2. Materials and methods

2.1 Study area

El Malmo Protected Forest Reserve is located 8 kilometers from Tunja (Boyacá), on the Tunja-Bogotá highway, in the Barón Germania trail (05°29'59" N and 73°25'00" W), between 3,050 and 3,200 meters and on the southwestern slope of the Alto del Muerto ridge (**Figure 1**)[17]. It was declared a protective forest reserve through Executive Resolution No. 362 of December 17, 1976 and Agreement No. 36 of October 28, 1976, with an area of 159 hectares[23]. According to Herrera[17], there is high Andean forest, tall grassland, wasteland and crops. Cabrejo and González[24] found, through taxonomic profiles, a distribution gradient of species characteristic of humid montain forests, which become shrublands and grasslands typical of Subpáramo as altitude increases; the dominant species (with a physiognomic predominance of 90%) is *Weinmannia tomentosa* L.f., followed by *Myrcianthes leucoxyla* (Ortega) McVaugh; with abundant epiphytism of the arboreal stratum with genera such as *Polytrhicum* sp. (mosses), *Odontoglosum* sp. (orchids) and *Tillandsia* sp. (bromeliads). The climatic conditions reported by the IDEAM UPTC station indicate an annual average rainfall between 800–1,000 mm and temperatures between 6–12 °C; according to the bimodal regime of the Colombian Andean region, with two rainy peaks from April to May and from October to November. However, the present study was conducted in a year influenced by the El Niño phenomenon, during the period of February–August 2016.

2.2 Sample design

For the establishment of the measurement setups, a previous visit was made to verify the coverages present, four main types of coverages were found: mature native forest, Acacia melanoxylon and *Acacia mearnsii* plantation, secondary successional vegetation dominated by *Chusquea scandens* and *Pennisetum clandestinum* (Chiov.) Morrone grasslands. Subsequently, a total of eight sampling points were installed, and two devices were installed on each, distributed in such a way as to cover the extension of the reserve (**Figure 1**), choosing sites where the topography of the terrain and the distribution of *C. scandens* allowed their correct installation.

2.3 Measurement and analysis of variables

In order to know the area and distribution of the vegetation cover present and to be able to make the sample design, a supervised land cover classification was first performed under the Corine Land Cover system for Colombia[25]. This classification was performed from a Spot-5 image with a spatial resolution of 5 × 5 m in bands 1, 2, 3 using the Geographic Information System program ArcGIS®[26]. Subsequently, in the eight selected sampling points, canopy density was measured with the help of a convex forest densitometer (Forestry Suppliers Model A Convex Spherical Densitometer) to obtain the estimated value of coverage. This information was analyzed with the non-parametric Kruskal-Wallis test ($p < 0.05$) and Dunnett's test to detect differences between the canopy density of each cover; and it was analyzed with the help of the SPSS® program[27].

For this research, the interceptor function of the canopy was measured as the internal precipitation, which is interpreted as that portion of rain that manages to pass through or slip from the canopy until it reaches the ground[28]. For its measurement, five wireless digital rain gauges were installed at each sampling point, with separation of 5 m between them. It has been reported that the flow of the stem and branches does not reach 2% of the total intercepted flow by the foliage[12], therefore, it was not taken into account in this study. In parallel, the precipitation reported at the IDEAM Climatological Station located at the UPTC Campus (Tunja) was recorded.

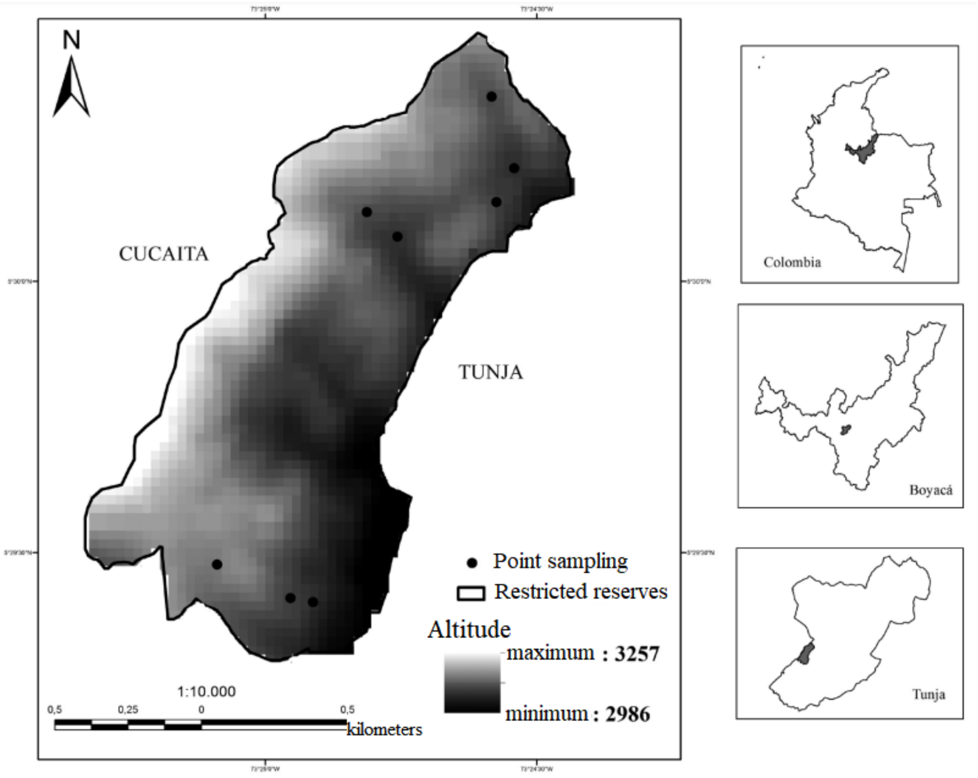


Figure 1. Location of sampling points within the “El Malmo” Protected Forest Reserve.

A conventional 1 m^2 closed runoff plot with a collection basin was also placed at each sampling point, 2 m away from the interception assembly. Each plot was constructed downslope (less than 1%) with galvanized sheeting buried 10 cm deep in the ground. The flow stored in the collection container was measured weekly with a calibrated instrument, and the container is emptied after each reading. To determine the relationship between soil moisture and surface runoff, soil texture, real and apparent density and porosity were analyzed for each type of cover[29,30]. For porosity values, the porosity index of Kaúrichev[29] was used, which indicates that soils with values lower than 40% have very low porosity, followed by those between 40 and 50, and it is satisfactory from 50 to 55, excellent from 55 to 70, and finally, soil with values of more than 70% have excessive porosity.

Internal precipitation (Pi) and surface runoff (Es) were measured during the 24 weeks, from February to August 2016. This information was analyzed with the non-parametric Kruskal-Wallis test ($p < 0.05$) and Dunnett’s test for significant differences using SPSS software®[27].

For the water quality study, two replicates were taken with 500 ml samples of the runoff stored in the collecting tank of each sampling point for examination in a certified laboratory, where total suspended solids (TSS) tests were performed. The results were analyzed under IDEAM[31] parameters using the Water Quality Index (ICAsst), which divides the tolerable ranges of sediment in water into very poor (0), poor, normal, acceptable and good (1). To find the relationship between the measured variables, the Spearman’s Rho (ρ) statistic, ideal in the treatment of non-parametric data, was used with the help of the SPSS® program[27].

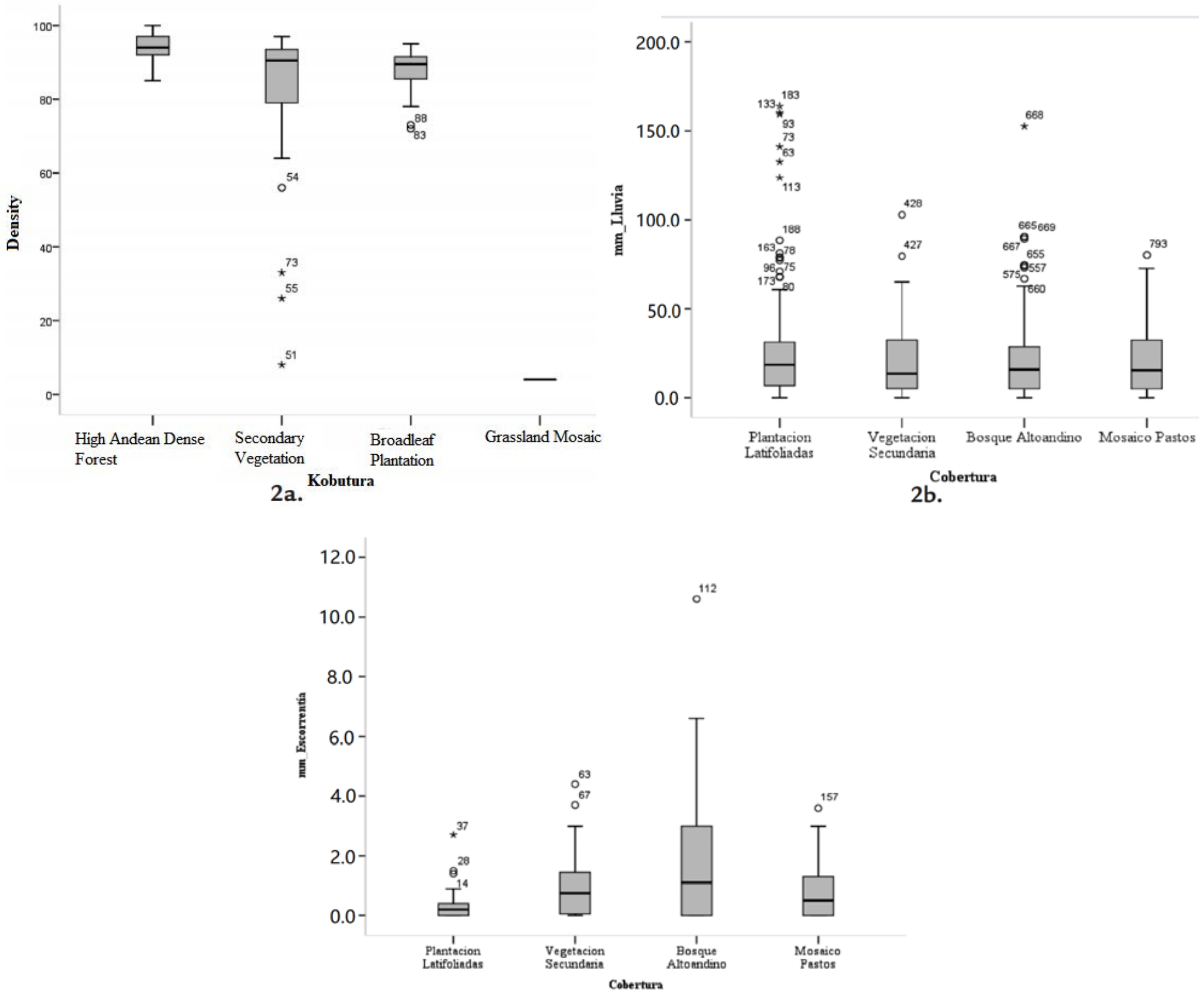
Finally, one of the simplest ways of knowing how many cubic meters of water a piece of land is contributing to its watershed is to know the average runoff. If the rainfall of one hectare per day in a year is the same, then the area, precipitation and runoff coefficient are used to indicate the input of liquid to the tributary. The calculation of the runoff coefficient (C), which expresses the portion of rainfall that will be converted into flow, was obtained by dividing the average internal precipitation in Es of each type of vegetation.

3. Results

3.1 Plant coverage

There are six different cover types present in the reserve, named by Corine LandCover[25] (**Figure 3**) as High Andean Dense Forest with 76.04 ha (mature native forest), Low Secondary Vegetation with 52.62 ha (secondary succession of C. scandens), Grassland Mosaic with Natural Spaces with 17.46 ha (P. clandestinum grassland), and Broadleaf Plantation with 1.01 ha (A. melanoxylon and A. mearnsii).

Dense Submoor Dense Shrubland (9.04 ha) and Bare or Degraded Land (1.63 ha) were not included in the analysis because they do not correspond to the evaluated life zone (high Andean forest); a total of 157.80 hectares delimited in the official cartography. In reference to the canopy cover, the High Andean Dense Forest is the most dense with 94.07%, followed by the Low Secondary Vegetation cover with 87.31% and the Broadleaf Plantation with 81.38% (**Table 1**). No significant difference was found between the density of Low Secondary Vegetation and Broadleaf Plantation (**Figure 2a**).



2a.

2b.

2c.

Figure 2. Kruskal-Wallis non-parametric analysis of variance; **2a**: the coverage density of each sampling point is divided into three categories: High Andean Dense Forest with the highest median, Broadleaf Plantation and Secondary Vegetation with no difference between them and finally Grassland Mosaic with the lowest median; **2b**: no significant differences were found between precipitation interception at each sampling site; **2c**: the surface runoff sheets present minimal differences in their volume, with Plantación de Latifoliadas being the lowest; Vegetación Secundaria and Bosque Altoandino are similar, while Mosaico de Pastos does not differ from the previous ones.

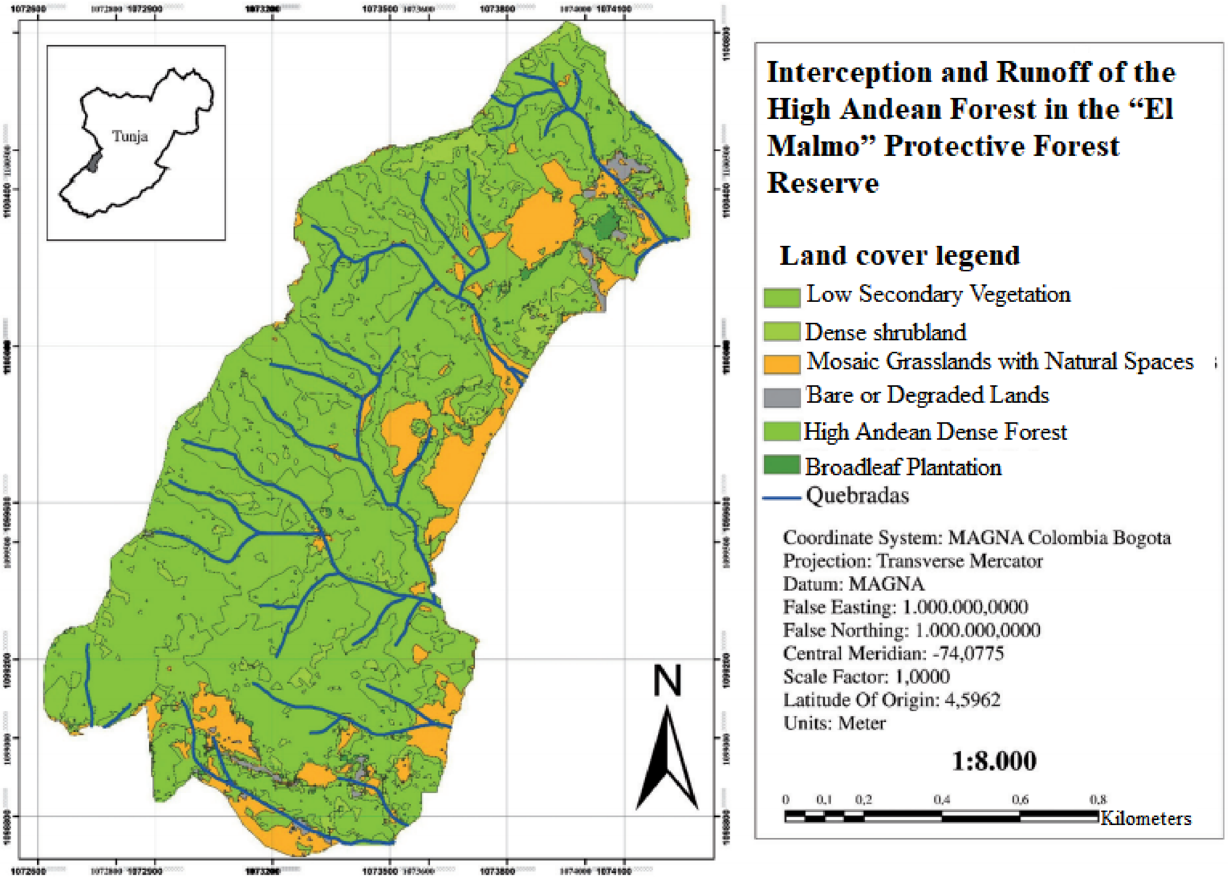


Figure 3. Supervised land cover classification of El Malmo Protected Forest Reserve according to the Corine Land Cover methodology adapted for Colombia.

Table 1. Extent and density of canopy cover in the El Malmo Protected Forest Reserve

Coverage	**Area (ha)**	**% Extension**	**% Canopy density**
High Andean Dense Forest	76.04	48.19	94.072
Low Secondary Vegetation	52.62	33.35	87.312
Mosaic Pastures with Natural Spaces	17.46	11.06	0.16
Broadleaf Plantation	1.01	0.64	81.38
Total	147.13	93.24	--

3.2 Precipitation interception

The Kruskal-Wallis test indicates that there is no significant difference between the interception in each vegetation type ($p > 0.10$) (**Figure 2b**) with average ranges from 395 to 420 mm of rainfall in the six months evaluated. The pluviometric records taken at each point show two peaks in April—May (120 mm/month on average) and July (around 160 mm/month), which coincide with the climatic data reported at the Tunja IDEAM station.

3.3 Surface runoff

The data obtained from the runoff plots indicate that the High Andean Dense Forest and Secondary Vegetation coverages behave similarly (96.73 and 88.79 mm respectively in the six months evaluated), the surface sheet of Broadleaf Plantation presents the lowest values (76.28 mm) and Grassland Mosaic does not differ significantly from the coverage of other threes ($p > 0.05$) (**Figure 2c**). The runoff values for each cover show two important increases that correspond to the rainy peaks recorded in April—May and July.

3.4 Runoff water quality

Table 2 indicates that the best water quality was obtained in the High Andean Forest cover with an average of 45.5 mg/l, while the worst was found in the Broadleaf Plantation with 207 mg/l. The averages for Secondary Vegetation and Grass Mosaic were 107 and 115 mg/l respectively.

Table 2. Soil physical parameters for each cover; water quality index for suspended solids and its category for each vegetation type and average runoff values (Vm) for each vegetation cover type in the El Malmo Protected Forest Reserve

Parameter	**Dense Forest Altoandino**	**Secondary Vegetation**	**Pasture Mosaic**	**Broadleaf Plantation**
Texture	Franco	Franco	Franco	Clayey
Actual density	2.11	2.17	2.38	2.04
Bulk density	0.62	0.77	0.76	1.45
Porosity	70.68%	64.05%	68.02%	28.83 %
	Excellent	Excellent	Excellent	Very Low
ICAsst (replica 1)	0.852	0.75	0.546	0.75
	Acceptable	Acceptable	Regular	Mala
ICAsst (replica 2)	0.915	0.648	0.804	0.648
	Good	Regular	Acceptable	Mala
C	0.08	0.05	0.03	0.01
Mean Pi (mm)	81.53	77.32	88.35	95.67
VM (m^3)	6.93	4.02	2.62	1.30

3.5 Soil physical parameters

The results of texture, solid density and apparent porosity of the soil of each coverage type are shown in **Table 2**. The most critical values were observed in Broadleaf Plantation.

3.6 Relationship between variables

Initially, the relationship between the density of each cover and the amount of internal precipitation was evaluated, with a result of -0.412 ($p < 0.05$), i.e. a weak negative correlation; the opposite happens when analyzing the relationship between canopy density and runoff sheet volume where Rho is equal to 0.393 (weak positive) and lacks statistical significance ($p > 0.10$).

Runoff water quality obtained a value of 0.429 (weak positive) also without significance ($p > 0.10$). However, the Spearman correlation between runoff and its quality with the Apparent Density (DA) parameter resulted in a strong negative relationship between DA and Es ($p = -0.821$ and $p > 0.05$). On the other hand, DA and quality measured in ICAsst have a strong negative relationship ($p = -0.893$ and $p > 0.05$).

4. Discussion

High Andean dense forest is the most common cover in the area. No research has been conducted on the successional status of the reserve, but it is possible to observe the advance of secondary successional species such as *C. scandens* that tend to begin their development in places where disturbance has ceased and where they find the ideal light and space to settle down, such as the edges of the original forest[19].

A dense structure formed by *C. scandens* was observed in the area, when its stems begin to exceed one meter in height. They tend to arch or adhere to nearby tree trunks, until they overtake them and cover their crowns, or in the worst case, bring them down with the excessive weight of their biomass. Although devastating for the native flora, *C. scandens* has been reported as an ideal plant for slope stabilization, since it reduces the erosive action of water and wind on steep slopes, largely due to the microclimate created by its physiognomy[19]. This species also contributes to the humidity balance in the soil along the edges of streams and secondary rivers, preventing landslides[32]. The land cover map drawn for this study confirms the preference of this herb for the edges of the streams that originate in the reserve, increasing its abundance in the forests of *W. tomentosa* and *M. leucoxyla*. It is hoped that ongoing research can evaluate its historical distribution to see if it can be completely replaced in the future (**Figure 3**).

Despite the presence of four cover types, the little difference between the densities of High Andean Dense Forest, Secondary Vegetation and Broadleaf Plantation, is a response to the morphology of trees such as *W. tomentosa*, *M. leucoxyla* and *A. mearnsii* of wide and dense branches completely covered with bromeliads, orchids and bryophytes, as well as the overlapping stems and nodes of *C. scandens* that form the ideal substrate for bryophyte mats; although the canopy projection of *A. melanoxylon* is not greater than 50 cm in diameter, the abundance of Bromeliaceae supports its high canopy closure values. This increase in the contact surface of fog and rain allows the interception process at each site to be so similar, especially because of the contribution of epiphytes that can accumulate up to three times their dry weight in water and gradually release it, decreasing the kinetic energy falling to the ground[33].

El Malmo Protected Forest Reserve is rich in diversity of vascular and non-vascular epiphytes[24,34] and the characteristics of its distribution within the forest correspond to high montane cloud forest[35]; it is found that the branches, stems and leaves are full of liverworts, hellebores, mosses, orchids and bromeliads, in which horizontal precipitation forms microturbulences that saturate its biomass in the so-called "sponge effect"[33]. The participation of tropical forest epiphytes in the biogeochemical processes and water balance of the forest is highlighted[36], as well as the intimate relationship between the high diversity, abundance of epiphytes and fog in the American tropics, where their duration will depend largely on this atmospheric phenomenon, contributing to the interception of water in dry periods[37]. Although it would be expected that Mosaico de Pastos would have different values of interception, it can be concluded that the antenna structure of the branches and inflorescences of species such as *P. clandestinum*, present in the reserve, allows for rain and fog interception similar to the branches of small trees[38], as long as livestock activity is not intensive and allows for the sexual development of the pasture. During the field phase of this study, the presence of cattle was limited to a couple of weeks. When the February drought was come to an end, the species were able to develop at the beginning of rainfall, allowing the variables of interest to be measured without human interference.

The dense native cover presented the highest surface runoff data, which can be explained by the condition of permanent saturation of the soil under high groundwater levels; various studies have shown that vegetation with medium and high water levels has the ability to regulate flow, which is conducive to the sustainable existence of aquifers and high water levels, and provides a basis for the formation of the nascent streams[30,39]. During this research, a significant increase in the groundwater level in the High Andean Dense Forest cover was observed at the end of May when the peak rainfall began to decrease; although this variable was not included in the experimental design, the runoff plots located there were lifted off the ground due to the pushing force exerted by the phreatic water, and this phenomenon did not stop even at the end of the study. It is likely that in the dry weather influenced by the El Niño Phenomenon of strong intensity recorded since December 2015[40], groundwater reserves in the area decreased and subsequently, heavy rainfall in the months of April and May recharged the aquifer again, returning permanent moisture to the loam soil of the cover, slowing infiltration and increasing surface runoff[41]. In dialogue with the person in charge of the Germania Veredal Aqueduct, the importance of the aquifer at the local level is evident, since water rationing strategies did not have to be implemented during the severe drought and the supply of water was stable. Secondary vegetation cover had a similar behavior, which may be influenced by the same phenomenon. Thus, it would be partially supporting the "trade-off infiltration-evapotranspiration" hypothesis of how the forest is able to allow infiltration and aquifer recharge to produce a slow and steady flow during drought[42,43]. Although the Mosaic Grassland cover would be expected to have higher runoff, the physical properties of its soil remain similar to the more canopy-protected sites. Compaction is not yet evident, since cattle trampling is not intensive, which is a disturbance that drastically alters infiltration and surface flow[30]. The various land uses and land covers influence the texture, density and amount of organic matter present in the soil, altering the hydraulic properties of the soil; e.g. bulk density can indicate the water holding capacity of the soil[44,45]. In addition, it has been established that water flux at the soil surface in mountain ecosystems is fluctuating within itself, i.e., between different vegetation types at the same site; making very general predictions and models for the same site may underestimate or overestimate water supply[45]. Low runoff values have been reported for tropical high mountain forests, related to the density of vegetation and high infiltration rate in soils with excellent porosity and low bulk density[46,47].

The strong presence of medium-grained sandstone in the area[17] makes the possibility of exploiting the material for construction in the reserve before it was declared a protected area very interesting, leaving at least one hectare of exposed rocky material and highly modified soil in its initial characteristics, including changes in texture and porosity that directly affect the distribution of surface water during rainfall events[48,49]. Such soil without cover would theoretically have the highest runoff values. However, carried out as a contingency to abandon the exploitation, the Plantation of Latifolias substantially decreases the volume of the surface water, which is influenced by two characteristics: the morphology of the young leaves of *A. melanoxylon* of copious leaf area that slows the kinetic energy of the rain and the totally flat shape makes the mining area have no slope that allows surface water flow.

Although water quality in watersheds is related to the types of cover that compose them[46,47,50], in the El Malmo Reserve there is evidence of a closer relationship with soil quality. The abundant leaf litter layers and organic matter content of the forest soils create physical conditions such as low bulk density and high macroporosity, which favor the filtration and decontamination of surface and subsurface runoff water[14]. The good physical conditions of the soil of the original forest of the reserve support these claims.

On the other hand, specialized literature has focused on evaluating the two extremes of water quality versus vegetation cover[51], but the middle term in tropical forests representing in secondary or successional areas does not have much information in this regard[43,50]. This work confirms that secondary vegetation and even pastures, can contribute to good water quality in the watershed as long as the soils maintain their original characteristics or have good “health”, thus retaining their natural capacity to retain excess nutrients and contribute to aquifer recharge[48]. Another case is the Plantation of Latifoliadas, which is a poorly executed mine abandonment contingency plan. At the end of the rock exploitation, highly invasive exotic species were planted[21] on clay and sandstone, pretreatment for the restoration of soil organic layer. It can be restored by applying compost and other methods to induce the growth of local vegetation, which is effective in the open sky mining area[52,53]; *A. melanoxylon* resistant to nutrient-poor clay soils[23] grew successfully and dispersed in the reserve over access trails and even some shoots are already observed in areas away from the initial planting; the physical characteristics evaluated can be indicative of soil quality[48]. Comparing samples of native and secondary cover, the soil is in very poor condition or even absent where the rock outcrops and detaches, promoting sediment transport, a condition that is reflected in the Water Quality Index.

The role of the “sponge effect” in the permanent saturation of the soil should be studied in more detail. Probably the constant dripping due to fog microturbulence may be contributing to the increase of runoff in the coverages where it occurs[33].

On the other hand, although the areas covered by pasture do not exceed 12%, there is concern about its possible increase due to cattle ranching activities. The reserve has a mixed character in which the area of private boundaries is unknown, which may or may not be within the local coverage. During the field phase of this study, at least twenty head of cattle were found grazing on the edge of the forest of *W. tomentosa*; the increase of the cattle frontier and the lack of governance in protected areas have become the most important causes of loss of native forest vegetation in Colombia[54,55].

Although the broadleaf plantation does not cover a large area, it is of vital importance to give it adequate forest management. *A. mearnsii* is cataloged among the 100 most invasive species in the world[21] and *A. melanoxylon* is considered pyrophilous[22], which have a high potential for dispersal and reproduction that is reflected in the colonization of areas away from the original plantation and may mean the arrival of a new competitor to the original forest.

The high biodiversity of this type of cover is the fundamental basis for the provision of services and is considered invaluable infrastructure and natural capital for human well-being[56,57].

Despite being a protected area, El Malmo Reserve urgently requires the intervention of government agencies in collaboration with the owners of surrounding areas to carry out management plans that contribute to the expansion of the original forest and the control of invasive species (exotic or not) that could replace it completely. This can lead to a decrease in the quality and quantity of the current supply. Farmers need to be made aware of the cost-benefit of substituting the use of land for cattle ranching with restoration, which in the long term will provide a constant water supply of common benefit for the three villages that supply their aqueducts from the Barón and Verbenal streams[4,7]. An alternative that can be offered by land managers is the implementation of payment schemes for water environmental services[58,59], providing a viable economic solution for land owners who are able to supplement and maintain municipal aqueducts, and change the livestock or agricultural tradition of their land to coverages that fulfill this mission[60].

One of the little mentioned elements within the natural capital is the soil, because it is a non-renewable resource, its conservation is essential to ensure the quality of the water supply[61,62]; erosion is one of the most serious problems of recent decades in the world, but not the only one[48]. Compaction and improper exploitation threaten the water resources of the soil in the reserve; the alteration of the quality of the liquid symbolizes the increase in the cost of treatment used by human beings[56], and the decrease in quantity forces the adoption of rationing measures, which has serious economic consequences for the health of producers and micro watershed residents in the region. Two aspects of long-term service can be ensured by teaching good agricultural practices to communities that have an impact on the reserve and implementing recovery plans involving soil physical variables.

5. Conclusions

The High Andean Dense Forest provides the best runoff water quality and the greatest amount of precipitation interception in the reserve, thanks to the sponge effect of its canopy and the good condition of its soil. The Secondary Vegetation and Grass Mosaic coverages have intermediate characteristics, but there is no difference between them due to density and soil characteristics; the planting area of the Broadleaf Plantation is the smallest.

It is inferred that the effect of vegetation coverage on the interception of precipitation in high Andean forests such as the one studied is not obvious. In this case, abundant epiphytes and abundant leaf layers combine to form a network that can effectively capture rain and fog and gradually release. On the other hand, the physical properties of soil have a great impact on runoff and water quality; those plant layers with well-developed organic layers will have cleaner and richer surface water even if there is no prominent crown.

Activities to increase vegetative cover in this reserve, such as those proposed in payment for environmental services schemes or other forest management activities, are ideal for reestablishing, maintaining and increasing the High Andean Dense Forest and improving the physical characteristics of the altered soils. There is a wide gap in knowledge about soil and subsoil hydrodynamics in this area, and this information may be crucial for water management of rural residents.

It is possible that the phenomena analyzed here are occurring in a similar way in the remnants of High Andean forest throughout the Cundiboyacense highlands: it is urgent to develop new research that makes a comparison between canopies and relates, among others, the variables of interception and runoff; thus, consolidating a clear concept about the water dynamics of the natural areas of the Cundiboyacense region. This work is the first step in this direction.

Conflict of interest

The authors declare that they have no conflicts of interest.

References

1. Van der Zaag P, Savenije H. Water as an economic good: The value of pricing and the failure of markets. Netherlands: UNESCO-IHE Institute for Water Education; 2006. p. 28.
2. International Conference on Water and the Environment (ICWE). International conference on water and the environment: Development issues for the 21st century. Geneva: World Meteorological Organization; 1992.
3. Millennium Ecosystem Assessment. Ecosystems and human well-being: Synthesis. Washington: Island Press; 2005; p. 139.
4. Millennium Ecosystem Assessment. Ecosystems and human well-being: A framework for assessment. Washington: Island Press; 2005. p. 245.
5. Calder I, Aylward B. Forest and floods: Moving to an evidence-based approach to watershed and integrated flood management. Water International 2006; 3(1): 87–99.
6. Carvalho-Santos C, Pradiño Honrado J, Hein L. Hydrological services and the role offorest: Coneptualization and indicator-based with an illustraion at a regional scale. Ecological Complexity 2014; 20: 69–80. doi: 10.1016/j.ecocom.2014.09.001.
7. Brauman K, Daily G, Duarte T, *et al*. The nature and value of ecosystem Services: An overview highlighting hydrologic services. Annual Review of Environment and Resources 2007; 32: 67–98. doi: 10.1146/annurev.energy.32.031306.102758.
8. Tellez P. Simulación del ciclo hidrológico en tres tipos de uso del suelo de la Amazonía colombiana (Spanish) [Simulation of the hydrological cycle in three types of land use in the Colombian Amazon]. Bogotá: Universidad Nacional de Colombia; 2003. p. 124.
9. David J, Valente F, Gash J. Evaporation of intercepted rainfall. In: Andreson M (editor). Encyclopedia of hydrological sciences. Hoboken: John Wiley and Sons; 2005. p. 627–634.
10. Holder C. Rainfall interception and fog precipitation in a tropical montane cloud forest of Guatemala. Forest Ecology and Management 2004; 190: 373–384.
11. Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM). Metodología del cálculo del Índice de Escases (Spanish) [Methodology for the calculation of the scarcity index]. Bogotá: Instituto de Hidrología, Meteorología y Estudios Ambientales; 2004. p. 37.
12. Livesley S, Baudinette B, Glover D. Rainfall interception and stem flow by eucalypt street trees—The impacts of canopy density and bark type. Urban Forestry & Urban Greening 2014; 13: 192–197. doi: 10.1016/j.ufug.2013.09.001.
13. Sánchez Nuñez D, Pinilla G, Mancera Pineda J. Efectos del uso del suelo en las propiedades edáficas y la escorrentía superficial en una cuenca de la Orinoquia Colombiana (Spanish) [Effects of land use on edaphic properties and surface runoff in a watershed of the Colombian Orinoquia]. Colombia Forestal 2015; 18(2): 255–272.
14. Neary D, Ice G, Jackson R. Linkages between forest soils and water quality and quantity. Forest Ecology and Management 2009; 258: 2269–2281.
15. Rodríguez A, Sepúlveda I, Camargo García J, *et al*. Pérdidas de suelo y nutrientes bajo diferentes coberturas vegetales en la zona Andina de Colombia (Spanish) [Soil and nutrient losses under different vegetation covers in the Andean zone of Colombia]. Acta Agronomica 2009; 58(3): 160–166.
16. Henriquez C, Azócar G, Aguayo M. Cambio de uso del suelo y escorrentía superficial: aplicación de un modelo de simulación espacial en Los Ángeles, VIII Región del Biobío, Chile (Spanish) [Land use change and surface runoff: Application of a spatial simulation model in Los Angeles, 8th District, Biobio, Chile]. Revista de Geografia Norte Grande 2006; 36: 61–74.
17. Herrera Y. Diagnóstico y concertación del Plan de Manejo de la Reserva Forestal Protectora El Malmo (Spanish) [Diagnosis and agreement of the Management Plan of the El Malmo Protected Forest Reserve]. Tunja: Corpoboyacá; 2005. p. 94.
18. Trujillo L, Vargas Rios O. Caracterización del borde de un relicto de bosque altoandino dominado por Chusquea Scandens y evaluación del efecto de disturbios experimentales sobre la regeneración natural en la Reserva Forestal Municipal de Cogua (Cundinamarca, Colombia) (Spanish) [Characterization of the edge of a high Andean forest relics dominated by Chusquea Scandens and evaluation of the effect of experimental disturbances on natural regeneration in the Municipal Forest Reserve of Cogua (Cundinamarca, Colombia)]. Acta Biológica Colombiana 2004; 9(2): 86–88.
19. Montenegro A, Vargas Ríos O. Caracterización de bordes de bosque altoandino e implicaciones para la restauración ecológica en la Reserva Forestal de Cogua (Colombia) (Spanish) [Characterization of high Andean forest edges and implications for ecological restoration in the Cogua Forest Reserve (Colombia)]. Revista de Biología Tropical 2008; 56(3): 1543–1556.

20. Cantillo Higuera E, Lozada Silva A, Pinzón Gonzalez J. Caracterización sucesional para la restauración de la Reserva Forestal Cárpatos, Guasca, Cundinamarca (Spanish) [Successional characterization for the restoration of the Cárpatos Forest Reserve, Guasca, Cundinamarca]. Colombia Forestal 2009; 12(1): 103–118.
21. . Lowe S, Browne M, Boudjelas S, *et al*. 100 of the world's worst invasive alien species: A selection from the global invasive species database. New Zealand: Fondation D'Entreprise Total; 2000. p. 12.
22. Arán D, García-Duro J, Reyes O, *et al*. Fire and invasive species: Modifications in the germination potential of *Acacia melanoxylon*, *Conyza canadensis* and *Eucalyptus globulus*. Forest Ecology and Management 2013; 302: 7–13. doi: 10.1016/j.foreco.2013.02.030.
23. Regional Autonomous Corporation of Boyacá-Corpoboyacá. Especies vegetales viveros Corpoboyaca (Spanish) [Plant species nurseries Corpoboyaca]. 2016. Available from: http://www.corpoboyaca.gov.co/cms/wp-content/uploads/2016/01/capitulo_i_descripcion_de_las_especies_vegetales_producidas_en_los_viveros_de_la_corporacion_autonoma_regional_de_boyaca-_corpoboyaca.pdf.
24. Cabrejo F, González G. Caracterización de la vegetación del bosque Altoandino del transecto Barón Germania de la Reserva Forestal "El Malmo" Tunja, Boyacá (Spanish) [Characterization of the vegetation of the High Andean forest of the Baron Germania transect of the Forest Reserve "El Malmo" Tunja, Boyacá]. Tunja: Universidad Pedagógica y Tecnológica de Colombia; 2002. p. 130.
25. Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM). Leyenda Nacional de Coberturas de la Tierra. Metodología CORINE Land Cover adaptada para Colombia Escala 1:100.000 (Spanish) [National land cover legend. CORINE Land cover methodology adapted for Colombia scale 1:100,000]. Bogotá: Institute of Hydrology, Meteorology and Environmental Studies; 2010; p. 199.
26. ESRI. ArcGIS Desktop. Version 10.3.1. Redlans: Environmental System Research Institute; 2015.
27. IBM. IBM SPSS Statistics for Windows. Version 23. Armonk: International Business Machines Corporation.
28. León Peláez J, Gonzalez Hernandez M, Gallardo Lancho J. Distribución del Agua Lluvia en Tres Bosques Altoandinos de la Cordillera Central de Antioquia, Colombia (Spanish) [Rainwater distribution in three high Andean forests of the Central Cordillera of Antioquia, Colombia]. Revista Facultad Nacional de Agronomía Medellín 2010; 63(1): 5319–5336.
29. Kaurichev I. Prácticas de edafología (Spanish) [Practice of soil science]. Moscow: Mir; 1984. p. 279.
30. Rios N, Cardenas A, Andrade H, *et al*. Escorrentía superficial e infiltración en sistemas ganaderos convencionales y silvopastoriles en el trópico subhúmedo de Nicaragua y Costa Rica (Spanish) [Surface runoff and infiltration in conventional and silvopastoral livestock systems in the subhumid tropics of Nicaragua and Costa Rica]. Agroforestería en las Américas 2006; 45: 66–71.
31. Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM). Hoja metodológica del indicador Índice de calidad del agua (Versión 1.00) (Spanish) [Methodological sheet of the water quality index indicator (Version 1.00)]. In IDEAM, Sistema de Indicadores Ambientales de Colombia. Bogotá: Instituto de Hidrología, Meteorología y Estudios Ambientales; 2011. p. 10.
32. Sarmiento Y, Torres N. Restauración en explotaciones de minas caliza (Spanish) [Restoration in limestone mining operations]. Revista Luna Azul 2008; 27: 75–84.
33. Levia D, Carlyle-Moses D, Tanaka T. Forest hydrology and biogeochemestry, synthesis of past research and future directions. New York: Springer; 2011. p. 740.
34. Álvaro W, Díaz M, Zabala J. Flórula de la Reserva Forestal Protectora El Malmo (Spanish) [Flora of the El Malmo Protected Forest Reserve]. Tunja: Universidad Pedagógica y Tecnológica de Colombia; 2006. p. 88.
35. Bruijnzeel L, Hamilton L. Decision time for cloud forest. Netherlands: UNESCO; 2000. p. 41.
36. Van Stan II J, Pypker T. A review and evaluation of forest canopy epiphyte roles in the partitioning and chemical alteration of precipitation. Science of the Total Environment 2015; 536: 813–824. doi: 10.1016/j.scitotenv.2015.07.134.
37. Obregon A, Gehrig-Downie C, Gradstein R, *et al*. Canopy level fog occurrence in a tropical lowland forest of French Guiana as a prerequisite for high epiphyte diversity. Agricultural and Forest Meteorology 2011; 151: 290–300. doi: 10.1016/j.agrformet.2010.11.003.
38. Ataroff M, Naranjo M. Interception of water by pastures of Pennisetum clandestinum Hochst. ex Chiov. and Melinis minutiflora Beauv. Agricultural and Forest Meteorology 2009; 149: 1616–1620.
39. Villegas J. Análisis del conocimiento en la relación aguasuelo-vegetación para el Departamento de Antioquia (Spanish) [Analysis of knowledge in the water-soil-vegetation relationship for the Department of Antioquia]. Revista EIA 2004; 1: 73–79.
40. Ministry of Agriculture and Rural-Minagriculture Development. Boletín Agroclimático Febrero de 2016 (Spanish) [Agroclimatic Bulletin February 2016]. Colombia: Institute of Hydrology, Meteorology and Environmental Studies; 2016. Available from: http://www.ideam.gov.co/web/tiempo-y-clima/boletin-agroclimatico/-/document_library_display/o7HBhnNMuqY0/view/552413.
41. Bruijnzeel L. Deforestation and dry season flow in

the tropics: A closer look. Journal of Tropical Forest Science 1989; 1(3): 229–243.

42. Krishnaswamy J, Bonell M, Venkatesh B, *et al*. The groundwater recharge response and hydrologic services of tropical humid forest ecosystems to use and reforestation: Support for the "infiltration-evapotranspiration trade-off hypothesis". Journal of Hydrology 2013; 498: 191–209.
43. Ogden F, Crouch T, Stallard R, *et al*. Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama. Water Resources Research 2013; 49: 8443–8462.
44. Sun F, Lu Y, Wang J, *et al*. Soil moisture dynamics of typical ecosystems in response to precipitation: A monitoring-based analysis of hydrological service in the Qilian Mountains. Catena 2015; 129: 63–75. doi: 10.1016/j. catena.2015.03.001.
45. Marín-Castro B, Geissert D, Negrete-Yankelevich S, *et al*. Spatial distribution of hydraulic conductivity in soils of secondary tropical montane cloud forests and shade coffee agroecosystems. Geoderma 2016; 283: 57–67.
46. Ruiz Suescún O, Acosta Jaramillo J, León Pelaez J. Escorrentía superficial en bosques montanos naturales y plantados de Piedras Blancas, Antioquia (Spanish) [Surface runoff in natural and planted montane forests of Piedras Blancas, Antioquia (Colombia)]. Revista Facultad Nacional de Agronomía Medellín 2005; 58(1): 2635–2649.
47. Córcega E, Silva, O. Evaluación de la intercepción de lluvia, escorrentía y erosión hídrica en bosques de laderas subhúmedo-secas (Spanish) [Evaluation of rainfall interception, runoff and water erosion in sub-humid-dry slope forests] [Internet]. 2011. Available from: http://www.sian.inia.gob.ve/repositorio/congresos/CVCS19/.
48. Karlen D, Mausbach M, Doran J, *et al*. Soil quality: A concept, definition, and framework for evaluation. Soil Science Society of America Journal 1997; 61: 4–10.
49. Álvarez-Herrera J, Fernández J. Evaluación de la erosión de un Inceptisol de Tunja con diferentes coberturas al impacto de lluvias simuladas (Spanish) [Erosion evaluation of an Inceptisol of Tunja with different coverages to the impact of simulated rainfall]. Ingeniería e Investigación 2009; 29(3): 86–91.
50. De Souza A, Fonseca D, Libório R, *et al*. Influence of riparian vegetation and forest structure on the water quality of rural low-order streams in SE Brazil. Forest Ecology and Management 2013; 298: 12–18. doi: 10.1016/j.foreco.2013.02.022.
51. Singh S, Mishra A. Spatiotemporal analysis of the effects of forest covers on stream water quality in Western Ghats of peninsular India. Journal of Hydrology 2014; 519: 214–224.
52. Gutiérrez Acevedo E, Cortés Pérez F, Gómez Albarrán N. Compost como inductor de la sucesión vegetal en un área afectada por minería a cielo abierto en la microcuenca del río La Vega, Tunja, Boyacá (Spanish) [Compost as an inducer of plant succession in an area affected by open-pit mining in the micro-watershed of La Vega river, Tunja, Boyacá]. Colombia Forestal 2015; 18(2): 241–254.
53. Lei H, Peng Z, Yigang H, Yang, Z. Vegetation and soil restoration in refuse dumps from open pit coal mines. Ecological Engineering 2016; 94: 638–646.
54. Nepstad D, Bezerra T, Tepper D, *et al*. Cómo abordar los motores agrícolas de la deforestación en Colombia (Spanish) [Addressing the agricultural driving force of deforestation in Colombia]. San Francisco: Earth Inovation Institute; 2013. p. 107.
55. Armenteras D, Rodríguez Erazo N. Dinámicas y causas de deforestación en bosques de Latino América: Una revisión desde 1990 (Spanish) [Dynamics and causes of deforestation in Latin American forests: A review since 1990]. Colombia Forestal 2014; 17(2): 233–246.
56. Karevia P, Tallis H, Ricketts T, *et al*. Natural capital, theory and practice of mapping ecosystem services. New York: Oxford University Press; 2011. p. 392.
57. Quin Y, Gartner T, Minnemeyer S, *et al*. Global forest watch water metadata document. Washington: World Resources Institute; 2016. p. 36.
58. Borkey P, Cassar A, Meadors L, *et al*. Freshwater ecosystem services. In: Ecosystems and human well-being: Policy responses. Washington: Island Press; 2005. p. 215–252.
59. Decree 953. Ministerio de Ambiente y Desarrollo Sostenible 17 de Mayo de 2013 (Spanish) [Ministry of Environment and Sustainable Development May 17, 2013].
60. Blanco J, Wunder S, Navarrete F. La Experiencia Colombiana en Esquemas de Pagos por Servicios Ambientales (Spanish) [The Colombian experience in payments for environmental services schemes]. In: Ortega S (editor). Reconocimiento de los servicios ambientales: Una oportunidad para la gestión de los recursos naturales en Colombia. Bogotá: Minambiente, UASPNN, WWF, CI, TNC; 2008. p. 109–170.
61. Karlen D, Ditzler C, Andrews S. Soil quality: Why and how? Geoderma 2003; 114: 145–156.
62. Food and Agriculture Organization (FAO). Soil is a non-renewable resource. Rome: FAO. 2015. Available from: http://www.fao.org/3/a-i4373s.pdf.