CHAPTER FOUR

Forested Watersheds, Water Resources, and Ecosystem Services, with Examples from the United States, Panama, and Puerto Rico

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1. INTRODUCTION

Forested watersheds offer access to vital natural resources, i.e., water supply for drinking, agriculture and industry, transport routes, and hydroelectric energy. Ecosystem services provided by these watersheds are numerous and, in addition to good quality water, include reduced peak river flow during storms; increased availability of groundwater and base flow in streams during seasonal dry periods and droughts; reduced soil erosion and landslide probability; enhanced resilience to wildfire, pathogens, and invasive species; biodiversity; genetic resources; and recreation [1–3].

These resource and esthetic benefits come with risks associated with floods, landslides, and wildfires, which are episodic natural disturbances in these settings. Furthermore, these disturbances compromise the provision of the ecosystem services listed previously. Nonetheless, natural landscape disturbance by floods has well-known benefits, i.e., delivery of nutrients to flood plains; landslides open forest gaps that create small-scale opportunities for successional vegetation growth, while hurricanes and wildfires similarly serve as large-scale mechanisms for resetting landscapes and creating new habitats.

More than half of the world population now lives in urban areas, which are expected to absorb all the population growth expected over the next four decades, mostly in the cities and towns of the less developed regions. The United Nations [4,5] has defined 23 megacities with at least 10 million inhabitants; all but 6 of these are in the developing world. These populations place large stresses on water and other resources.

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Societies that derive ecosystem services from forested watersheds face multiple challenges. Loss of forest cover during the 20th century has been well described [1,6]. This loss continues in the 21st century, and work by Hansen et al. [7] and Kim et al. [8] shows that forest cover in tropical America is in decline. For example, from 1990 to 2010 in Panama, forest cover decreased from 4.6 to 4.01 M ha [8]. Land cover change during this period is more complex in Puerto Rico, where, according to Gould et al. [9], forest increased in the eastern part of the island, regenerating on abandoned lands, while urbanization intensified in areas surrounding the Luquillo Experimental Forest (LEF; also located in eastern Puerto Rico). The reduction and fragmentation of forest cover compromises virtually all ecosystem services: water availability and quality, hydroelectric energy, wood products, carbon sequestration, maintenance of biodiversity, and reduction of natural hazard and vulnerability. Moreover, changing climate is already reducing the capacity for some forested watersheds to provide important services, as described in the following.

Societal use of forested watersheds and ecosystem services in the Americas, as elsewhere in the world, has increased substantially as global population has grown to the current level of 7.3 billion. The intensity of this use puts all ecosystem services at risk and requires attention at multiple societal and governmental levels so that these services are not severely compromised. This paper describes ecosystem services derived from new-world tropical and temperate forested watersheds and provides first-order examples of the value placed on these services.

In the US and other countries, public and private sector policies are increasingly placing values, often monetized, on ecosystem services so that these services can be better understood, and management decisions, including trade-offs, can be made collaboratively and transparently [10]. As these valuation and management approaches become more sophisticated, there is a concurrent need for more advanced and comprehensive monitoring and accounting systems, requiring investment from public and private entities. Some general US and Caribbean region examples are described in the following, with discussion of water resources and other ecosystem services. For Panama, the Panama Canal watershed is the focus, and in Puerto Rico, examples are drawn from the Luquillo Mountains.

2. CLIMATE CHANGE

Climate change is well documented and poses a number of direct challenges for our ability to continue to extract benefits from forested watersheds.

Additionally, population growth will require more arable land for agriculture, pushing managed forests onto areas of degraded and lower-quality soils [11]. One example of an observed change in climate is from long-term stream flow data in the northwestern US. According to Stewart et al. [12], peak snowmelt runoff is now approximately 2 weeks earlier than observed during the period from 1948 to 2000 in many western rivers and is predicted to be 30—40 days earlier as the 21st century progresses. Missouri River stream flow has also changed during the period from 1960 to 2011, with changes in climate and land use practices, according to a US Geological Survey (USGS) analysis of data at 227 streamgages?? [13]. Some regions (Kansas and southern Nebraska) of that watershed have reduced flows, while some northern tributaries, mainly in North and South Dakota, show increases in flow.

Water resource management challenges are likely to intensify over most land areas in the 21st century with the increases in the frequency, intensity, and/or amount of heavy precipitation that are expected as a result of a warmer atmosphere [14]. At the same time, warmer air temperatures and increases in intensity and duration of drought and heat stress are likely over many land areas [14,15], contributing to greater likelihood of major droughts, water stress, disease, and wildfires. Additionally, droughts and warmer temperatures stress forests, making them more susceptible to insect-borne diseases [15,16] (Fig. 4.1). Fluctuations between these

Figure 4.1 View of lodgepole pine forest in the northern Williams Range Mountains, Colorado, US. Pine bark beetles have killed more than 80% of the mature trees in this forest; mortality is visible in the red (dark gray in print versions)—brown (darker gray in print versions) color of the dead or dying trees. *Photo source: USGS, http://minerals.cr.usgs.gov/projects/colorado_assessment/*.

extremes of drought and heavy precipitation are likely to occur in spatial and temporal patterns that do not conform to past weather and climate patterns [17].

What have we already observed? Globally averaged air temperatures over land and ocean warmed by 0.85°C from 1880 to 2012. Moreover, the period from 1983 to 2012 was the warmest 30 years of the last 1400 years in the northern hemisphere [14]. Since 1901, an increase in average midlatitude northern hemisphere land area precipitation has been observed. From 1901 to 2010, global mean sea level rose by 0.19 m, and from 1979 to 2012, annual mean Arctic sea ice extent decreased 3.5−4.1% per decade [14]. For example, Arctic sea ice extent in January 2016 was the lowest January extent in the satellite record and was below the previous record January low in 2011 (Fig. 4.2). This is particularly relevant to Panama, as the Arctic Ocean is predicted to transition to a seasonally ice-free state during the middle of the 21st century [18]. The revenues derived from shipping through the Panama Canal are a major part of the economy of the nation. As navigational (bathymetric data are sparse) and security systems (coast guard resources in the region are limited) are developed, this will provide potential Arctic shipping routes as cost-effective alternatives to the Panama (and Suez) Canal because of distance reductions of 35−60%.

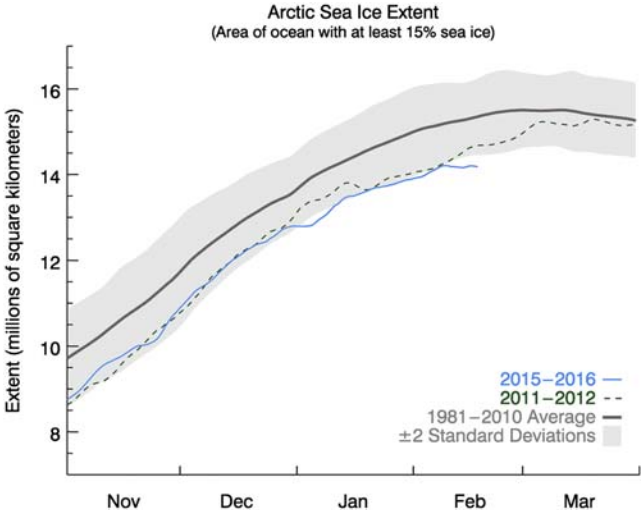

Figure 4.2 Winter Arctic sea ice cover for the period November through March. *Image courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder, https://nsidc.org/arcticseaicenews/.*

Temporal and spatial patterns of precipitation distribution continue to change in North America and elsewhere, challenging water resource managers in their already difficult decision-making for allocation of water supplies. For example, water from the Lake Mead Reservoir is used for public supply and irrigation in Arizona, Nevada, California, and northern Mexico. The Las Vegas Valley is particularly dependent on the reservoir for its water supply. Barnett and Pierce [19] have estimated that there is a 50% chance that Lake Mead, a key source of water for the southwestern US, will be dry by 2021 if the climate warms as predicted and if regional water consumption is not reduced. There is evidence that we are seeing this change now. USGS and NASA Landsat satellite imagery from 2000 to 2015 shows that the lake, located at the Nevada/Arizona border, has been losing water volume for most of that period of record [20] (Fig. 4.3). The Southern Nevada Water Authority has been responding to this challenge by proactively implementing a wide range of water conservation strategies, such as lawn and golf course watering restrictions and incentives that include a rebate to customers of $2 per square foot ($0.19 per m^2) of grass removed and replaced with desert landscaping up to the first 5000 square feet (465 m^2) converted per property. In addition, the Authority has extensive water reuse requirements and practices in place in public use areas.

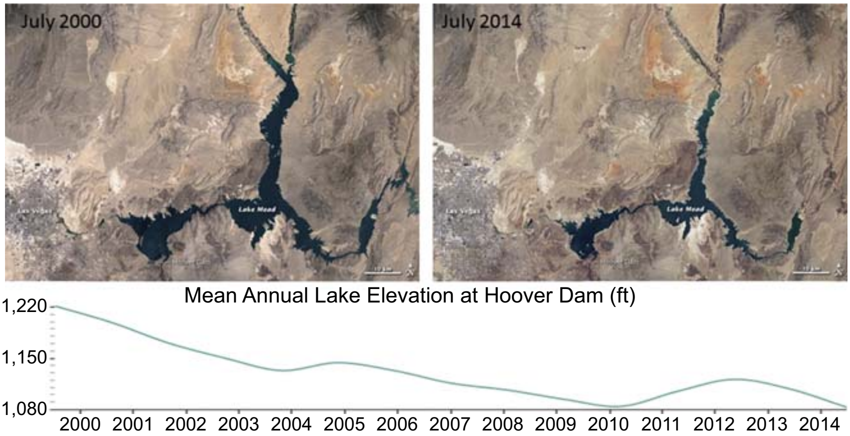

Figure 4.3 Landsat 7 and Landsat 8 images comparing Lake Mead areal extent in 2000 and 2014. Note substantial shrinkage. The mean annual lake elevation plot shows that water storage in the lake is in a multiyear decline. *Images from USGS/NASA, http://earthobservatory.nasa.gov/IOTD/view.php?id=86426.*

3. ECOSYSTEM SERVICES AND VALUATION

The Millennium Ecosystem Assessment established a benchmark for ecosystem services based on a 4-year United Nations assessment of the condition and trends of the world's ecosystems and the services we draw from them [21]. They further broadly defined ecosystem services as provisioning services, regulating, cultural, and supporting [22]. Although the term "ecosystem services" has become widely used and discussed, the concept is not new [23]; for example, von Thünen [24] discussed land use and landscape-derived services needed to sustain an agrarian-based self-sufficient state.

A regulating ecosystem service is easily understood, for example, as the improvement in water quality that is gained by protecting a watershed to enable the ecosystem to provide this service instead of depending on the construction and operation of water treatment facilities [21]. This difference has been described as green versus gray infrastructure.

Water sustains life on earth and is critical to nearly all other ecosystem services. Global estimates of ecosystem service values are provided by Coates et al. [25] and van der Ploeg et al. [26] in US dollars per hectare as $452 for water supply; $1966 for a set of regulatory services, which includes water flow regulation, waste treatment, and water purification; mitigation of extreme events (floods, droughts) and other regulatory services (air quality, climate regulation, erosion prevention, pollination, and biological control); and $398 for cultural services.

As has been stated by many, "*you can't manage what you don't measure.*" Measuring the effects ecosystem services valuation policies is complex because of the many forces involved, including climatic, local- to global-scale markets, and various intersecting, sometimes conflicting policies. In addition, long-term monitoring of forest cover, land use change, streamflow, agricultural practices, etc., is costly and in many cases not sustained by governmental agencies. For example, Sánchez-Azofeifa et al. [27] evaluated a payment for ecosystem services (PES) program that was implemented in Costa Rica in the 1990s to reduce deforestation. The authors did not observe significant effects of the PES program, but state that other policies, such as the creation of national parks and biological reserves, had already lowered deforestation rates and may have reduced the PES impact on land use practices.

3.1 United States: Ecosystem Service Payment Programs

PES is not new to the US. Starting in the 1980s, the US Conservation Reserve Program, which is administered by the US Department of

Agriculture, initiated payments to farmers to refrain from planting crops in environmentally sensitive areas. Wilson and Carpenter [28] synthesized the results of 30 different US studies from the period of 1971 to 1997 to describe the state of knowledge and gaps in understanding for the valuation of water resource ecosystem services. They stated that these valuation estimates tend to be specific to particular ecosystems and socioeconomic settings, and posit that physical and social scientists need to collaborate more effectively to improve future management and research.

The Obama administration, concerned over the impacts of climate change on the US private and public sector, has directed federal agencies with natural resource missions to develop ecosystem services assessment methods and approaches to devise innovative payment methods for ecosystem services. These approaches are designed to improve the management of these services [29]. According to Schaefer et al. [10], the federal agencies' ecosystem services approaches are grouped into enhancing investment in conservation and natural resource management, improving the cost-effectiveness of programs, making trade-offs transparent and avoiding unintended negative consequences of policy actions on ecosystems, enhancing resilience, and supporting public participation in the planning process. The agencies collaborated with the Duke University Nicholas Institute for Environmental Policy Solutions to produce a guidebook that describes and provides case study examples of ecosystem services approaches [30]. Because the guidebook was produced in 2014, it is not yet known how effective this strategy will be.

Carbon sequestration, water quality regulation, and biodiversity habitat protection, as well as suites of services such as wetland mitigation and conservation easements, have been assigned economic values in a number of states in the US [31]. Mercer et al. [31] describe three types of payments to landowners: payments directly from the government; voluntary payments from businesses, individuals, and nongovernmental organizations; and payments made to comply with government regulations, such as the Clean Water Act or the Endangered Species Act. The revenues for governmental and private sector PES derived from forested watersheds in the US were estimated at \$1.9 billion in 2007 by Mercer et al. [31]. They note that because they lacked data on payments for some services, \$1.9 billion is a conservative estimate. Their estimate includes \$365 million from government sources (19%) and \$1.5 billion (81%) from nongovernmental sources, including payments for wetland mitigation, conservation easements, and carbon offsets. Nongovernment payments come from conservation organizations such as the Nature Conservancy, the Trust for Public Land, the

Conservation Fund, and Ducks Unlimited, who provide funds to conserve land for ecosystem services such as water quality protection and biodiversity.

In another estimate of economic value obtained from an ecosystem, Batker et al. [32] estimated that the value of the natural infrastructure provided by the Mississippi River Delta ecosystem would be $330 billion to $1.3 trillion for a combination of hurricane and flood protection, water supply, water quality, recreation, and fisheries.

In a detailed report describing US federal and other programs that provide incentives for maintaining or enhancing ecosystem services, Scarlett and Boyd [33] include brief descriptions of various payment schemes from around the country:

- Florida pays farmers to maintain wetlands with a goal of improving water storage.
- In Seattle, new efforts to maintain natural landscapes have reduced storm water runoff at a cost that is 25% lower than traditional engineering solutions.
- Farmers in the Tualatin Basin, Oregon, were paid $6 million by water managers to plant trees along streams to meet water temperature requirements. The resulting shade along riparian corridors reduces water temperatures in the river channel and along the near-channel banks and floodplains. This allowed the water agencies to avoid a $60 million cost for refrigeration systems to cool wastewater effluent and storm water runoff. Riparian forests provide additional ecosystem benefits because they enhance bird and other wildlife habitats.
- New York City spent over $1.5 billion to protect and restore watersheds in the Catskill Mountains to maintain good water quality for the city. This avoided a $9 billion cost to construct and maintain water filtration and treatment facilities.
- The US Fish and Wildlife Service initiated a terrestrial carbon sequestration program to restore areas of the Lower Mississippi River Valley. They collaborated with a number of private and nonprivate entities, including energy companies and nonprofit organizations, to add 16,200 ha of restored habitat to their system of refuges and restored 32,400 ha to native habitats. In addition, they planted 22 million trees that, in the coming century, are estimated to sequester 33 million tons of carbon. This is roughly equivalent to the annual emissions from 5.5 million cars in the US.
- The state of Ohio started a Water Resource Restoration Sponsorship Program to provide loan rate reductions for wastewater treatment

projects in cases where the loan recipient commits to use a portion of their cost savings to protect watersheds and restore a land trust, park district, or other watershed protection project.

Avoiding hazardous areas such as floodplains reduces exposure for people and infrastructure. Many communities in the US use land management strategies, such as defining and zoning areas for conservation lands in floodplains, and other hazards, such as steep hillslopes. As discussed previously, this practice reduces exposure, thereby minimizing disaster costs associated with floods and landslides.

Kousky et al. [34] estimated benefits provided by floodplain conservation lands in an 11,330-ha area along the Meramec River, Missouri. In their analysis, approximately $13 million per year of flood damages were avoided by preventing development in the 500-year floodplain of the study area. They further estimated that this was a 38% reduction from average damages expected if these lands were not in a conservation area. In their simple benefit—cost analysis, they note that when considering this potential damage savings along with the recreational and esthetic benefits obtained, these conservation lands yield benefits for the region that exceed the opportunity costs of development.

It is widely recognized that vegetation, particularly forest, can stabilize steep slopes. Although not a US example, a study by Rickli and Graf [35] examined the effect of forest on shallow landslides. The authors showed that landslides were less frequent in forested terrain than in open land in six study areas in Switzerland. Their data also show that landslides mapped in forests occurred on steeper slopes than landslides mapped in open land.

Landslide losses are increasing in the US (and around the world) in association with growing population and development. Spiker and Gori [36] maintain that this trend will continue because of development in hazardous areas, expansion of transportation infrastructure, deforestation of landslide-prone areas, and climate change. These authors outlined a national landslide hazards mitigation strategy that would reduce the cost of landslide hazards and would require new partnerships between government, academia, and the private sector to sustain and expand a range of approaches, including research and development of mapping and other mitigation tools.

3.2 Ecosystem Services Obtained From the Panama Canal Watershed

The 3313 km^2 Panama Canal watershed is located at 9° north latitude with elevations that are generally 300 m or less above sea level, although several peaks reach 1000 m elevation [37,2]. Annual rainfall is variable across the watershed, from a low on the Pacific side of the isthmus of 1600 mm to more than 3000 mm on the Caribbean/Atlantic side. Approximately half of the watershed is in forest, mostly evergreen canopy, defined as tropical moist forest; however, forests near the Pacific coast are about 25% deciduous, while the wetter region near the Atlantic has few deciduous trees and includes wet forest and submontane?/forest [37,38].

Ecosystem services derived from the Panama Canal watershed provide a robust example of multiple high-value services with national, regional, and global significance [11]. Water is the most important control on virtually all canal watershed ecosystem services [39]. Annual precipitation in the canal watershed is reported as a volume of 8.9 km^3 for the period from 1993 to 2004 [40]. This translates to an annual stream flow volume of 4.4 km^3, with 2.6 km^3 (59%) used for lockages of vessels transiting the canal, 1.2 km^3 (27%) for hydroelectric power generation, and 0.27 km^3 (6%) for drinking water supply, according to an average canal watershed water budget published by Stallard et al. [2]. The balance, 7%, is mainly evaporation and groundwater infiltration [40].

Most of the nation's population of close to four million resides in or near the canal watershed, mainly along the canal route. Financial income is a major ecosystem service of the canal. A total of $1.91 billion in tolls were collected in 2014 for ships using the canal. About half of this is used for operations, and the balance goes into the general fund for the Republic of Panama. The Panama Canal Authority (ACP) has 9000 employees, but activities directly or indirectly related to canal operations generate some 200,000 jobs [41].

Shipping companies pay to use the canal because of major fuel and time savings, which prevents substantial burning of fossil fuel and consequent emission of greenhouse gases. For example, a ship traveling between New York and San Francisco saves about 13,000 km by using the Panama Canal instead of going around Cape Horn. About 14,000 ships use the canal every year [42]. Most of these are from the US, followed by those from China, Chile, Japan, Colombia, and South Korea. As such, the fuel savings and greenhouse gas emissions reductions achieved by the shipping companies from these countries (and others) are a valuable ecosystem service provided by the canal watershed but used globally. For example, shipping cargo from Shanghai to New York through the Suez Canal takes about 77 days for a round trip, but only 56 days per trip through the Panama Canal. When the Panama Canal starts use of its expanded set of locks in June 2016, which will allow greater capacity vessels to transit the system, it is expected that total reduced fuel consumption will decrease CO_2 emissions by an estimated 160 million tons in the first 10 years of operation.

Approximately 197,000 m^3 of water has been used for each vessel to transit the canal on average in recent years [43]. That totals 2.76 km^3 of water per year for shipping purposes, which, using the $1.91 billion in tolls, equals a value of 1.4 m^3 of water per dollar, or conversely, a value of $0.69 per m^3 of water. Using the 3313 km^2 area of the Panama Canal watershed, the annual shipping value per hectare of land is $5765. These are overly simplistic valuations of water and land, but provide a gauge of the value of the land used to support this particular water use in Panama. The approximate value does not include the important hydroelectric, esthetic, recreational, carbon sequestration, biodiversity maintenance, or overall ecosystem habitat values that are also provided by this water.

An additional complication of placing a specific economic value on water in the Panama Canal watershed is that each cubic meter of this water gains more importance during shortage periods. Average annual rainfall is 2659 mm at the Smithsonian Tropical Research Institute, administered Barro Colorado Island Nature Monument, located within the Panama Canal watershed (Fig. 4.4). Rainfall totals have a large interannual variation in accumulation, with a low of 1699 mm in 1997 and a high of 4487 mm in 1981. During drought years, the ACP has sometimes had to require that

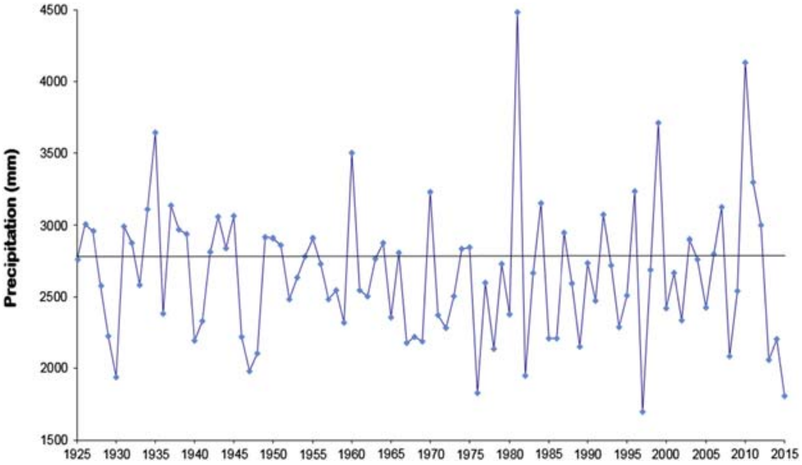

Figure 4.4 Annual rainfall totals, 1925 to 2015, Smithsonian Tropical Research Institute, Barro Colorado Island, Panama. Average for the period is 2659 mm. Note large interannual variation in accumulation. *Data source: Steven Paton, Smithsonian Tropical Research Institute, http://biogeodb.stri.si.edu/physical_monitoring/research/barrocolorado.*

vessels transiting the canal do so with reduced draft, which means that the fees paid by the shipping companies are also reduced.

Drinking water and energy production are the other major economically quantified ecosystem services of this watershed. Drinking water for more than half of the nation's population is obtained from the watershed; energy production for more than half of Panama's electrical energy supply is hydroelectric from dams in the canal watershed. In 2014, the canal generated $246 million in revenue from the sale of electric power and $29.4 million from the sale of potable water [43]. The Panama water authority (the Instituto de Acueductos y Alcantarillados Nacional) charges approximately $0.26 per m^3 to the consumer for potable water [44].

As noted previously, recreation, tourism, carbon sequestration, and maintenance of biodiversity are other important ecosystem services derived from the Panama Canal watershed. Total annual tourism revenue for the nation in 2015 from an estimated two million visitors was approximately $4 billion. Because data are limited, estimating economic values for carbon sequestration and maintenance of biodiversity is beyond the scope of this paper (see Ref. [11] for discussion of these services).

At 9° north latitude, Panama has the good fortune to be located just south of the Atlantic—Caribbean and Pacific hurricane zones. In the past 150 years of tracking of hurricanes, none have directly impacted the country. Nonetheless, floods caused by other weather systems, often convective disturbances associated with the location of the intertropical convergence zone (a dynamic band of convective moisture associated with the convergence of near-equatorial easterly trade winds from the northern and southern hemispheres), are not uncommon, and flood risk is the principal natural hazard faced by Panama, where many people live along or near riparian corridors. Storms with significant flooding in the canal watershed tend to occur at the end of the rainy season, for example: October 1923, November 1931, November 1932, November 1966, December 1985, December 2000, November 2004, and December 2010 [45]. A notable example of a major storm on this list with associated significant flooding is the event of December 2010. This storm, known as La Purisima, serves as a good illustration of flood and landslide hazard mitigation as an ecosystem service in the Panama Canal watershed [46]. The storm also illustrates what happens when hazard-related ecosystem services are at or beyond their limits when a rare, large-magnitude storm affects hillslopes and riparian corridors.

La Purisima, described as the largest 3-day storm in the Canal watershed's 100-year recorded history, was associated with the interaction of a frontal system and the intertropical convergence zone, and produced 760 mm of rainfall in 24 h. Mean stream flow for the principal canal watershed fluvial system, the Chagres River, was 908 m^3 per second, and a 3-day total steam flow volume of 235 million m^3 was calculated. This volume has a recurrence interval of approximately 300 years and was the largest flow recorded in the 78 years since recordkeeping began [46]. In a rare mitigation step, the ACP was forced to open the canal locks to discharge water, halting ship transit through the Canal for 17 h [46]. Additionally, the rainfall caused more than 500 landslides and temporarily closed the two roads that connect the two major cities of the country, Panama City and Colón. The landslides also introduced a massive pulse of sediment into river channels, raising water turbidity at a key public supply intake to 600 nephelometric turbidity units, closing water supply facilities and leaving parts of Panama City without normal water supply for 50 days. These aspects of the environmental response to this rare storm illustrate what happens when ecosystem services are fully or partially overwhelmed by the magnitude of the event.

About half of the canal watershed has been deforested, and the official policy in the canal watershed (Law 21) is to reforest in anticipation of regaining ecosystem services [2]. Canal watershed locks and dams were at their design limits during this flood, meaning that if there was much more stream flow, which would have been the case if more of the watershed had been deforested, the dam and the locks could have failed, a major disaster for Panama and world shipping. This averted disaster shows the high ecosystem service value of the forested areas of the Panama Canal watershed. Important services, including canal operations, were temporarily compromised, but canal infrastructure held up. Furthermore, an essential measure of the value of an ecosystem service with regard to hazard mitigation is loss of life. In spite of the large magnitude of this storm, few casualties were reported. The great importance of maintaining forest in this watershed, with extensive high-value infrastructure downstream, as well as critically important public water supplies, cannot be overemphasized. The environmental response provides a good example of when green (forested land) and gray (dams, locks) infrastructure is overwhelmed. The dams and locks (gray infrastructure) reached their design limits, and the green “infrastructure” (forests) was at capacity for mitigation.

With respect to ongoing management of flood hazard as an ecosystem service, the ACP has a flood control program that identifies, mitigates, and responds to conditions that pose a danger to communities and property located along riparian corridors (and on key ACP reservoirs and canal infrastructure) that could potentially interrupt canal operations [45]. The ACP, like many agencies that manage multiuse reservoirs (i.e., reservoirs used for a combination of flood control, hydroelectric energy production, drinking water supply, irrigation, and recreation) uses a complex set of metrics to control canal watershed reservoir levels to ensure water availability for human consumption, ship transit, and hydropower generation. One of the annual challenges faced by the ACP is associated with the timing and amount of rainfall delivered to the canal watershed by storms at the end of the wet season in December. The largest storms are often at the very end of the season, when reservoirs may be at, or close to, their maximum volume.

4. ECOSYSTEM SERVICES OBTAINED FROM THE LUQUILLO MOUNTAINS, PUERTO RICO

Puerto Rico, the smallest island (9000 km^2) of the Greater Antilles, is located in the northeastern Caribbean at 18° north latitude, about 1700 km southeast of Miami, US. It is an island of high relief with a maximum elevation in the central east—west trending mountain range of 1338 m. The rectilinear island measures 65 km north—south and 180 km east—west. Gradual forest removal began in the 1600s as land was cleared for agriculture by European settlers. After three centuries of extensive subsistence and plantation agricultural land use, most (94%) of Puerto Rico had been deforested by the late 1940s [9]. A shift away from agriculture toward industry began in the 1950s and resulted in much abandoned pasture and farmland that are now in secondary forest [9].

Topography in the Luquillo Mountains is rugged, stream channels are deeply incised, and annual rainfall averages more than 4000 mm in the upper elevations [47]. The mountains are largely within the boundaries of the El Yunque National Forest (EYNF), also known as the LEF, an intensely studied 11,300-ha preserve that is completely forested and under the administration of the US Forest Service. Because of the 1000-m elevational, temperature, and precipitation gradient, multiple forest types are present in the LEF, including subtropical moist forest and subtropical wet forest, with subtropical rainforest, lower montane wet forest, and lower montane rainforest at high elevations [9,48].

Prior to the 1898 US invasion, the Luquillo Mountains had been afforded some degree of forest protection during the 19th century by the Spanish crown because of the value of the hardwood there for shipbuilding and other purposes. This, along with localized cutting of wood to make charcoal, was one of the first described ecosystem services derived from the forest. During the 20th century, the mountains gained new uses as they were managed by the US Forest Service as a recreational area and as the Puerto Rico Water Authority (PRASA) began to use high-quality streamflow for drinking water supply in the region [49]. A first approximation of the value of public supply water from the LEF was estimated by Crook et al. [49] using stream flow from the nine rivers that drain the mountains. These rivers have modest water extraction sites, operated by PRASA, which is required to limit extraction in order to maintain minimum stream flow so as to sustain ecological function of the streams [50]. Water is extracted from 34 locations along these rivers, and on a typical day, 70% of stream flow from within the forest is diverted before reaching the ocean (Fig. 4.5). Two intakes draw particularly large amounts of water: the intake at Río Mameyes, which is permitted to extract 18,940 m^3/day, and the intake at Río Fajardo, permitted to extract 45,460 m^3/day [49].

In 2004, an approximate total of 0.252 million m^3/day of water was withdrawn from streams draining the LEF. PRASA charges $1.06 per m^3 for average residential customers. Using this price to the consumer for potable water in Puerto Rico, the daily volume of potable water withdrawn from the LEF has a total maximum possible value of approximately $267,000.

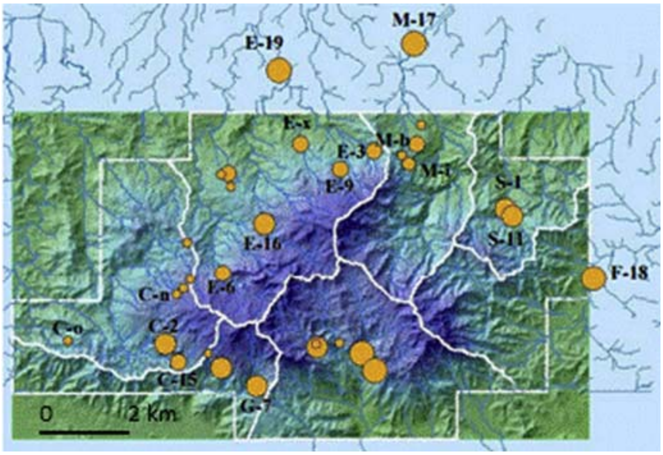

Figure 4.5 Map of public supply water intakes on streams draining the Luquillo Experimental Forest, eastern Puerto Rico. Forest boundary shown in white orthogonal lines; watershed boundaries are nonrectilinear white lines. Intakes shown with circles in which diameter is proportional to the intake withdrawal capacity, ranging from less than 10 m^3 per day to more than 10,000 m^3 per day. *Figure simplified from Crook KE, Scatena FN, Pringle CM. Water withdrawn from the Luquillo experimental forest, 2004. U.S. Department of Agriculture, Forest Service, General Technical Report GTR-IITF 34; 2007. 26 p.*

Hydropower represents only 1% of total electric energy for Puerto Rico, most of which (69%) is generated by oil-burning power plants [51]. Hydropower generation is severely limited because the 224 rivers in Puerto Rico are relatively short in length (a few tens of km), with only modest catchment size. This small watershed size, in combination with episodic droughts, makes hydroelectric energy unreliable [52]. A small hydroelectric facility on the south side of the Luquillo Mountains, on the Río Blanco, has a capacity to generate 5 MW, according to Liu et al. [51]. This is 12% of the 41.8 MW capacity from a total of 21 hydroelectric units on six rivers around the island. Puerto Rico's electricity costs are about 27 cents per kilowatt hour, approximately twice what they are in the US [53]. One megawatt equals 1000 kW, so at $0.27 per kilowatt, if the Río Blanco facility was operating at full 24 h/day capacity (it is reportedly not doing so), it would be producing electricity valued at $32,400 per day ($11.8 million/year).

The US Forest Service describes a "site visit" as the entry of one person to a national forest site or area to participate in recreational activities for an unspecified period of time. A "national forest visit" can be composed of multiple "site visits." In 2006, there were 1.336 million site visits to the EYNF, and in 2011, there were 1.123 million (written communication, Jose Ortega, Recreational Program Leader, EYNF, Puerto Rico, US Forest Service, September 8, 2015). The American Sportfishing Association [54] quantifies the economic value of visits to US Forest Service managed lands that are made for hunting, fishing, and wildlife viewing activities. Hunting and fishing are not permitted within the EYNF boundaries, so information for Puerto Rico was restricted to wildlife viewing activities. Bird watching is one the principal wildlife viewing activities as Puerto Rico, in combination with the US Virgin Islands, has approximately 270 species of birds [55]. Additionally, there is great interest in the dwindling populations of the once widely distributed Puerto Rican parrot. Between 2000 and 2003, an estimated annual average of $3.2 million was spent in Puerto Rico for wildlife viewing associated with the EYNF [54]. As the number of visitors to the forest has increased since 2003, it is likely that the economic contribution of wildlife viewing associated with the EYNF has also increased. US Forest Service data show an EYNF recreational visitor rate in excess of 1,000,000 per year.

Carbon sequestration and maintenance of biodiversity are other important services derived from the Luquillo Mountains and the forested 11,300 ha of the LEF, but these are beyond the scope of this paper.

Mitigation of flood and landslide hazards that not only threaten people and infrastructure, but compromise ecosystem services, is achieved largely through the practices of strong governance. An important part of the governance is minimization of forest removal in steeply sloping regions and zoning to prevent housing or other construction on or near the base of steep hillslopes [56]. Forested hillslopes provide a landslide hazard mitigation ecosystem service that also applies to flood hazard mitigation for people and structures located along riparian corridors. The presence of forest reduces storm runoff volume and reduces storm runoff peak stream flow in rivers, spreading the runoff volume over a larger time step than would occur if no forest were present [3].

In its recorded history, floods have caused the largest loss of life in Puerto Rico, which is the case for most countries around the world. Major floods during the 19th and 20th centuries were associated with rainfall delivered by tropical disturbances (depression, storms, hurricanes), and killed thousands [57]. Most of these flood deaths were prior to 1940 when zoning for housing location and construction standards were not well defined or regulated. Improved governance, including planning and zoning, has greatly reduced loss of life from flooding across the island. Effective governance is also evident in Puerto Rico, where a well-coordinated response system of governmental agencies is initiated each time that a tropical disturbance or other heavy rain threatens the island. Additionally, general education of the public for hazard preparation and a well-informed, decentralized civil defense network have combined to reduce loss of life to near zero during large storms.

CONCLUSIONS

The US, Panama, and Puerto Rico provide examples of a variety of payment programs for ecosystem services and for the services derived from forested watersheds, and offer insights into how we consider and take advantage of these services. The examples show the benefits and limitations of the ecosystem services provided by forested watersheds and how some of the services are valued. The examples also illustrate the importance of the maintenance and expansion of watershed forest cover as well as strong governance, which includes well-informed science- and engineering-based infrastructure zoning, planning, and design. Not surprisingly, because of its geographic size, large economy, and well-established natural resource regulatory policies, the US has the most developed set of PES.

In most countries, PES from forested watersheds is indirect. It is a value that is most commonly extracted for hydroelectric energy, water supply, and recreation through governmental or private sector charges to deliver these commodities to users. As the brief examples listed above demonstrate, most US programs that offer payments for ecosystem services don't focus on a single service. The programs are meant to incentivize general conservation practices, which support a range of benefits obtained from forested watersheds and other environments.

In spite of the numerous large investments made by federal, state, and local governments, as well as those made by nongovernmental organizations, many landowners do not participate in these PES programs. See Mercer et al. [31] for a discussion of data and statistics on this topic. Mercer et al. [31] further state that *"the economic and social forces that have led to forest fragmentation and loss in the US are so strong that PES payments have so far not had a significant impact on forest land use at the regional or national level"* and that *"changes in government and corporate policy will be critical for PES to result in large enough financial returns to effectively compete with development and other economic drivers of land use in the US in order to have a significant impact on the provision of forest-based ecosystem services."*

To best manage water resources and other ecosystem services, there is an increasing need for local land management actions and adaptation, which includes sustaining diverse forest cover, minimizing soil erosion and degradation, and assuring that road networks and essential infrastructure are well planned [58] and not built in areas subject to flood, landslide, and other hazards [59,60]. These actions assure that both the natural and built environments (green and gray infrastructure) are managed in coordination, improving and enhancing the benefits derived from each [61,62].

Additionally, mountains and rivers are often transboundary, crossing political and cultural divisions. As such, effective management of ecosystem services is highly dependent, not just on local strong governance, but also on the cooperation of local stakeholders, regional and national institutions, and in many cases, international institutions [63]. Additionally, timely access to governmental communication of accurate information associated with hazards, i.e., precipitation, streamflow, estimated fire probability, flood and landslide warnings, is key to effective response of at-risk communities so that loss of life is minimized.

Lastly, with changing climate, water resources management and flood (and landslide) hazard mitigation challenges are now increasing because the long-standing approach for estimating streamflow and flood probability is based on the principal of stationarity, which means that the present likelihood of streamflow and floods in a watershed can be well determined by examining the past 30 or more years of stream flow record. This approach has been weakened by changing rainfall and stream flow patterns observed in recent decades [17,64]. The intergovernmental panel on climate change (IPCC) [14] Fifth Assessment Report concluded that climate change has begun to affect the frequency, intensity, and length of many extreme events, thus increasing the need for additional timely and effective adaptation.

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