Land-cover composition, water resources and land management in the watersheds of the Luquillo Mountains, northeastern Puerto Rico

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Summary: *An important element of the wise use of water-related ecosystem services provided by El Yunque National Forest, located in the Luquillo Mountains in northeastern Puerto Rico, is the facilitation of a clear understanding about the composition of land cover and its relation to water resources at different scales of analysis, management, and decision making. In this study we present the results of a site-specific analysis that identify and quantify the land cover of the watersheds of the main rivers that have their headwaters in El Yunque National Forest and relate land-cover data to three water-quality parameters. Based on the results, we identify watersheds where opportunities are present to engage in immediate actions to sustain water-related ecosystem services.To promote and facilitate knowledge and understanding about land-cover dynamics, watershed-related processes, and water conditions, we present our findings and analyses in a way that can be communicated to a broad range of stakeholders, highlighting the implications of land cover to ecosystem processes and water resources.*

Key Words
WATER RESOURCES ECOSYSTEM SERVICES PUERTO RICO

Introduction

The northeastern region of the Caribbean island of Puerto Rico is dominated by views of the Luquillo Mountains. Most of the landscape of the Luquillo Mountains is composed of El Yunque National Forest (El Yunque)—conterminous with the Luquillo Experimental Forest—the largest protected area in Puerto Rico which contains the forested headwaters of rivers that are the main sources of water for the region (Ortiz-Zayas *et al*., 2010; Harris *et al*., 2012). Recently, the El Yunque Hydrology, Environment, Life and Policy initiative (Ortiz Zayas & Scatena, 2004) and a study about El Yunque's ecosystem services (López-Marrero & Hermansen-Báez, 2011a) stated the importance of identifying key issues and opportunities to promote actions that support the water-related ecosystem services provided by El Yunque. More specifically, they stressed the need for landscape assessments that can provide information for a broad audience about the relationships between land cover, land-cover changes, and the effects of diverse land covers upon the water resources provided by El Yunque. Such type of information can be used as a starting point to exchange information, promote learning, and initiate collaborative projects whose actions move forward conservation, wise use, and the management of El Yunque water resources and the lands that sustain them.

To promote and facilitate knowledge and understanding about land-cover dynamics, water-related processes and water conditions, we present the results of a site-specific analysis that presents land-cover information of the watersheds with their headwaters in El Yunque. More specifically, we identify and quantify the land cover of the watersheds that have their headwaters in El Yunque, both at the watershed level and at a five-metre buffer zone along main channels (i.e., the riparian zone), compare and analyze land-cover composition within and between watersheds (both at the watershed and riparian zone levels), relate land-cover data and basic water-quality parameters, and identify watersheds where opportunities are present to engage in immediate actions to sustain water-related ecosystem services. Findings of our analyses are presented in a way that can be communicated to a broad range of stakeholders, highlighting the implications of human activities and land management to ecosystem processes and water resources.

Water and land-cover dynamics: an overview

Different land-cover types have a variety of effects on water resources and water-related processes; they can contribute to decreased water quality, create unsafe living conditions (e.g., occurrence of floods and landslides), and negatively affect aquatic fauna,which in turn alters recreation and consumption potential of water resources (Table 1). These interactions of land-cover types and water resources occur at different spatial scales, including the watershed and riparian zone levels. A watershed is the unit within a landscape that collects, moves, and drains precipitation and surface flows toward a body of water or water course (e.g., stream, river, lake). Thus, a watershed delineates or defines the land that contributes drainage and water flow; therefore it is often defined as the catchment area to a particular body of water.Within watersheds or catchment areas, the riparian zones are the part of the land that is immediately most adjacent to a body of freshwater. Usually riparian zones tend to be corridors in the landscape that demark or outline where the land ends and where the flowing water or bodies of freshwater begin. In a nested hierarchy, the riparian zone of a body of water is contained within, and is affected by, that body of water's catchment area or watershed.

The areal extent of land defined by a watershed controls water recharge capacity, affects water conditions, and is the unit ultimately linked to efficient management and conservation of the resources contained therein (Hunsaker & Levine, 1995; Cid & Pouyat, 2013). It is well known, for instance, that watersheds with exposed or bare soils and urban/built-up areas deliver large quantities of sediments, develop erosion gullies, and create increased peak flow conditions that lead to increased flash floods (Thorm *et al.,* 2001; Ramos-Scharrón & MacDonald, 2007; Cashman *et al.,* 2010). The impervious surfaces and roads associated with urban/built-up land deliver additional sediments that

TABLE 1: Examples of effects of different land covers on water resources and ecosystem processes

Land cover	Effects on water resources and ecosystem processes	Source
Forest	Closed-canopy forests intercept almost half of incident rainfall and buffer changes in rain pH. The eventual slow release of intercepted rain decreases erosion and maximizes recharge of surface and subsurface water reservoirs. Low water temperatures and highest dissolved oxygen values are retained.Land use that converts to non-forest covers in tropical lowlands alters climate and water resources in adjacent mountain ecosystems.	Heartsill Scalley *et al*., 2007; Lawton *et al.,* 2001
Shrub	Early successional shrubby vegetation offers similar benefits to closed-canopy forests, but with decreased interception, retention, and recharge capacity compared to forest cover with more layers of vegetation. Shrubland has a middle range of water temperatures and dissolved oxygen values in relation to pasture and forest.	Heartsill Scalley & Aide, 2003
Wetland	Forested and non-forested wetlands can intercept and retain high amounts of water in their surface and subsurface soils. They serve as water reservoirs, dissipate water flow energy, and retain particles in their saturated soils.	Lugo *et al*., 1990
Pasture	Pasture and grasses, including agricultural lands, do not intercept and retain much rainfall, and contribute to overland flows and increases in water temperature. Conversion of forest to pastures in adjacent coastal plains also contributes altered rainfall regimes in mountain systems.	van der Molen *et al*., 2011; Ray *et al.,* 2006; Beaulac & Reckhow, 1982
Urban/ built-up	Land with impervious surfaces has no water-holding capacity; therefore it is more prone to flash flood events. Urban/built-up land contributes to increases in water temperature and low dissolved oxygen values. Increased temperature impacts of land-cover and land-use changes in tropical islands under conditions of global climate change alters local climate and affects water-related resources.	Comarazamy *et al.,* 2013; Thorm *et al*., 2001; Beaulac & Reckhow, 1982
Bare ground	Exposed or bare soils are highly erodible and have limited water-holding capacity. They are most prone to form erosion gullies and landslides, and they contribute to increases in water temperature and decreases in water quality.	Ramos-Scharrón & MacDonald, 2007

would otherwise have settled and accumulated in watersheds and riparian zones with vegetated land cover (Thorm *et al*., 2001). In the case of forest cover, this cover type decreases the amount and speed of overland water flow, promoting infiltration and soil water recharge, which contributes to the maintenance of high water quality and recharge.

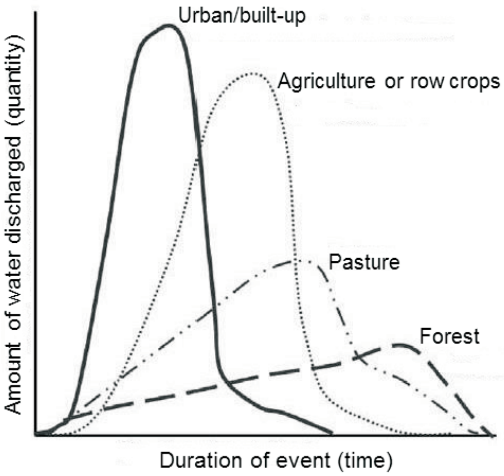

FIGURE 1: Schematic of duration and amount of water discharge in relation to catchment (watershed) and land cover (adapted from Beaulac & Reckhow, 1982)

In addition, the contribution of plant materials such as leaves, woody debris, fruits, and flowers into streams surrounded with forest cover are important resources for the aquatic organisms that depend mainly on these terrestrially produced sources of energy (Tabacchi *et al*., 1998; Cross *et al*., 2008). Changes in land cover such as forest conversion to bare soil and paved surfaces are drastic modifiers of natural peak flows and sediment pulses (Figure 1). When vegetated land cover is changed to impervious surfaces, overland water flow increases. Consequently, soil water-holding and recharge capacity is decreased with impervious surfaces, leading to decreased water availability during non-storm flow conditions.

Another aspect of land-cover change is landscape fragmentation.When land-cover types within a landscape are represented by relatively small and disconnected patches or extents of land, the distribution and configuration of land cover can override the influence and characteristics of the land-cover type. Fragmented patches of forest within watersheds and riparian areas will, for example, have a different influence on water conditions than large extents of unfragmented forest or vegetated land cover. Changes in watershed and riparian zone land cover, along with fragmentation, affect the physical structure and ecosystem processes of river systems, particularly headwaters (Hunsaker & Levine, 1995; Heartsill Scalley & Aide, 2003; Gomi *et al*., 2002). Fragmented riparian forest cover over stream channels, for example, affects water temperature regimes and vegetation inputs to stream systems. Riparian forest cover fragmentation consequently alters ecosystem processing and habitat quality for migrating stream fauna by increasing water temperatures and decreasing the contributions of terrestrial vegetation to the stream and river systems (Sedell *et al*., 1990; Kikkert *et al*., 2009; Lorion & Kennedy, 2009). Due to the cumulative and connected nature of hydrologic systems, alterations in land cover and disconnection occurring in headwater catchments are reflected downstream and upstream at watershed scales (Allan, 2004; Freeman *et al*., 2007; McCluney *et al*., 2014; Pringle,1997; 2001).

Changes in watershed land cover influence water-related processes and functions of the riparian zones. Changes from forest to agriculture, to pasture, or to urban/built-up areas at the watershed level increase water and sediment inputs and change their delivery dynamics into riparian zones. These changes in land cover alter the capacity of riparian zones to act as sinks and filters for terrestrial areas of the surrounding waterbodies. In addition, land-cover change in the watersheds may occur in the actual riparian zones, which would then directly modify the physical conditions and channel structures of streams and rivers. Vegetated riparian zones filter materials that may reach the water channel through overland flow paths, accumulate sediments and particles, and also slow the velocity of water flowing into the channel. At the same time, the forested or otherwise vegetated riparian zones serve as local-scale controls on water temperature by providing shade. Shaded stream channels have low water temperatures,which are associated with high oxygen-retention capacity of the water; these conditions in turn increase a river system's ability to sustain aquatic life, which is important for recreation and subsistence fisheries. Moreover, land-cover condition in watersheds and riparian areas has an immediate impact on inputs of materials, sediments loads, and peak flows, while ultimately affecting general water conditions and associated freshwater resources.

These apparently simple contributions of vegetated land cover to shade, physical structure, aquatic fauna food sources, and sediment loads make all the difference to the maintenance of water resources. The quality of freshwater resources and their ecosystems services, which are essential to human well-being, are consequently linked to land-cover changes at the watershed and riparian zone scales.

Study area

The study area is located in northeastern Puerto Rico and includes seven of the eight watersheds that have their headwaters in El Yunque: those of the Río Espíritu Santo, Río Mameyes, Río Sabana, Río Pitahaya, Río Fajardo, Río Santiago, and Río Blanco (Figure 2). Although the Río Grande de Loíza has a small fraction of its headwater tributaries originating in El Yunque, most of its headwaters are outside the study area. Therefore, for the purposes of this study, the Río Grande de Loíza was not included, as it merits its own independent analysis.

The area of the seven watersheds covers 30,870ha in total. These watersheds occur in five of the eight municipalities in eastern Puerto Rico that have a portion of El Yunque within their territorial boundaries.The watersheds of the Sabana and Pitahaya rivers occur within the territorial boundaries of the municipality of Luquillo, the watersheds of the Santiago and Blanco rivers are located within the boundaries of Naguabo, and the watershed of the Espíritu Santo River is located within the boundaries of Río Grande. Two watersheds—those of the Mameyes and Fajardo rivers—occur within the boundaries of multiple municipalities. In the case of the Río Mameyes watershed, it is located in the municipalities of Río Grande and Luquillo. The watershed of the Río Fajardo occurs within the boundaries of two municipalities: Fajardo and Ceiba (Figure 2).

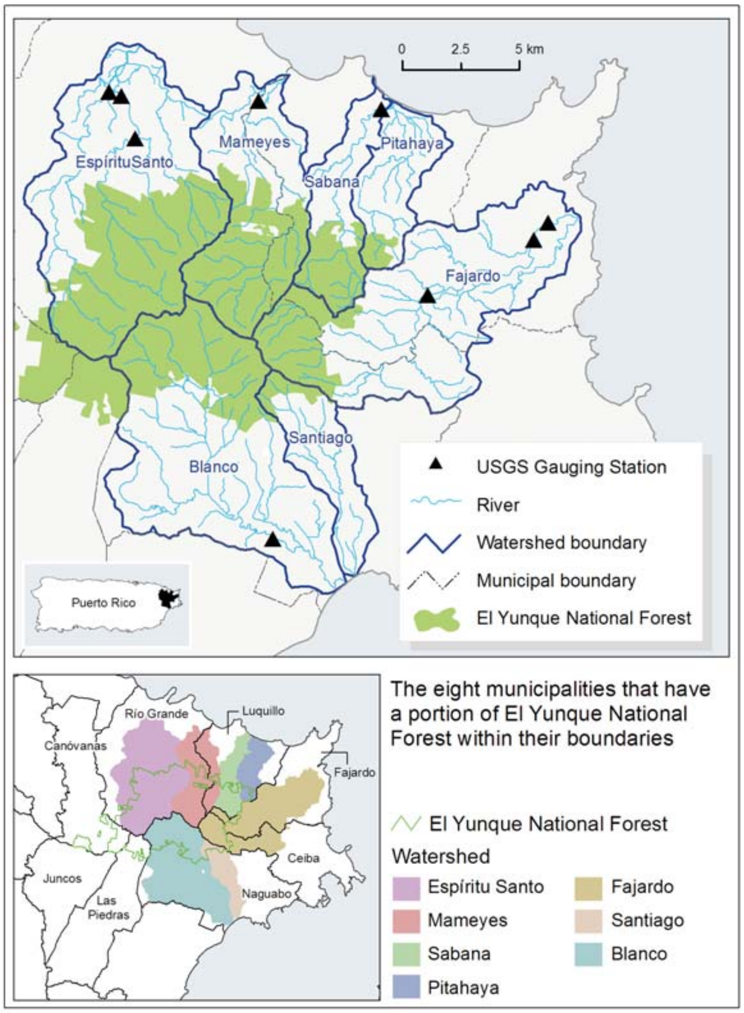

FIGURE 2: Study area in northeastern Puerto Rico (colour figure available on the article's digital version)

El Yunque is located in the Luquillo Mountains and spans an elevation range from the foothills to 1,075m above sea level. Mean air temperature ranges from as high as 27ºC at the base of the mountains to as low as 17ºC at the peaks (Harris *et al*., 2012). Mean rainfall is approximately 3,879mm per year, ranging from 1,500mm per year in coastal areas to more than 5,000mm per year at the highest peaks (García-Martinó *et al*., 1996). Periods without rain in the Luquillo Mountains occur in a scale of days and weeks, with the driest periods occurring January to March (Heartsill Scalley *et al*., 2007). Rainfall in this region consists of a high frequency of low-intensity showers, with periodic high-intensity events (Holwerda *et al*., 2006). The seasonal rainfall trends recently observed in the study area are similar to those of the Caribbean region with drier periods having further decreased precipitation and wetter periods having more high-intensity rainfall events (Taylor *et al*., 2012).

The rivers that drain El Yunque have steep gradients with boulder and bedrock channels (Ahmad *et al*., 1993). The combination of a high rainfall regime with steep and abrupt elevation changes is conducive to flash floods, landslides, and high overland flow events (Ortiz Zayas & Scatena, 2004; Larsen *et al*., 1999). In landscapes such as these, decreases in vegetated or forested land cover and increases in denuded and impermeable land cover exacerbate storm flows and flash floods (Pringle & Scatena, 1999; Roa-García *et al*., 2011).The main soil types in the study area are coarse textured soil derived from quartz-diorite and a highly weathered and finely textured soil originating from volcaniclastic sediments of andesitic composition (Renken *et al*., 2002; Huffacker, 2002).

The streams and rivers of El Yunque have been determined to be among the cleanest on the island, and water conditions (such as quality for consumption) have been described as high (Santos-Román *et al*., 2003). The rivers of El Yunque are the main water supply for more than 20 percent of the island's population (Scatena & Johnson, 2001). Even though the region around El Yunque is the wettest in Puerto Rico, current water demands from the population in the surrounding municipalities are not being met. Intermittent or minimal water delivery services are a common occurrence in the rural mountain areas, due, in part, to limitations of the water delivery systems (Minnigh & Ramírez Toro, 2001; Minnigh *et al*., 2005). Waterflow in the river systems of the study area have high diversion rates for residential, recreational, and tourism industry uses. When diversion rates are consistently high and do not account for seasonal fluctuations, these can compromise the needs of the environment and the ecosystem services they provide. It was calculated that the mean daily percentage of water from El Yunque's river systems that is diverted in the region before reaching the ocean has increased from 54 percent in the 1990s to 70 percent in 2004 (Naumann, 1994; Crook *et al*., 2007).

In terms of population dynamics, a relatively high rate of population growth had characterized the northeastern region of Puerto Rico. Between 2000 and 2010, for example, rates of population change were higher for the region composed of the eight municipalities that contain El Yunque than for the whole island of Puerto Rico (JPPR, 2015). Compared to the island as a whole, which had negative population growth (-2.2 percent), the region experienced a population increase of 3.5 percent. In the region, only two municipalities had population decreases, while the remaining six experienced increases (Table 2).The municipalities of Naguabo and Las Piedras had the highest increase (approximately 12 percent), followed by Juncos and Canóvanas with about a 10 percent increase each.

The northeastern region of Puerto Rico has experienced a high degree of urban/built-up expansion during the last decades (Ramos-González, 2001; López-Marrero, 2003; Lugo *et al*., 2004; Ramos-Scharrón *et al*., 2015). Table 2 shows in the eight municipalities that have a portion of El Yunque lands within their boundaries, urban/built-up areas increased by 21 percent between 1998 and 2010 (López-Marrero & Hermansen-Báez, 2011b). Rates of urban/built-up expansion were, in fact, higher than

TABLE 2: Total population and urban/built-up land cover for each municipality

	Total population*			Urban/built-up **	
Municipality	2000	2010	% change	Area (ha) 2010	% change 1998-2010
Canóvanas	43,335	47,648	10	281.8	31
Ceiba	18,004	13,631	-24.3	52.2	8
Fajardo	40,712	36,993	-9.1	113.8	10
Juncos	36,452	40,290	10.5	250.6	36
Las Piedras	34,485	38,675	12.2	184.6	23
Luquillo	19,817	20,068	1.3	87.4	17
Naguabo	23,753	26,720	12.5	113.4	20
Río Grande	52,362	54,304	3.7	251.0	21
Region	268,920	278,329	3.5	1,334.8	21

*SOURCES NOTES: * JPPR, 2015 ** López-Marrero & Hermansen-Báez, 2011b*

rates of population change for similar time periods. Natural resources (e.g., beaches, mangroves, forests, streams, rivers) have served as focal points not only for local urbanization and private housing, but for tourism and associated activities, particularly in the municipalities of Río Grande, Luquillo, and Fajardo where land use devoted to these activities also has increased during past decades. Also, the relatively close proximity of some municipalities to San Juan, Puerto Rico's capital (approximately 45km), and road infrastructure that has been built during the last decade make it easier for people to live in these municipalities and commute to work in the San Juan metropolitan area. High rates of urban/built-up expansion and an influx in population bring a high demand for water for domestic, recreational, tourism, and commercial consumption.

Methods

Development and analysis of land-cover data

Land-cover data were created by the on-screen digitization of 0.3m resolution aerial photographs taken in 2010. The digitization was conducted at a (screen) scale of 1:8,000, using a minimum mapping unit of 2,500m^2. Seven land-cover categories were used for the classification of the aerial photographs (Table 3). Land-cover data were calculated at the watershed level by delineating the catchment areas of selected United States Geological Survey [USGS] gauging stations representing the seven major river systems that have their headwaters in El Yunque, and for a five-metre buffer zone (what we refer to as the riparian zone) for stream or river channels identified as perennial on topographic maps at a 1:20,000 scale. For this study, a boundary around perennial channels of five metres in width was chosen because this is currently the space that should remain vegetated and protected for public access according to the Puerto Rico Water Law (Law 136 of 1976).

TABLE 3: Descriptions of land-cover categories used in aerial photograph classification

Land-cover category	Description
Forest	Open and closed-canopy forest (>80% tree cover)
Shrub	Early successional shrubby vegetation (>80% vegetation cover)
Wetland	Forested and non-forested wetlands (>80% vegetation cover)
Pasture	Active and non-active pasture and grasses, which can include agricultural lands (up to 20% tree cover, shrubs, or isolated housing)
Urban/built-up	Impervious surface (>80% cover), including low- and high-density built-up land
Bare ground	Exposed soil
Water	Water bodies

Land-cover data were developed and analyzed using the Geographic Information System Software ArcMap 10.0 (ESRI, 2010).

The extent of three protected areas (El Yunque National Forest, the Río Espíritu Santo Natural Reserve, and the Humacao Pterocarpus Natural Reserve) was used to identify the extent of protected and non-protected areas within the watersheds. This allowed us to compare and analyze the status of protected and non-protected forest among watersheds and in riparian zones. In addition, urban/built-up land-cover data from 1998 (López-Marrero & Hermansen-Báez, 2001b) were used to calculate urban/built-up land cover for each watershed. These data were compared to the urban land-cover data from 2010 to calculate urban increase at the watershed level. These two pieces of information, protected and non-protected forest and urban/built-up expansion, are presented and discussed in terms of potential implications regarding water-related ecosystem services.

Selection of water-quality parameter data

Water condition was defined by three parameters: temperature; specific conductance; and dissolved oxygen. These parameters were selected because of their common use in water-quality studies and their robust interpretation (http://water.usgs.gov/edu/dictionary.html). In addition, temperature, specific conductance, and dissolved oxygen are widely applicable to the measurement of water conditions for fauna habitat, ecosystem function, and recreational uses (Scatena, 2002; Swanson *et al*., 2002).These parameters are also consistently measured in most of the gauging stations within the study area. A description of these parameters along with examples of potential effects on human activities and ecosystems are presented in Table 4.

The data for the water-quality parameters were obtained from nine gauging stations of the USGS National Water Information System Web database distributed within the study area (http://nwis.waterdata.usgs.gov/usa/nwis/qwdata) (Figure 2). The data were selected to include all dates from 2006 to 2010, for a total of 56 observations of the three

TABLE 4: Water-quality parameters used to relate to land-cover categories in watersheds of the Luquillo Mountains, Puerto Rico

Parameter	Interpretation	Examples of affected activities and processes*
Temperature (°C)	High stream water temperatures can cause changes in fauna abundance and composition as the oxygen retention ability of water decreases.	Decreases attractiveness for fishing, wading, swimming, passive recreation; also affects aquatic fauna.
Specific conductance (µS/cm, 25°C)	High values of conductance indicate high concentration of dissolved solids resulting from seasonal stream flow changes, erosion, agricultural run-off, or industrial inputs that alter water chemistry.	Decreased recreation and consumption potential; may affect taste and odor.
Dissolved oxygen (O_2mg/L)	Low values of dissolved oxygen in stream water affect ecosystem processes and the ability to sustain aquatic fauna.	Diminished ability to sustain aquatic fauna; alters stream ecosystem, fishing, and passive recreation.

*NOTE: * Adapted from Dissmeyer (2002) and water.usgs.gov/edu.*

parameters in the nine gauging stations. All of the data used were coded as satisfactory results by the USGS data-quality indicator code.

Analysis of land-cover and water-quality data

Nine USGS water-quality stations were identified within the watersheds of the study area (Figure 2). For each of the nine stations, a catchment area was delimited following drainage and contour lines to define its sub-watershed. Within each sub-watershed, a five-metre buffer zone was also delimited (i.e., the riparian zone).The percentage of each land-cover category was determined for each sub-watershed and its riparian zones. The water-quality parameters from the individual USGS stations and their associated percentages of land cover were used to conduct Pearson correlation analyses using SAS Version 9.4. The correlation analyses were conducted at both spatial scales: the sub-watershed and the riparian zone. Correlation analyses provide a simple way of displaying the relationships between river and stream conditions with their associated land cover, and thus are considered an effective first step in transmitting information and engaging efficient communication for management of watershed resources (Gergel *et al*., 2002).Water-quality parameter data for all three variables had normal distributions, and therefore no transformations were conducted.

Results

Land-cover composition

Forest was the most abundant land-cover type in the study area as a whole, covering 60.7 percent (Figure 3). Pasture was the second most dominant land-cover type (28.1 percent), followed by urban/built-up (5.9 percent) and shrubs (4.0 percent). The remaining land-cover categories consisted of less than 1.5 percent in total.

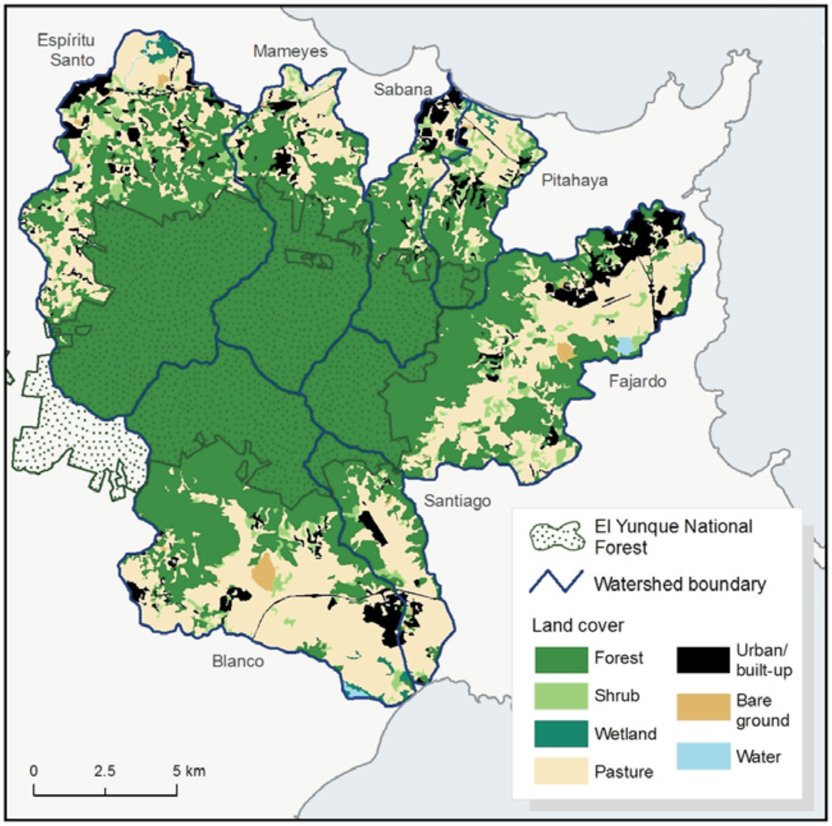

FIGURE 3: Land cover within the watersheds in 2010 (colour figure available on the article's digital version)

The composition of land cover was proportionally the same among the watersheds, with forest occupying the greatest amount of area, followed by pasture, urban/built-up, and shrubs. Only in one watershed, Pitahaya, was the extent of shrub cover slightly greater than urban/built-up cover. The Espíritu Santo and Fajardo watersheds had the most extensive forest cover (5,096ha and 3,537ha, respectively), while the Pitahaya and Santiago watersheds had the least (755ha and 791ha, respectively). In terms of percentages, however, the Mameyes and Sabana watersheds had the highest percentage of their land in forest cover (76.5 percent and 71.4 percent, respectively) (Table 5). Regarding pasture, this type of cover was most extensive in the Blanco and Fajardo watersheds (2,475ha and 2,213ha, respectively), but the Santiago watershed had the highest percentage of pasture cover (45 percent of its land). In terms of urban/built-up land cover, the Fajardo watershed had the most extensive cover (550ha), followed by the Espíritu Santo watershed (389ha). The Sabana watershed, however, had the highest percentage of urban/built-up cover (8.8 percent), followed by the Pitahaya and Fajardo watersheds (with 8 percent each).

TABLE 5: Total area and percentage of land covers for each watershed, 2010

Watershed	Total area (ha)	Land-cover category (% cover)						
		Forest	Shrub	Wetland	Pasture	Urban/ built-up	Bare ground	Water
Espíritu Santo	7,501	67.9	3.5	0.8	21.9	5.2	0.6	0.2
Mameyes	4,022	76.5	2.3	0	17.4	3.5	0.1	0.2
Sabana	1,878	71.4	3.4	0.2	15.8	8.8	0.2	0.1
Pitahaya	1,634	46.2	10.3	0.9	34.3	8.1	0.2	0.1
Fajardo	6,775	52.2	5.8	0	32.7	8.1	0.6	0.6
Santiago	1,765	44.8	3.6	0.3	44.5	6.5	0.4	0
Blanco	7,295	56.6	2.8	0.5	34.1	4.5	1.1	0.3

Riparian land-cover patterns were similar to those observed at the watershed scale, with the greatest percentage in forest cover, followed by pasture (Table 6).The exception was that the percentage of shrub land cover was greater than that of urban/built-up cover in riparian areas, the opposite of what was observed at the watershed scale (Table 5).The Sabana watershed had the greatest percentage of riparian zones in forest cover (84.4 percent) and the least amount of pasture (11.7 percent). In contrast, the Santiago watershed had the least amount of riparian zones in forest cover (33.8 percent) and the greatest amount of pasture (58.7 percent). Of all the watersheds in the study, the Pitahaya had the greatest percentage of urban/built-up cover and wetland cover in riparian zones.

Approximately 33 percent of the entire study area is under protection status; the remaining 67 percent is non-protected. Most of the protected lands in the study area are those of El Yunque National Forest (97.5 percent); the remaining 2.5 percent belong to two natural reserves, the Río Espíritu Santo Natural Reserve and the Humacao Pterocarpus Natural Reserve. Protection status varied among watersheds (Table 7, Figure 4). The Río Espíritu Santo watershed had the most extensive protected area (3,616ha), while the Río Mameyes watershed had the highest percentage of land under protection (52.7 percent). The Río Santiago watershed had the least area of protected lands (221ha), whereas the Río Pitahaya watershed had the smallest percentage of protection (10.6 percent).

The Espíritu Santo and Mameyes watersheds had the most extensive forest cover under protection (3,496ha and 2,115ha, respectively). These two watersheds also had the highest percentage of forest cover under protection, with approximately 69 percent of their total forest cover (Table 7, Figure 4). The Pitahaya and Santiago watersheds had the least forest area and percentage of their forest cover under protection (22.9 percent and 27.9 percent of protected forest, respectively).

Urban/built-up land cover increased by 227ha between 1998 and 2010 in the total area of the seven watersheds, which represents a 14.2 percent increase. Rates of

TABLE 6: Total area and percentage of land covers in five-meter riparian zones for each watershed, 2010

Watershed	Total area (ha)	Land-cover category (% cover)						
		Forest	Shrub	Wetland	Pasture	Urban/ built-up	Bare ground	Water
Espíritu Santo	104	61.9	4.0	1.4	26.4	2.4	0.1	3.9
Mameyes	60	71.7	1.9	0	20.9	2.7	0	2.8
Sabana	26	84.4	1.3	0	11.7	1.9	0	0.7
Pitahaya	29	42.6	7.8	5.8	37.4	5.7	0.5	0.3
Fajardo	100	48.1	10.2	0	38.7	1.5	0	1.4
Santiago	27	33.8	4.5	0.2	58.7	2.0	0.8	0
Blanco	97	50.4	3.0	0.3	43.2	2.2	0.9	0

urban/built-up land-cover increase varied among the watersheds (Table 7). The Sabana and Blanco watersheds had the highest percentage of increase in urban/built-up area (30.6 and 20.4 percent, respectively), whereas the Fajardo watershed had the lowest increase (5.9 percent).

Water-quality trends and relationships with land cover

Independent of land cover, the values for water temperature ($r = 0.48$, $P = 0.0002$) and specific conductivity ($r = 0.57$, $P < 0.0001$) tended to increase throughout the observed period. There was also a negative trend in dissolved oxygen values ($r = -0.39$, $P = 0.003$) throughout the five-year period.

All water-quality parameters were significantly correlated to various land-cover categories (Table 8). For the sub-watershed scale, the percentage of area in forest cover was negatively correlated to water temperature and specific conductance, while positively correlated to dissolved oxygen values. That is, temperature and specific conductance were lower, and dissolved oxygen higher, when a greater percentage of the watersheds were in forest cover, which is the desirable condition for high water-quality sites.

The land-cover categories of shrub, pasture, bare ground, and urban/built-up were all positively correlated to water temperatures. Higher values of water temperatures were observed to occur in all non-forest land covers (shrub, pasture, bare ground, and urban/built-up).These are land covers that do not form canopies over riparian areas and thus yield higher values for water temperatures. The percentages of the area in pasture, bare ground, and urban/built-up cover were also positively correlated to water specific conductance, and negatively correlated to dissolved oxygen. The strongest correlations (higher correlation coefficients) were observed between increased urban/built-up cover

TABLE 7: Percent of area protected, forest cover, protected forest, urban/built-up cover, and urban/built-up change for each watershed

Watershed	% Protected area	% Forest (2010)	% Protected forest (2010)	% Urban/ built-up (2010)	% Urban/built-up change (1998 to 2010)
Espíritu Santo	48.2	67.9	68.6	5.2	15.8
Mameyes	52.7	76.5	68.7	3.5	11
Sabana	41.6	71.4	58.1	8.8	30.6
Pitahaya	10.6	46.2	22.9	8.1	17.9
Fajardo	16.9	52.2	32.3	8.1	5.9
Santiago	12.5	44.8	27.9	6.5	14.3
Blanco	30.7	56.6	50.8	4.5	20.4

TABLE 8: Pearson correlation coefficient (r) and significance level (P) for sub-watershed and riparian zones: land-cover vs water-quality parameters

	Water-quality parameter					
	Temperature		Conductivity		Dissolved oxygen	
Watershed level	*r*	P	*r*	P	*r*	P
Forest	-0.48	0.000	-0.39	0.003	0.34	0.01
Shrub	0.33	0.012	*NS*		*NS*	
Pasture	0.43	0.001	0.34	0.01	-0.32	0.02
Bare ground	0.38	0.004	0.54	<0.000	-0.66	<0.000
Urban/built-up	0.55	<0.000	0.61	<0.000	-0.36	0.01
Riparian zone						
Forest	-0.40	0.002	-0.32	0.015	0.31	0.021
Shrub	0.26	0.055	*NS*		*NS*	
Pasture	0.41	0.002	0.37	0.005	-0.35	0.008
Bare ground	-	-	-	-	-	-
Urban/built-up	0.45	<0.000	0.61	<0.000	-0.24	0.07

NOTES: n=56
non-significant values denoted as NS
no data denoted by -

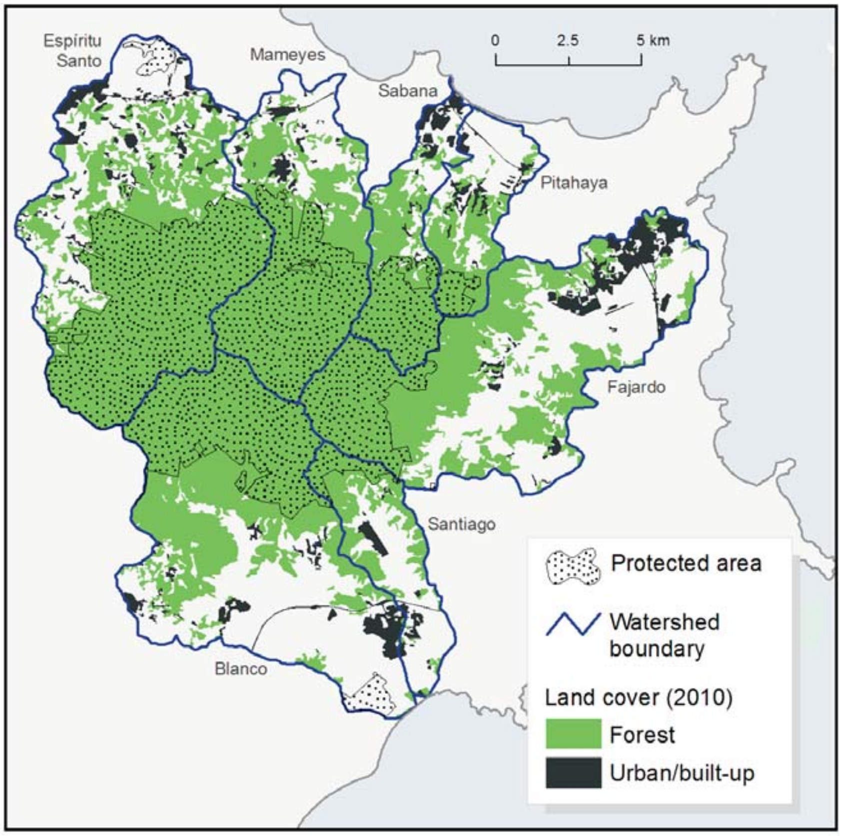

FIGURE 4: Situation of each watershed in terms of forest cover, urban/built-up lands, and protection status (colour figure available on the article's digital version)

and higher water temperature and specific conductance, and between bare ground and specific conductance and decreased dissolved oxygen (Table 8).

Following the same patterns as the sub-watershed scale, riparian zones with a greater percentage of forest land cover were negatively correlated to water temperatures and specific conductance, while positively correlated to dissolved oxygen. As the percentage of urban/built-up cover of riparian areas increased, so did water temperature and specific conductance, while dissolved oxygen values decreased (Table 8). In riparian zones, the strongest correlations were between increased urban/built-up cover and higher water temperature and specific conductance. Increased pasture land cover in riparian areas had the strongest negative correlation to dissolved oxygen values.

Discussion

The analysis demonstrated a relationship between water conditions and land-cover composition. The relationships were more evident regarding urban/built-up and forest land covers. In the study area, both at the watershed and riparian scales, an increase in the percentage of urban/built-up land cover meant an increase in water temperatures and specific conductance, both undesirable water conditions for various uses and services. A greater percentage of forest cover, in contrast, was associated with desirable water-quality conditions as identified by low water temperature, low specific conductance, and high dissolved oxygen values. These are suitable conditions for ecosystem processes, consumption of resources, fishing, and recreation. Consequently, the combination of forest and urban/built-up land-cover dynamics along with the protection of certain areas at the watershed level in the study area has implications for water-related ecosystem services. The current situation of each watershed in terms of these variables is summarized in Figure 4 and Table 7; some implications of these conditions are discussed next.

Urban/built-up land cover occupied less than 10 percent of the total study area. Even at this relatively low percentage, urban/built-up values were clearly related to low water-quality parameters. Between 1998 and 2010, moreover, all watersheds had an increase in the percentage of urban/built-up land, with four of the watersheds having increases of more than 15 percent. The distribution of urban/built-up land cover generally occurred in the foothills, lowlands, and coastal valleys of the watersheds, a situation that can disrupt landscape and hydrological connectivity (i.e., from mountainous to coastal areas), increase forest fragmentation, and influence processes that can negatively affect water conditions, use, and consumption. Hydrological and ecological connectivity is necessary between the headwaters and the downstream coastal waters of a river system. These connections contribute to the function of river systems by allowing the exchange of mass, energy, and organisms within a watershed system (Pringle, 1997; Nadeau & Rains, 2007). Interactions between river channels and floodplains, such as flood waters and sediment movement events, are affected by urban/built-up infrastructure in the lowland coastal valleys, which in turn also interrupts and diminishes the preserving effects of the protected forested headwaters on water quality.

In terms of forested lands, the percentage of forest cover, protected area, and protected forest varied considerably in the studied watersheds (Figure 4, Table 7). Although the percentage of forest cover was relatively high in all watersheds (>44.8 percent), the percentage of protected forest had more variation, in some cases being less than 25 percent of the forested areas. In fact, protection status also varied considerably, with some watersheds having about 50 percent of their area under protection and others with less than 15 percent of areas protected. Protected areas with vegetated cover contribute to sustain water-related ecosystem services in the region.While the establishment of protected areas is an often-used mechanism for the support of forest ecosystem services in Puerto Rico (including the study area), sometimes the passive status of protection designation does not guarantee the provision of ecosystem services, in this case, those provided by the forests within and around El Yunque. Different stakeholders, for instance, have pointed out that human activity in forested areas within and around El Yunque—including inadequate waste disposal, forest overuse, species introductions and removals, and the use of all-terrain vehicles—can affect the delivery of water-related ecosystem services specifically, and forest ecosystem services more generally (López-Marrero & Hermansen-Báez, 2011a). Consequently, the establishment of protected areas should be accompanied by other mechanisms to ensure the conservation and wise use of forests and their ecosystem services.

In addition to the establishment of protected areas as a mechanism for the conservation and wise use of forests and their ecosystem services, other mechanisms can be explored to promote the same. The conservation of privately owned lands—specifically landowner incentives for forest conservation—is one mechanism that El Yunque's administration has identified as having the potential to maintain and increase forest cover around El Yunque (López-Marrero & Meyn, 2010). For this type of initiative to be implemented and to succeed in the study area, there is a need to provide information about existing conservation programmes and associated types of incentives. Moreover, some obstacles need to be overcome, including, for example, the lack of confidence and distrust that owners have in governmental agencies and institutions associated with these types of programmes, and resolving land tenure issues and joint inheritances that inhibit participating in these programmes even if landowners are willing to do so (López-Marrero & Meyn, 2010).

Land-use planning and regional land-use regulations are mechanisms that have been used in the study area as conservation tools to protect forested areas and guide different land-use development, particularly urban expansion around El Yunque National Forest (Lugo *et al*., 2000; Lugo *et al*., 2004). In 1983, a regional zoning regulation was implemented by the Puerto Rico Planning Board for the eight municipalities that have El Yunque lands within their boundaries. The main objective of the regulation was to limit urban expansion around El Yunque and minimize its effects on the forest. Today, and according to the Autonomous Municipalities Act (Law 81 of 1991), each municipality should develop and implement a land-use plan. Of the eight municipalities that contain El Yunque, three have developed their autonomous land-use plans, while the remaining five are in the process of developing them. Despite the existence of this mechanism (at the regional and municipality levels), different studies have shown the expansion of urban/built-up land cover in zoning districts where urban uses were not intended (López-Marrero & Hermansen-Báez, 2011c; Lugo *et al*., 2004). Due to poor enforcement, variations, and exemptions granted from land-use regulations, high percentages of the urban expansion that have occurred over the past 25 years (over 70 percent) occurred in non-urban zoning districts, such as agricultural and forest zones. Consequently, the implementation of land-use plans and regulations is, however, critical; their development alone is insufficient.

An additional factor that has to be considered, specifically as related to land-use planning at the municipal level, is the mismatch between political boundaries (such as those delimiting different municipalities) and natural boundaries (such as those delimiting watersheds). The extension of the terrain of a watershed area into different political units often precludes the development of effective land-use planning (Kingsford *et al*., 1998). For example, the communication of announcements of land-use plans and public hearings on infrastructure development and zonation changes are usually conducted at the scale of communities, wards, and municipalities. There is no requirement to share this information throughout the natural-resource containing unit, such as the watershed, where implementation of the proposed plans will have their effects. A planning focus from the perspective of watersheds as management units needs to be developed to ensure provision of water-related ecosystem services. For the benefit of water-related resources and ecosystems, both management and regulation actions must be defined at the scale of the watershed and should include all constituents and stakeholders as defined by the watershed (Kingsford *et al*., 1998). In the study area, two watersheds, the one for the Río Fajardo and the other for the Río Mameyes, occur within the boundaries of two municipalities, a situation that complicates land-use planning and implementation. Due to the potential problems that can arise because of the mismatches between scales and units of management, the development and implementation of comprehensive, integrated, and updated land-use assessments and plans have been identified as priority actions for ensuring the continued provision of El Yunque's ecosystem services, including those related to water (López-Marrero & Hermansen-Báez, 2011a).

Current landscape composition presents both management opportunities and limitations to sustaining water-related ecosystem services. Watersheds with extensive mountainous forest cover, high percentages of forests under protection, low amounts of urban/built-up cover, and low increases of urban/built-up areas have the most suitable conditions for water quality and water-related ecosystem services (Table 1, Table 4). In the study area, the Río Mameyes and the Río Espíritu Santo watersheds have such characteristics; they are among the ones with the most extensive forest cover (and the highest percentages of land in forest cover), the highest amounts and percentages of forest cover under protection status, and the lowest percentages of urban/built-up land and urban/built-up land-cover expansion (Figure 4, Table 7). In the study area, the Río Mameyes is the only remaining river that does not contain a dam for water extraction and therefore is an important component of the sustained free-flowing dynamics of the migrating aquatic fauna of El Yunque, while also contributing to regional species habitat (March *et al*., 2003; Pringle, 1997; 2001). In spite of its high amount and percentage of forest land cover and protection status, the Río Mameyes riparian zone had the second largest percentage of urban/built-up area. Riparian zones with high amounts of urban/built-up land cover may contribute to decrease the quality of water ecosystem services and require continuous management actions, such as the control of run-off, sediments, and the maintenance of built-up infrastructure. In this case, promoting actions that limit the negative effects of urban/built-up land cover in the riparian zones and emphasizing the importance of forest and other vegetated covers in these zones would complement the conditions at the watershed level. In addition, concentrating urban/built-up infrastructure of urban areas in the lowland and coastal regions contributes to effective watershed management (Cashman *et al.*, 2010). Actions like these can be taken at different levels (e.g., municipality, community), but they are also possible at other levels, such as the individual, private land owner, level.

There are other watersheds that do not have the optimum conditions for water resources, yet they present opportunities for improving conditions to sustain water-related ecosystem services; for example, the watersheds of the Pitahaya and Blanco rivers. The Pitahaya watershed is among the ones with the least amount of forest cover, the smallest percentage of forest cover, and the lowest amount of protected forest area (Figure 4, Table 7). At the same time, it is among the watersheds whose percentage of urban/built-up land cover (both at the watershed and the riparian zone levels) and urban/built-up expansion are the highest. The Pitahaya watershed also contains large expanses of unprotected land (pastures, shrubs, forest) along main regional roads, which if unchecked, could lead to poorly planned land-cover changes to built-up/urban cover (Gould *et al*., 2008; Trejo-Torres *et al*., 2014). If no actions are taken in this watershed, decreased water conditions due to potential increases in sedimentation, run-off, water temperature, and decreased dissolved oxygen would lead to a loss of water-related ecosystem services and to the potential negative effects to the near shore environments and local fisheries associated with the Pitahaya River ecosystem. Despite these potentially unfavourable conditions for water quality and water-related ecosystem services, there are opportunities for protection designation in the coastal areas of these watersheds. For the Pitahaya and Sabana watersheds, protection in the coastal sections will be favourable for water condition and also favour coastal-mountain connectivity; which in turn supports other ecosystem processes. The proposed North East Corridor Reserve and the Greater North East Region Protected Area, if designated and effectively implemented, would provide protection from unplanned urban/built-up expansion in the northern coastal regions of the study area (DNER, 2010; GELAPR, 2013).

The Río Blanco watershed has both suitable and unsuitable conditions to support water-related ecosystem services. After the Río Espíritu Santo watershed, it is the watershed with the second most abundant amount of forest cover and half of these forests are under protection status. These are desirable conditions for water-related ecosystem services. In terms of urban/built-up land cover, however, the watershed is among those with the highest amounts of urban/built-up areas and it has the second highest percentage change in urban/built-up increase between 1998 and 2010. The southern part of El Yunque, where the Río Blanco watershed is located, is not as urbanized as areas north and northeast of the forest (López-Marrero & Hermansen-Báez, 2011b), thus presenting an opportunity to proactively plan for projects that can protect El Yunque and its water-related services. For example, forest corridors can be maintained across the landscape—from the mountains to the coast—while vegetated land cover is still connected and open space is available. Such projects should to be developed and implemented considering the inputs of different stakeholders to be an effective component of water-related ecosystem services management.

Concluding Remarks

The purpose of the landscape assessment presented in this study was quantifying land-cover composition at the watershed and riparian-zone levels, and correlating this information to water-quality parameters. The analysis showed a relationship between land-cover composition and water condition, especially regarding urban/built-up cover and forest land cover. Providing information to different stakeholders about land-cover composition and its implications in terms of water conditions is a first step to start a dialogue to develop initiatives and actions to support water-related ecosystem services. This type of information is also valuable for the development of adaptable management practices that integrate urban/built-up and forest land within watersheds (Antrop *et al.,* 2013). Such information needs to be accessible and effectively transferred to a wide range of stakeholders, and it needs to include different units or scales of actions and stakeholder involvement (e.g., individual level, riparian zone, community level, watershed level, municipal level). Stressing the importance of different land covers on water condition—specifically, the role of land with vegetated cover—along with the associated benefits of maintaining and increasing forested and other vegetated land covers in order to sustain water-related ecosystem services in the short and long terms needs to be an integral aspect of information communication initiatives in both urban and rural areas.

Different factors should be taken into consideration when developing mechanisms, management practices, and actions to support water conditions and water-related ecosystem services in the study area. The scales at which management and actions take place are important, particularly where there are mismatches between the political units of management and the scale at which ecosystem processes occur. Political units of action and management (such as municipalities) should work actively on the integration of natural landscapes units (such as watersheds) for the conservation of water-related ecosystem services (Schimdt, 2013). For stakeholders within municipalities, for instance, actions can start at the scale of stream and river sections, followed by riparian zones, and then scaling up to entire watersheds. Here, it is important to stress the complementary benefit of management actions at different scales. Developing and effectively implementing comprehensive land-use plans that take into consideration ecosystem services as an integral part of the plans is also crucial. Additionally, promoting adaptive and participatory management is important. Exchanging information, promoting learning and active participation, and initiating collaborative projects and actions are fundamental to sustaining water resources and their ecosystem services, especially outside of officially designated protected areas (Pahl-Wostl *et al*., 2008; Cid & Pouyat, 2013).These efforts certainly need the inclusion and effective participation and collaboration of different stakeholders in the study area, and the need to promote actions and management in forested areas and urban areas all the way to the coast. The watersheds' land-cover conditions, associated water-quality, and the recommendations provided to maintain and enhance water-related ecosystem services apply to the studied watersheds specifically but also to other watersheds in the Caribbean region and beyond.

Acknowledgements

We thank Frank H. Wadsworth, Ariel E. Lugo, Eileen Helmer (USDA Forest Service, International Institute of Tropical Forestry), Pedro Ríos (USDA Forest Service, El Yunque National Forest), Carlos Ramos-Scharrón (The University of Texas at Austin), and anonymous reviewers for the review of the manuscript. Editorial assistance was provided by Christine Sweeney. All research at the International Institute of Tropical Forestry, USDA Forest Service, is done in collaboration with the University of Puerto Rico. Part of the research conducted by the second author and presented in this article was done in collaboration with the Centers for Urban and Interface Forestry,USDA Forest Service Southern Research Station (Cooperative agreement #SRS 07-CA-1130150-068).

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