Water, hazard mitigation, and other ecosystem services derived from tropical forested watersheds: benefits and risks

M.C. Larsen, *Smithsonian Tropical Research Institute, Panama*
E-mail address: larsenmc@si.edu

Abstract

Forested watersheds are sources of high quality water supply for drinking, agriculture, and industry. Additionally, tropical (and other) montane forests include other benefits such as wood products, recreation, and esthetic values. Advantages afforded by these environments are offset by episodic risks for communities located there as floods, landslides, wildfires, and volcanoes cause loss of life and damage or destroy infrastructure and crops. A basic understanding of rainfall and flood patterns, as well as hillslope stability by residents in these environments can mitigate these risks. However, modern global urbanization, particularly in regions of rapid economic growth, has resulted in much of this "organic" knowledge being lost, as megacities encroach on floodplains and mountain fronts. Moreover, the most likely occupants of these hazardous locations are often marginalized economically, which increases their vulnerability. In addition to the well-described services, ie. water, food, hydroelectric energy, wood products, carbon sequestration, maintenance of biodiversity, effective stewardship of river floodplains and upstream forests maintains a key ecosystem service: reduction of natural hazard and vulnerability. Examples of ecosystem services are presented, for areas of Panama, Puerto Rico, and Venezuela, with discussion of benefits and risks.

keywords: ecosystem services, water resources, natural hazards, tropics, Panama, Puerto Rico, Venezuela

Introduction

People prefer to live near rivers, mountains, and coasts, for reasons of access to natural resources, *ie*. water supply for drinking, agriculture and industry, transport corridors, but also because of esthetic values. Human settlement in or near montane forests is related in part to access to food and wood supply (Noble and Dirzo, 1997), hydroelectric energy, and high quality water resources derived from these montane watersheds where upstream human disturbance and associated environmental degradation is generally reduced.

Environmental benefits from forested watersheds are numerous and 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, and enhanced resilience to wildfire, pathogens, invasive species, biodiversity, and genetic resources (Noble and Dirzo, 1997; Stallard et al., 2010; Ogden et al., 2013; Chavez-Tafur and Zagt, 2014).

The resource and esthetic benefits of riparian, montane, and coastal environments come with risks associated with floods, landslides, and wildfires, which are episodic natural disturbances in these settings. Landscape disturbance by floods has well known benefits, ie. 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 re-setting 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 (Fig. 1). The United Nations (2011) has defined 23 megacities with at least 10 million inhabitants; all but six of these are in the developing world. These populations place large stresses on water and other resources. Additionally, most cities in Latin America and the Caribbean, including those discussed herein, are exposed to significant natural hazards. In general, flooding is the most frequent and greatest hazard for the 633 largest cities (United Nations, 2011). Rapid population growth in these urban centers means that traditional environmental understanding has been eroded, and more people are now at risk as megacities encroach on riparian corridors, floodplains, mountain fronts, and coastlines (Fig. 2) (United Nations, 2011). Moreover, the most likely occupants of these hazardous locations are often marginalized economically, increasing their vulnerability (IPCC, 2014).

20th century forest cover loss has been well described (Noble and Dirzo, 1997; FAO, 1997). This loss continues in the 21st century and recent work by Hansen et al. (2013) and Kim et al. (2015) shows that forest cover in tropical America is in decline. For example, from 1990 to 2010 in Panama and Venezuela, forest cover decreased from 4.6 to 4.01 M ha and 51.2 to 47.1, respectively (Kim et al., 2013). The reduction and fragmentation of forest cover compromises water availability and quality as well as other ecosystem services derived from forested areas, and elevates risk for flooding, landsliding, and wildfires. Moreover, water resources management challenges, flood risks, and landslide risks are likely to increase 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 (IPCC, 2014). At the same time, warmer air temperatures and increases in intensity and duration of drought are likely over many land areas (IPCC, 2014), contributing to greater likelihood of major droughts, water stress, and wildfires. Fluctuations between these extremes of drought and heavy precipitation are likely to occur in spatial and temporal patterns that may not conform with past weather and climate patterns (Milly et al., 2008).

To best manage water resources and to take advantage of hazard mitigation 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, assuring that road networks and essential infrastructure are well-planned (Larsen and Parks, 1997), and avoiding the most hazardous areas (Larsen and Torres Sanchez, 1998; Annan, 1998; Larsen and Wieczorek, 2006; IPCC, 2014). A recent review of these concepts is found in Cochard (2013), who describes hazard mitigation ecosystem services as those that serve to regulate global, regional and local climates (via carbon storage, evapotranspiration, and albedo), provide structural stability to soil substrates (reducing risk of shallow landslides, and erosion during flooding), retain and transpire water (reducing flooding frequencies and intensities in catchments); and buffer against solid and fluid mass impacts (landslides, rockfalls, snow avalanches, wind-driven sea waves, storm surges, and tsunamis).

Human 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 tropical forested watersheds and riparian corridors and discusses hazard mitigation as an ecosystem service.

Three tropical American examples in the Caribbean region (Panama, Puerto Rico, and Venezuela) are described below, with discussion of water resources, other ecosystem services and natural hazards for each location. The Panama Canal watershed, the Luquillo mountains of Puerto Rico, and the coastal mountains of Venezuela (Fig. 2) illustrate water-resources challenges and how and where hazard-mitigation ecosystem services have been used or in some cases, not well understood or managed, resulting in sometimes severe consequences.

Ecosystem services: benefits and risks

Water is critical to nearly all other ecosystem services, and sustains life on earth. The Millennium Ecosystem Assessment established a benchmark for ecosystem services based on a four-year United

Nations assessment of the condition and trends of the world's ecosystems and the services we draw from them (MEA, 2003). Although the term "ecosystem services" has become widely used and discussed, the concept is not new (SCEP, 1970), for example, von Thünen (1842) discussed land use and landscape-derived services needed to sustain an agrarian-based self-sufficient state.

Discussion of hazard mitigation as an ecosystem service is also not a new concept, but as governments and societies increasingly attempt to assign specific economic values to ecosystem services, reduction of hazard has received more attention (SCEP, 1970; MEA. 2003; Kosoya et al., 2007; Cochard, 2013; IPCC, 2014; Hall et al., 2015). Hazard mitigation however, is notoriously difficult to evaluate economically because of the dilemma of estimating a cost for an event that did not occur. As well stated by Kofi Annan, former UN Secretary General:

Building a culture of prevention is not easy. ***While the costs of prevention have to be paid in the present, its benefits lie in a distant future. Moreover, the benefits are not tangible; they are the disasters that did NOT happen*** *(*UN Secretary General, 1999*).* (bold text emphasized by author)

Panama

The 3,313 km^2 Panama Canal watershed is located at 9° north latitude, with elevations that are mostly 300 m or less above sea level, although several peaks reach 1,000 m elevation (Condit et al., 2001; Stallard et al., 2010). Annual rainfall is variable across the watershed, from a low on the Pacific side of the isthmus of 1,600 mm, to more than 3,000 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 (Condit et al. 2001).

Ecosystem services derived from the Panama Canal watershed provide a robust example of multiple high-value services with national, regional, and global significance (Hall et al., 2015). Water is the most important control on virtually all canal watershed ecosystem services. Annual precipitation in the canal watershed is reported as a volume of 8.9B m^3 for the period 1993-2004 (IDB, 2008). This translates roughly to an annual streamflow 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. (2010). The balance, 7%, is mainly evaporation and groundwater infiltration (IDB, 2008).

Most of the nation's population of close to 4 million resides in or close to 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 9,000 employees, but activities directly or indirectly related to canal operations generate some 200,000 jobs (Panama Canal, 2015).

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 (Smith, 2014). Most of these are from the U.S., followed by those from China, Chile, Japan, Colombia and South Korea. As such, the fuel savings and greenhouse gas emissions achieved by the shipping companies from these countries (and others) are a valuable ecosystem service provided by the canal watershed but used globally.

Approximately 197,000 m^3 of water was used for each vessel to transit the canal on average in recent years (Panama Canal, 2015). That totals 2.76 km^3 of water per year for shipping purposes, which, using the $1.91B 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. This is an overly simplistic valuation of the water, but provides a gauge of the value of this particular water use to 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.

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 $246M in revenue from the sale of electric power and $29.4M from the sale of potable water (Panama Canal, 2015). The Panama water authority, the (Instituto de Acueductos y Alcantaeillados Nacional), charges approximately $0.26 per m^3 to the consumer for potable water (IDAAN, 2015).

As noted above, recreation, tourism, carbon sequestration and maintenance of biodiversity are other important ecosystem services derived from the Panama Canal watershed. Estimating dollar values for these services is a complex exercise, beyond the scope of this paper (see Hall et al., 2015 for discussion of these services).

Panama is fortunate in having fewer natural hazards than much of neighboring Central American or Andean region, where seismicity and volcanism are greater and the percentage of population located on or near mountain hillslopes is higher (Simkin et al., 2006) (Figs. 2, 3). Nonetheless, some regions of Panama are vulnerable to earthquakes and volcanoes, particularly near the borders with Costa Rica and Colombia (Garwood et al., 1979; Sherrod et al., 2008). Volcán Barú, located near the Costa Rican border, is a potentially active volcano that has had four eruptive episodes in the past 1,600 years, most recently in the past 400–500 years (Sherrod et al., 2008). In 1976, two large magnitude earthquakes (6.7M and 7.0M) affected an area of 450 square kilometers and associated landslides denuded 54 square kilometers of forest in Panama in the Darien province, near Colombia (Garwood, 1979). Earthquakes of this magnitude are considered to be rare in Panama and seismic activity in Panama, as noted, generally affects regions near the borders, where population density is low (Figs. 2, 3).

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 (Fig. 3). Nonetheless, floods caused by other weather systems, often convective disturbance associated with the location of the intertropical convergence zone (a dynamic band of convective moisture associated with the convergence of near-equatorial easterly tradewinds 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 (Cuevas, 2011). 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 (Espinosa, 2011). 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 three-day storm in 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 hours. Mean streamflow for the principal Canal watershed fluvial system, the

Chagres River, was 908 m^3 per second, and a three-day total steamflow volume of 235M 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 record keeping began (Espinosa, 2011). 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 hours (Espinosa, 2011). 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 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 (Stallard et al., 2010). Canal watershed locks and dams were at their design limits during this flood, meaning that if there was much more streamflow, 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 infrastrucure 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, no 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.

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 (Cuevas, 2011). The ACP, like many agencies that manage multi-use reservoirs (ie. 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 hydro-power 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.

Puerto Rico

Puerto Rico, the smallest island (9,000 km^2) of the Greater Antilles, is located in the northeastern Caribbean at 18° north latitude, about 1,700 km southeast of Miami, USA. It is an island of high relief with a maximum elevation in the central east-west trending mountain range of 1,338 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 (Gould et al. 2012). A shift away from agriculture towards industry began in the 1950s and resulted in much abandoned pasture and farmland that is now in secondary forest (Gould et al., 2012).

The Luquillo mountains, the focus of this discussion, are located in eastern Puerto Rico, and after Smithsonian Institution research sites in Panama, are the area with the longest, most detailed scientific record of natural processes in the neotropics (Leigh et al., 1983; Heckadon et al., 1999; Condit et al., 2001; Ibanez et al., 2002; Walker and Bellingham, 2010; Harris et al., 2012; Murphy and Stallard, 2012a,b). Both regions have more than 100 years of extensive scientific data collection with resulting peer-reviewed scientific publications surpassing several thousand at each site.

Topography in the Luquillo mountains is rugged, stream channels are deeply incised, and annual rainfall averages more than 4,000 mm in the upper elevations (Murphy and Stallard, 2012). The mountains are largely within the boundaries of the El Yunque National Forest (EYNF), also known as the Luquillo Experimental Forest (LEF), an intensely studied 11,300- ha preserve that is completely forested and under the administration of the U.S. Forest Service. Because of the 1,000 m elevational, temperature, and precipitation gradient, multiple forest types are present in the LEF, including subtropical moist forest, subtropical wet forest, with subtropical rain forest, lower montane wet forest, and lower montane rain forest at high elevations (Gould et al., 2012).

Prior to the 1898 U.S. 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 ship building an 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 U.S. 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 (Crook et al., 2007). A first approximation of the value of public-supply water from the LEF was estimated by Crook et al. (2007) using streamflow 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 streamflow so as to sustain ecological function of the streams (PRASA, 2012). Water is extracted from 34 locations along these rivers and on a typical day, 70% of streamflow from within the forest is diverted before reaching the ocean. 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 (Crook et al., 2007).

In 2004, an approximate total of 0.252M m^3/day of water was withdrawn from streams draining the LEF. PRASA charges $1.06 per m^3 for 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.

Hydropower represents only one percent of total electric energy for Puerto Rico, most of which (69%) is generated by oil burning power plants (Liu et al., 2013). Hydropower generation is severely limited because the 224 rivers in Puerto Rico are relatively short in length (a few 10's of km), with only modest catchment size. A small hydroelectric facility on the south side of the Luquillo mountains, on the Río Blanco, has a capacity to generate 5 Megawatts according to Liu et al. (2013). This is 12% of the 41.8 Megawatt 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 U.S. (Gross, 2014). One Megawatt equals 1,000 kilowatts, so at $0.27 per kilowatt, if the Río Blanco facility was operating at full 24 hour/day capacity (it is reportedly not doing so), it would be producing electricity valued at $32,400 per day ($11.8M/y).

The U.S. 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, El Yunque National Forest, Puerto Rico, U.S. Forest Service, September 8, 2015). The American Sportfishing Association (2007) quantifies the economic value of visits to U.S. 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. Birdwatching is one the principal wildlife-viewing activities as Puerto Rico, in combination with the U.S. Virgin Islands, has approximately 270 species of birds (Raffaele, 1989). Additonally, there is great interest in the dwindling populatations of the once widely-distributed Puerto Rican parrot. Between 2000 and 2003, an estimated annual average of $3.2M was spent in Puerto Rico for wildlife viewing associated with the EYNF (ASA, 2007). 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. U.S. 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.

Puerto Rico is susceptible to earthquake, tsunami, landslide, and flood hazards, listed here in order of increasing frequency and associated loss of life during the 500 years of recorded history. Because earthquakes and tsunamis are beyond the scope of this paper, the reader is refered to reviews by von Hillebrandt-Andrade and Huerfano (1999) and Clinton et al. (2006).

The island of Puerto Rico is characterized as being moderately to highly susceptible to landsliding (Monroe, 1979). The majority of landslides documented during the 20th century were triggered by intense or prolonged rainfall (Monroe, 1979; Jibson, 1989; Larsen and Simon, 1993; Larsen and Torres-Sànchez, 1998; Larsen, 2012). During the period 1959 to 1991, 41 storms caused 10's to 100's of landslides on the island, resulting in infrastructure damage and loss of life (Larsen and Simon, 1993). The worst of these was in 1985 when 129 people were killed (Fig. 4); most of these deaths were in a single unplanned community on a hillslope near the city of Ponce (Jibson, 1989).

Although rainfall-triggered landslides are relatively common, a large earthquake could also cause 100's of landslides in the steeply sloping regions of San Juan and elsewhere in Puerto Rico. Most secondary (two-lane) roads are likely to be blocked and access to communities will be extremely limited. Seismic hazard mitigation is mainly achieved through well-based planning, zoning, and construction practices, all of which are a function of strong governance. In addition to these requirements, maintenance of forest on and near hillslopes can, to some degree, minimize earthquake-induced landslide hazard, mainly through limiting the impact of small rockfalls.

Mitigation of landslide hazard is achieved largely through the practices of strong governance, as described above. 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 (Fig. 5) (Keefer and Larsen, 2007). 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 streamflow in rivers, spreading the runoff volume over a larger time step than would occur if no forest was present (Ogden et al., 2013).

Larsen and Torres Sanchez (1998) documented a higher average frequency of landslides on hillslopes in agricultural land use as well as in land used for roads and structures in three regions of Puerto Rico, and showed that although mean annual rainfall is high, intense storms are frequent, and hillslopes are steep, forested hillslopes are relatively stable as long as they are not modified by humans. The greater the modification of a hillslope from its original, forested state, the greater the frequency of landslides. Additionally, in the three regions of Puerto Rico studied by Larsen and Torres Sanchez (1998), a slope angle in excess of 12° is a threshold above which the frequency of landslides increased, demonstrating that maintenance of forest cover on steeper hillslopes is particularly important.

In it's 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 (Ramos-Gines, 1999). 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. Strong governance is also evident in Puerto Rico where an effective 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.

Venezuela

Vargas State, on the Caribbean coast, just north of Caracas, is the geographic focus of this example. Located at 10° 36’ north latitude, Vargas is a narrow rectilinear state that extends some 50 km to the east from the Caracas airport (Aeropuerto Internacional Simón Bolívar), on the Caribbean coast at Maiquetilla. Vargas is notable with respect to hazard vulnerability because its population is essentially all on densely populated coastal alluvial fans. These communities are bounded closely on their south by a 2,000 m high east-west trending mountain range with steeply sloping, forested hillslopes, the Sierra del Litoral, known as the Sierra de Ávila, much of which is a forested preserve established in 1958 now called Parque Nacional Waraira-repano. The crest of the Sierra de Ávila rises 2,765 m above sea level within 6-10 km of the coast. The rivers and streams of this mountainous region drain to the north and emerge from steep canyons onto alluvial fans before emptying into the Caribbean Sea. The rainy season in coastal Venezuela normally lasts from May through October. Mean annual precipitation at the International Airport at Maiquetia, which is 43 m above mean sea level, is 750 mm [MARN, 2000]. However, there is a strong orographic gradient and annual rainfall can exceed 1,000 mm in the upper areas of the Sierra de Ávila. This moisture gradient and a marked dry season explain the multiple forest types that are present in the Sierra de Ávila, which although are largely evergreen forest, range from xeric and dry tropical forest in the low elevations to montane wet forest and sub-páramo forest at upper elevations, to cloud forest near the mountain crests.

The Vargas state began a period of rapid development beginning in the 1970's, taking advantage of a multi-lane highway connecting the city of Caracas with the Caracas airport located on the coast at Maiquetia. Relatively little low-gradient area is available in Vargas for development, with the exception of the alluvial fans, where by the late 1990's, the population had grown to approximately 300,000. Because most Vargas residents had lived there for less than a few decades, local knowledge of debris-flow and flood hazard was limited prior to a major storm in 1999 (Larsen and Wieczorek, 2006).

Economically quantifiable ecosystem services derived from the Sierra de Ávila are modest. Streams are short and steep, eliminating hydropower as an option and limiting potable freshwater withdrawals. Because of the steep gradients and narrow canyons through which streams flow, few areas exist for water storage, so water extraction is restricted to local, low-volume run-of-the river intakes and small impoundments. In addition, because of strong seasonal rainfall variation, the smaller catchments host only ephemeral streams, making water supply unreliable.

Recreational use is perhaps the greatest economic value of the Sierra de Ávila, with the national park (Parque Nacional El Ávila) serving visitors and residents of the adjacent city of Caracas, with a population of 5.2M. Visitation to the park consists mainly of day-hikers who use an extensive hiking trail network. Two cableways carry visitors from Caracas and from Macuto (in Vargas) to the top of the mountain (Pico El Ávila) where the now-closed Humboldt Hotel, and few small facilities exist for recreation and food purchase. Extensive recreational use is limited in part because of modest economic investment in facilities and trail maintenance. Carbon sequestration and maintenance of biodiversity are other important services derived from the mostly forested Ávila mountains, but these have not been well documented and are beyond the scope of this paper.

The population of Vargas is vulnerable principally to tsunami, seismic, landslide, and flood hazards, listed in order of increasing frequency, but not necessarily potential impact (Wieczorek et al., 2002; Larsen and Wieczorek, 2006; USGS, 2015).

Landslides and flooding are relatively common in Vargas. Historical records indicate that severe flooding and/or landslides occurred in this region in 1740, 1780, 1797, 1798, 1909, 1912, 1914; 1938, 1944, 1948, 1951, and 1954 (Rohl 1950, Singer et al., 1983, Audemard et al., 1988, Salcedo, 2000; Lopez et al., 2003). Because of the extremely steep stream channels and short channel lengths, the floods are invariably flash floods, which are particularly hazardous as little to no warning can be given to downstream communities in this area. Furthermore, because stream channels actively laterally erode and migrate across alluvial fans, riparian corridors in these geomorphic settings are among the most hazardous environments in the world. During floods, channels can quickly agrade their beds and shift to steeper gradient areas of the alluvial fan.

A rare, high-magnitude storm in northern Venezuela in December 1999 triggered debris flows and flash floods, and caused one of the worst natural disasters in the recorded history of the Americas. Cumulative rainfall of 293 mm during the first 2 weeks of December was followed by an additional 911 mm on December 14 through 16. An estimated 10,000 to 15,000 people were killed and 15,000 people were rendered homeless when approximately 41,000 houses were damaged, with almost half of these structures being declared uninhabitable. The debris flows and floods inundated coastal communities on the alluvial fans at the mouths of the coastal mountain drainage network and destroyed property estimated at more than $2 billion (Fig. 6). Landslides were abundant and widespread on steep slopes from near the coast to slightly over the crest of the mountain range. Some hillsides were entirely denuded by single or coalescing failures, which formed massive debris flows in river channels flowing out onto the densely populated alluvial fans at the coast (Fig. 7). The massive amount of sediment derived from 24 watersheds along the 50 km of coastline during the storm and deposited on alluvial fans and beaches has been estimated at 15 to 20M m^3 (Larsen and Wieczorek, 2006). Sediment yield for the 1999 storm from the approximately 200 km^2 drainage area of watersheds upstream of the alluvial fans was as much as 100,000 m^3/km^2. The combination of rapid economic development, much of it unplanned and unregulated, the dynamic geomorphic environment (ie. extremely steep hillslopes with high-gradient streams), the recent large population taking advantage of proximity to the capital city of Caracas, and the severe rain storm, all contributed in the death of approximately 5% of the population (300,000 total prior to the storm) in the Vargas state.

By 2006, Vargas state population had partially returned to the population estimated in 1999, and rebuilding of damaged infrastructure was in progress. However, the value of real estate had declined by as much as 70%. In the 15 years following the disaster, governmental work has focused on the construction of 5,000 houses, plus 63 small dams and 22 kilometers of stream channelization as part of an effort to reduce some of the flood potential (Fernandez, 2009; Noriega Ávila, 2014) . In addition, approximately 500 kilometers of roads are being reconstructed. Many of the damaged homes remain so, with a number of these being occupied without legal title by those who lost their homes in the 1999 disaster.

Discussion

Maintaining forest cover in watersheds provides numerous important ecosystem services including a service that reduces, but does not eliminate hazards such as landslides and floods. A recent example of this in Panama, as described by Espinosa (2011), was the 2010 storm of record for the Canal. Landslide and flood impacts would likely have been far worse if the less of the watershed had been forested. According to the ACP, dam and lock infrastructure was at design limits during the storm runoff and could well have been damaged had more runoff occurred, as would have been the case if less of the watershed was forested (Stallard, 2015). Furthermore, landsliding was likely reduced because steeply sloping hillslopes are mostly forested, which of course, limits exposure through prevention of human occupation and development of infrastructure in these settings. The additional benefit is that that forest cover generally results in fewer landslides in most montane settings (Keefer and Larsen, 2007).

Like Panama, Puerto Rico gains similar natural hazard reduction benefits from maintaining forest on hillslopes, which is particularly important because much of the island is mountainous, with numerous small communities distributed throughout the countryside. Unfortunately, some of these communities are located on, or at the base of steep hillslopes and along riparian corridors, which, typical of a largely mountainous region, offer one of the relatively few low-gradient locations chosen for housing and other infrastructure such as schools and hospitals (Fig. 5). In addition, limited economic opportunity means that a number of unplanned, unregulated communities exist, in locations where individuals or groups have occupied otherwise unused land, in hazardous areas along coasts, steep hillslopes, and riparian corridors. These areas are typically zoned as no-build areas, but without strong local and national governance, sometimes become unregulated, informal settlements (Fig. 5).

In the Venezuela example, some degree of hazard mitigation was afforded by the stewardship of forested watersheds with the establishment of Parque Nacional Waraira-repano. This national park, upstream of the coastal communities that developed rapidly after 1970, provides an ecosystem service because it is forested, but because it has extremely steep slope gradients and episodic high-intensity rainfall, the protective effect of the forest cover is limited (Figs. 6, 7). The mitigation effect of the forested national park during the 1999 storm was further reduced because of two additional factors: 1) the extremely rare storm magnitude, estimated to have an approximate recurrence interval variably estimated at between 150 and 1,000 years (Larsen and Wieczorek, 2006); and, 2) the lack of planning and regulation in the siting of houses and other structures on extremely vulnerable alluvial fans along the Vargas coast (Figs. 6,7).

Alluvial fans are one of the most hazardous geomorphic settings on earth (Fig. 8). The fans exist because flash floods and debris flows emanating from stream channels draining steep mountain fronts episodically deliver massive quantities of water and sediment out into lower gradient valleys fronting mountain ranges. Over time scales of centuries to millennia, which is of course beyond human lifetime experience, thereby limiting the accumulation of direct observational knowledge, these episodic events slowly build the fan surface in a largely unpredictable, violent fashion. As such, structures built on the alluvial fan are likely to be impacted or destroyed unless significant, detailed planning and costly preventative engineering works are undertaken.

The location of structures as far away from the mountain front and stream channels as possible reduces their vulnerability. Other protective measure are engineered structures such as barriers in stream channels and large debris-flow/flashflood catchment basins located upstream of communities (Fig. 9). The challenges associated with these structures are the initial high cost to build them and the sustained high cost of maintaining them, including the requirement for regular removal of any sediment and debris trapped in the basins. Additionally, without strong governance and planning, these types of engineering works, like levees along rivers, sometimes serve to increase vulnerability by giving a false sense of security to those who might choose (or have no economic alternative) to reside on or near a mountain front or river flood plain (White, 1945; Palmer et al., 2015).

Unfortunately, "*Although landslide hazard evaluation and mitigation strategies are advancing in many fundamental areas, the loss of life and destruction of property by landslides around the world will probably continue to rise as the world population increases, urban areas of many large cities impinge* *more on steep slopes, and deforestation and other human landscape alterations affect ever-larger areas*." (Keefer and Larsen, 2007).

Conclusions

Panama, Puerto Rico, and Venezuela provide examples of water resources and other ecosystem services derived from forested watersheds, and offer insights into how we consider and take advantage (or sometimes ignore) the value of hazard mitigation as an ecosystem service. Each location shows the benefits and limitations of the ecosystem services provided by forested watersheds with respect to water supply and hazard mitigation. The examples also show the importance of the maintenance and expansion of forest cover in montane watersheds as well as strong governance, which includes well informed science- and engineering-based infrastructure zoning, planning, and design.

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 (ISDR, 2005). Additionally, timely access to and communication of accurate information associated with hazards, ie. precipitation, streamflow, estimated fire probability, landslide probability predictions, and tsunami warnings from governmental entities, is key to effective response of at-risk communities so that loss of life is minimized.

The examples presented here illustrate a key limitation of hazard mitigation as an ecosystem service: natural hazards are highly stochastic in nature. The timing, frequency, and magnitude of catastrophic events is confoundingly difficult (floods, landslides), or impossible (earthquakes) to precisely predict, (seismically-triggered tsunamis cannot be predicted, but because there is often lead time of minutes to hours following the causative earthquake, warnings can be issued). However, with detailed, long-term study, a probability of occurrence for a given region can be estimated at scales of 10's to 100's of km^2, with reasonable confidence. Predictive science is most advanced with respect to flood hazard (Bales et al., 2007; FEMA, 2012). A more general approach is used for earthquake hazard, by necessity because as yet, we cannot predict when a seismic event will occur (Peterson et al., 2014). A similar approach applies for estimating landslide hazard, as science is unable to determine exactly when, or which hillslope will fail, and where on a given hillslope, during or after intense or prolonged rainfall. Landslide rainfall thresholds and generalized maps showing failure probability are most commonly used at present (Caine, 1980; Keefer et al., 1987; Larsen and Simon, 1993; Baum and Godt, 2010). These models give civil defense officials a tool that can be used to issue warnings or alerts, and to define hazardous areas on maps made available to the public.

Flood hazard is the most predictable of the hazards discussed here: we know where floods are most likely to affect population and infrastructure. Flood hazard can be well estimated using topographic maps and streamflow records to provide well constrained maps of flood probability and magnitude (Bales et al., 2007; FEMA, 2012). Sadly, in spite of this knowledge, flooding remains the leading cause, throughout the world, for loss of life associated with natural hazards. This is a failure, not of science and engineering as much as one of poverty, limited economic development, and a lack of strong governance (IPCC, 2014; United Nations, 2011, 2014). As stated by Gilbert White: *Floods are an act of God, but flood losses are largely an act of man.* (White, 1945). A similar unattributed Spanish language statement: "*Dios siempre perdona, el hombre a veces, la naturaleza nunca*".

Furthermore, flood (and landslide) hazard mitigation challenges are now increasing because the long-standing approach for estimating flood probability is based on the principal of stationarity, which means that the present likelihood of floods in a watershed can be well determined by examining the past 30 or more years of streamflow record. This approach has been weakened by changing rainfall and streamflow patterns observed in recent decades (Milly et al., 2008). The IPCC (2014) 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.

To gain the maximum hazard mitigation value of ecosystem services from forested watershed, we can take advice from Kofi Annan:
"*Our tasks are clear. Development, land use and habitation policy must be informed by a thorough understanding of the scientific and technical requirements of prevention.*" Kofi Annan, former UN General Secretary (Annan, 1999).

Lastly, this set of examples emphasizes the need for a science-based approach to placing an economic value on hazard mitigation, which will always be difficult to precisely calculate anywhere because, as stated by former U.N. Secretary General Annan, "*the benefits are not tangible; they are the disasters that did NOT happen*".

Acknowledgements

Funding support for work on this paper was derived through the budget of the Smithsonian Institution. This paper was improved by comments from Robert F. Stallard, U.S. Geological Survey, Stanley Heckadon, Smithsonian Tropical Research Institute, Pedro Delfin, Universidad Central de Venezuela, and anonymous reviewers.

References

Annan, Kofi, 1999. NY Times editorial. Sept. 10, 1999. http://www.nytimes.com/1999/09/10/opinion/10iht-edannan.2.t.html

Annan, Kofi, 2002. Foreword to Living with Risk: A Global Review of Disaster Reduction Initiatives, (UN/ISDR). Quoted in UN/ISDR, 2003: Disaster Reduction and Sustainable Development. A background paper for the World Summit on Sustainable Development; http:// www.unisdr.org (2006):1.

ASA, 2007. American Sportfishing Association (ASA). State and National Economic Effects of Fishing, Hunting and Wildlife-Related Recreation on U.S. Forest Service-Managed Lands. Report prepared for the Wildlife, Fish and Rare Plants U.S. Forest Service U.S. Department of Agriculture. 15 November 2013: http://www.fs.fed.us/biology/resources/pubs/wildlife/usfs_wildlife_based_recreation_economic_contributions_1_03_07.pdf

Audemard, F. A., De Santis, F., Montes, L., Lugo, M., and Singer, A., 1988. El alud torrencial del 6-9-1987 del Río Limón, al norte de Maracay, Estado Aragua. Informe Interno FUNVISIS (Fundación Venezolana de Investigaciones Sísmicas), Caracas, Venezuela, 9 p.

Bales, J.D., Wagner, C.R., Tighe, K.C., and Terziotti, Si., 2007. LiDAR-derived flood-inundation maps for real-time flood-mapping applications, Tar River basin, North Carolina. U.S. Geological Survey Scientific Investigations Report 2007–5032, 42 p.

Baum, R.L., and Godt, J.W, 2010. Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7, p. 259-272

Benz, H.M., Tarr, A.C., Hayes, G.P., Villaseñor, Antonio, Furlong, K.P., Dart, R.L., and Rhea, Susan, 2011. Seismicity of the Earth 1900–2010 Caribbean plate and vicinity. U.S. Geological Survey Open-File Report 2010–1083-A. scale 1:8,000,000.

Bush, M.B., McMichael, C.H., Piperno, D.R., Silman, M.R., Barlow, J., Peres, C.A., Power, M., Palace, M.W., 2015. Anthropogenic influence on Amazonian forests in prehistory: An ecological perspective. Journal of Biogeography.

Caine, N, 1980. The rainfall intensity-duration control of shallow landslides and debris flows. Geografiska Annaler 62A, 23-27.

Chavez-Tafur, Jorge and roderick J. Zagt (eds.)., 2014. Towards Productive Landscapes. Tropenbos International, Wageningen, The Netherlands, 224 pp.

Clinton, J.F., Cua, G., Huerfano, V., von Hillebrandt-Andrade, C. G., Martinez Cruzado, J., 2006. The current state of seismic monitoring in Puerto Rico. Seismological Research Letters 77, p 532.

Cochard, R., 2013. Natural Hazards Mitigation Services of Carbon-Rich Ecosystems, in, Ecosystem Services and Carbon Sequestration in the Biosphere, Eds: Lal, R., Lorenz, K., Hüttl, R.F., Schneider, B.U., von Braun, J., Springer Science and Business Media, Dordrecht. p 221-293.

Colinvaux, P., and Bush, M.B., 1991. The rain-forest ecosystem as a resource for hunting and gathering. American Anthropologist 93. 153-160.

Condit, R.S., Robinson, D.W., Ibanez, R., Aguilar, S., Sanjur, A., Martinez, R., Stallard, R.F., Garcia, T., Angehr, G.R., Petit, L.J., Wright, S. J., Robinson, T.R., and Heckadon-Moreno, S., 2001. The Status of the Panama Canal Watershed and Its Biodiversity at the Beginning of the 21st Century. Bioscience 51(5), 135-144.

Crook, K.E., Scatena, F.N., and Pringle, C.M., 2007. Water Withdrawn From the Luquillo Experimental Forest, 2004. U.S. Department of Agriculture, Forest Service, General Technical Report GTR-IITF 34. 26 p.

Cuevas, J. A., 2011. The Panama Canal Authority's Flood Control Program, in, Building Knowledge Bridges for a Sustainable Water Future, Proceedings of the Second International Symposium on Building Knowledge Bridges for a Sustainable Water Future, Panama, Republic of Panama, 21-24 November, 2011. Published by the Panama Canal Authority (ACP) and UNESCO.

Dentan, R. K., 1991. Potential food sources for foragers in Malaysian rainforest; Sago, yams and lots of little things. in: Bijdragen tot de Taal-, Land- en Volkenkunde 147, no: 4, Leiden, 420-444.

Dolan, J.F. and Mann, P., 1998. Active strike-slip and collisional tectonics of the northern Caribbean Plate Boundary Zone. Geological Society of America Special Paper 326, 174 p.

FAO, 1997. Food and Agriculture Organization, State of the World's Forests, FAO, United Nations, Rome, Italy.

FEMA, 2012. Risk Map, Community engagement. Federal Emergency Management Agency. www.fema.gov/rm-main 2 p.

Fernandez, A., 2009. Complaints and Ruins 10 Years after Vargas, Venezuela Flooding Tragedy.Latin American Herald Tribune. http://www.laht.com/article.asp?CategoryId=10717&ArticleId=348951 accessed on September 17, 2015.

Garwood, N.C., Janos, D.P., Brokaw, N., 1979. Earthquake-caused landslides: a major disturbance to tropical forests. Science 205, 997-9.

Gould, W.A., Martinuzzi, S., and Parés-Ramos, I.K., 2012. Land use, population dynamics, and land-cover change in eastern Puerto Rico, ch. B in Murphy, S.F., and Stallard, R.F., eds., Water quality and landscape processes of four watersheds in eastern Puerto Rico. U.S. Geological Survey Professional Paper 1789, p. 25–42.

Gross, D., 2014. Why Is Puerto Rico Burning Oil to Generate Electricity? Slate. http://www.slate.com/articles/business/the_juice/2014/05/puerto_rico_is_burning_oil_to_generate_electricity_it_s_completely_insane.html accessed on September 8, 2015.

Hall, J.S., Kirn, V., and Yanguas Fernández, E., eds. 2015. Managing watersheds for ecosystem services in the steepland neotropics. Inter-American Development Bank. IDB Monograph 340. 186 p.

Hansen, M. C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A. Tyukavina, A., Thau, D., Stehman, S.V. Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., and Townshend,J. R. G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850-853.

Harris, N.L.; Lugo, A.E.; Brown, S.; and Heartsill Scalley, T. (eds.), 2012. Luquillo Experimental Forest: Research history and opportunities. EFR-1. Washington, DC: U.S. Department of Agriculture. 152 p.

Hart, T. B., and Hart, J.A., 1986. The ecological basis for hunter-gatherer subsistence in African rain forests: the Mbuti of eastern Zaire. Human Ecology 14, 29-55.

Headland, T. N., and Bailey, R. C., 1991. Introduction: Have Hunter-Gatherers Ever Lived in Tropical Rain Forest Independently of Agriculture? Human Ecology 19, 115-122.

Heckadon Moreno, S., and Ibáñez, R., eds., 1999. La Cuenca del Canal: deforestación, urbanización y contaminación. Instituto Smithsonian de Investigaciones Tropicales. 120p. http://pdf.usaid.gov/pdf_docs/pnaea549.pdf

IDB, 2008. Panama Canal Expansion Program. Inter-American Development Bank Environmental and Social Management Report PN-l1032. 38 p.

IDAAN. 2015. Instituto de Acueductos y Alcantaeillados Nacional. http://www.idaan.gob.pa/ accessed September 2, 2015.

Ibáñez, R., Condit, R.S., Angehr, G.R., Aguilar, S., Garcia, T., Martinez, R., Sanjur, A., Stallard, R.F., Wright, S.J., Rand, A.S., and Heckadon-Moreno, S., 2002. An Ecosystem Report on the Panama Canal: Monitoring the Status of the Forest Communities and the Watershed. Environmental Monitoring and Assessment 1, 65-95.

IPCC, 2014. Climate Change 2014. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

ISDR, 2005. Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters. World Conference on Disaster Reduction 18-22 January 2005, Kobe, Hyogo, Japan. International Strategy for Disaster Reduction. Extract from the final report (A/CONF.206/6) www.unisdr.org/wcdr 25p.

Jibson, R.W., 1989. Debris flows in southern Puerto Rico. Geological Society of America Special Paper 236, p. 29-55.

Keefer, D.K., Wilson, R.C. Mark, R.K., Brabb, E.E., Brown, W.M., Ellen, S.D., 1987. Real-time landslide warning during heavy rainfall. Science 238, p. 921-925.

Keefer, D.K., and Larsen, M.C., 2007. Assessing Landslide Hazards. Science, 316, p. 1136-1138.

Kim, D.H., Sexton, J.O., and Townshend, J. R., 2015. Accelerated deforestation in the humid tropics from the 1990s to the 2000s. Geophys. Res. Letters 42, doi:10.1002/2014GL062777.

Kosoya, N., Martinez-Tunaa, M., Muradianb, R., Martinez-Aliera, J., 2007. Payments for environmental services in watersheds: Insights from a comparative study of three cases in Central America. Ecological Economics 61, Issues 2–3, 1, p. 446–455.

Larsen, M.C., 2012. Global change and water resources, where are we headed? Water Resources Impact, American Water Resources Association 14, no. 5, p. 3-7.

Larsen, M.C., 2012. Landslides and sediment budgets in four watersheds in eastern Puerto Rico, Ch. F in Murphy, S.F., and Stallard, R.F., eds., Water quality and landscape processes of four watersheds in eastern Puerto Rico. U.S. Geological Survey Professional Paper 1789, p. 153-178.

Larsen, M.C. and Parks, J.E., 1997. How wide is a road? The association of roads and mass-wasting disturbance in a forested montane environment. Earth Surface Processes and Landforms 22, p. 835 848.

Larsen, M.C., and Simon, Andrew, 1993. Rainfall-threshold conditions for landslides in a humid-tropical system, Puerto Rico: Geografiska Annaler 75A (1-2), p. 13-23.

Larsen, M.C., and Torres-Sanchez, A.J., 1998. The frequency and distribution of recent landslides in three montanetropical regions of Puerto Rico. Geomorphology 24, p. 309-331.

Larsen, M.C., and Torres Sanchez, A.J., 1998. The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico. Geomorphology 24, p. 309-331.

Larsen, M.C. and Webb, R.M.T., 2009. Potential effects of runoff, fluvial sediment and nutrient discharges on the coral reefs of Puerto Rico. Journal of Coastal Research 25, p. 189-208.

Larsen, M.C., and Wieczorek, G.F., 2006. Geomorphic effects of large debris flows and flash floods, northern Venezuela, 1999. Tropical Geomorphology with Special Reference to South America, Latrubesse, Edgardo, ed., Zeitschrift für Geomorphologie Suppl. 145, p. 147-175.

Larsen, M.C. and Santiago-Román, Abigail, 2001. Mass wasting and sediment storage in a small montane watershed: an extreme case of anthropogenic disturbance in the humid tropics, in Dorava, J. M., Palcsak, B.B., Fitzpatrick, F. and Montgomery, D., eds., Geomorphic Processes and Riverine Habitat: American Geophysical Union, Water Science & Application Series 4, p. 119-138.

Larsen, M.C., 2000. Analysis of 20th century rainfall and streamflow to characterize drought and water resources in Puerto Rico. Physical Geography 21, 494-521.

Leakey, R., 1994. The Origin Of Humankind. Perseus Book Group. 171 p.

Leigh, E. G., Rand, A. S., Windsor, D. M., eds., 1983. The ecology of a tropical forest: Seasonal rhythms and long-term changes. Smithsonian Institution Press, Washington D.C., 468 p.

Liu, H., Masera, D. and Esser, L., eds., 2013. World Small Hydropower Development Report 2013. United Nations Industrial Development Organization; International Center on Small Hydro Power. www.smallhydroworld.org.

Lopez, J.L., Bello, M.E., Gonzalez, N., Toyo, A., Shucheng, Z., Peng, C. & Fangquiang, W., 2003. Lecciones aprendidas de la tragedia de Vargas: el caso de Carmen de Uria. Acta Cientifica Venezolana 54, p. 49-62.

MARN, 2000. Informe Preliminar Sobre los Aspectos Ambientales Vinculadas al Desastre Natural Ocurrido en Venezuela Durante el Mes de Diciembre de 1999. Ministerio del Ambiente y de los Recursos Naturales, Venezuela, unpublished report, 55 p.

Martín, J.G., Mendizábal, T., Schreg, R., Cooke, R.G., Piperno, D., 2015. Pre-Columbian raised fields in Panama: First evidence. Journal of Archaeological Science, Reports 3, 558–564.

MEA, 2003. Millennium Ecosystem Assessment. Ecosystems and Human Well-Being: A Framework for Assessment. Washington DC: Island Press. http://www.maweb.org accessed on September 19, 2015.

Milly, P.C.D., Betancourt, J. Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity is dead: whither water management. Science 319, p. 573-574.

Monroe, W. H., 1979. Map showing landslides and areas of susceptibility to landsliding in Puerto Rico. U.S. Geological Survey Miscellaneous Investigations Series Map I-1148, scale 1:240,000.

Murphy, S.F. and Stallard, R.F., eds., 2012a. Water quality and landscape processes of four watersheds in eastern Puerto Rico. U.S. Geological Survey Professional Paper 1789. 292 p.

Murphy, S.F., and Stallard, R.F., 2012b. Hydrology and climate of four watersheds in eastern Puerto Rico—Chapter C, in Murphy, S.F. , and Stallard, R.F., eds, Water quality and landscape processes of four watersheds in eastern Puerto Rico. U. S. Geological Survey Professional Paper 1789–C, p. 43-84.

NOAA, 2009. Tropical cyclones of the North Atlantic Ocean, 1851 – 2006. Historical climatology series 6-2. National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, Washington, DC. 239 p.

Noble, I.R. and Dirzo, R., 1997. Forests as Human-Dominated Ecosystems. Science 277, p.522-525.

Noriega ÁVILA, N., 2014. Venezuelan Vargas state still bears the scars of a tragedy. El Universal. http://www.eluniversal.com/nacional-y-politica/141220/venezuelan-vargas-state-still-bears-the-scars-of-a-tragedy accessed September 18, 2015.

Ogden, F.L., Crouch, T.D., Stallard, R.F., and Hall, J.S., 2013. Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama, Water Resources Research 49, no. 12, p. 8443-8462.

Palmer, M.A., Liu, J., Matthews, J.H., Mumba, M., D'Odorico, P. 2015. Manage water in a green way. Science 349, p. 584-585.

Panama canal, 2014. Annual report, 2014, 120 p. http://www.pancanal.com/eng/general/reporte-anual/index.html

Panama canal, 2015. (http://www.pancanal.com/eng/general/canal-faqs/physical.html accessed September 2, 2015)

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014. Documentation for the 2014 update of the United States national seismic hazard maps. U.S. Geological Survey Open-File Report 2014–1091, 243 p.,

PRASA, 2012. Puerto Rico Aqueduct and Sewer Authority report. 500 p. http://www.gdb-pur.com/investors_resources/documents/praqueductsewerauth02a-fin-295mm.pdf

Raffaele, H.A., 1989. A Guide to the Birds of Puerto Rico and the Virgin Islands. Princeton, New Jersey: Princeton University Press.

Ramos-Ginés, O., 1999. Estimation of magnitude and frequency of floods for streams in Puerto Rico: New empirical models. U.S. Geological Survey Water-Resources Investigations Report 99-4142, 41 p.

Rohl, E., 1950. Los diluvios en las montañas de la cordillera de la costa. Boletín de la Academia de Ciencias Físicas, Matemáticas y Naturales, Venezuela 38, p.1-28.

Salcedo, D.A., 2000. Los flujos torrenciales catastróficos de Diciembre de 1999, en el estado Vargas y en Caracas: Características y lecciones apprendidas. Memorias XVI Seminario Venezolano de Geotecnica, Caracas, p. 128-175.

SCEP, 1970. Study of Critical Environmental Problems, Man's Impact On The Global Environment - Assessment and Recommendations for Action: Cambridge, Massachusetts, The MIT Press, 319 p.

Sherrod, D.R., Vallance, J.W., Tapia Espinosa, A., and McGeehin, J.P ., 2008. Volcán Barú—eruptive history and volcano-hazards assessment. U.S. Geological Survey Open-File Report 2007–1401, 33 p., 1 plate, scale 1:100,000.

Simkin, T., Tilling, R.I., Vogt, P.R., Kirby, S.H., Kimberly, P., and Stewart, D.B.. 2006. This dynamic planet: World map of volcanoes, earthquakes, impact craters, and plate tectonics. U.S. Geological Survey Geologic Investigations Series Map I-2800, scale 1:30,000,000 (http://mineralsciences.si.edu/tdpmap/).

Singer, A, Rojas, C. and Lugo, M., 1983. Inventario nacional de riesgos geológicos, mapa, glosario y comentarios. Serie Técnica FUNVISIS, Fundación Venezolana de Investigaciones Sísmicas 03-83, 126.

Smith, R., 2014. A hundred years old today, the Panama canal is about to get a lot bigger. National Geographic. http://news.nationalgeographic.com/news/2014/08/140815-panama-canal-culebra-cut-lake-gatun-focus/?rptregcta=reg_free_np&rptregcampaign=2015012_invitation_ro_all# Accessed September 2, 2015.

Stallard, R.F., Ogden, F.L., Elsenbeer, H., and Hall, J., 2010. Panama Canal Watershed Experiment: Agua Salud Project. Water Resources Impact 12, no. 4, p. 17-20.

Stallard, R.F., 2015. Understanding Natural Capital, part A: Geophysical Context, in Hall, J.S., Kirn, V., and Yanguas Fernández, E., eds. 2015. Managing watersheds for ecosystem services in the steepland neotropics. Inter-American Development Bank. IDB Monograph 340. p. 20-34.

UN Secretary General. 1999. "Introduction to Secretary-General's Annual Report on the Work of the Organization of United Nations, 1999" document A/54/1.

United Nations, 2011. World Urbanization Prospects, The 2011 Revision. UN Department of Economic and Social Affairs/Population Division, 318 p.

United Nations, 2014. Department of Economic and Social Affairs, Population Division (2014). World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

USGS, 2015. U.S. Geological Survey. Historic world earthquakes. http://earthquake.usgs.gov/earthquakes/world/historical_country.php#venezuela accessed September 12, 2015.

von Hillebrandt-Andrade, C. G., Huerfano, V. A., 1999. Contributions of the Puerto Rico seismic network toward seismic hazard assessment, awareness, and emergency response. Seismological Research Letters 70, no.2, p. 272.

von Thünen, J.H., 1842. Der isolierte Staat in Beziehung auf landwirtschaft und Nationalökonomie. 3rd Edition. Berlin, Rostock.

Walker, L.R. and Bellingham, P., 2011. Island Environments in a Changing World. Cambridge University Press, Cambridge, U.K. ISBN: 9780521732475

White, G.F., 1945. Human Adjustment to Floods. University of Chicago Department of Geography Research Paper No. 29. University of Chicago Department of Geography.

Wieczorek, G.F., Larsen, M.C., Eaton, L.S., Morgan, B.A. & Blair, J.L. 2002. Debris-flow and flooding deposits in coastal Venezuela associated with the storm of December 14-16, 1999. U.S. Geological Survey, Geologic Investigation Series Map I-2772. http://pubs.usgs.gov/imap/i-2772/

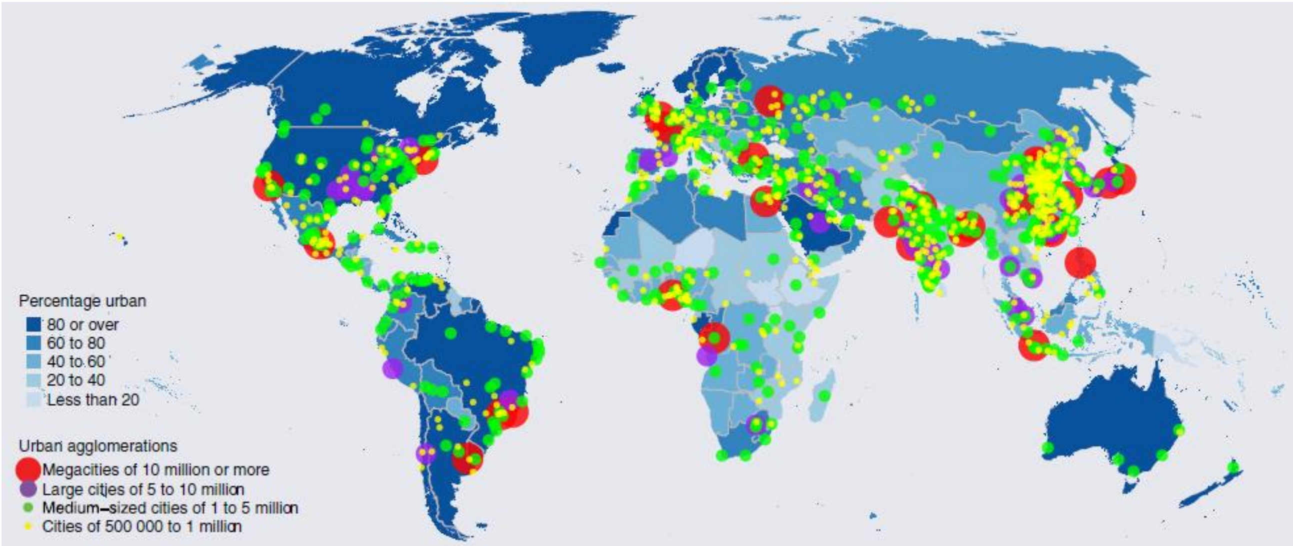

Figure 1. Locations of large urban areas with at least 0.5M inhabitants, 2014. Source: United Nations, 2014.

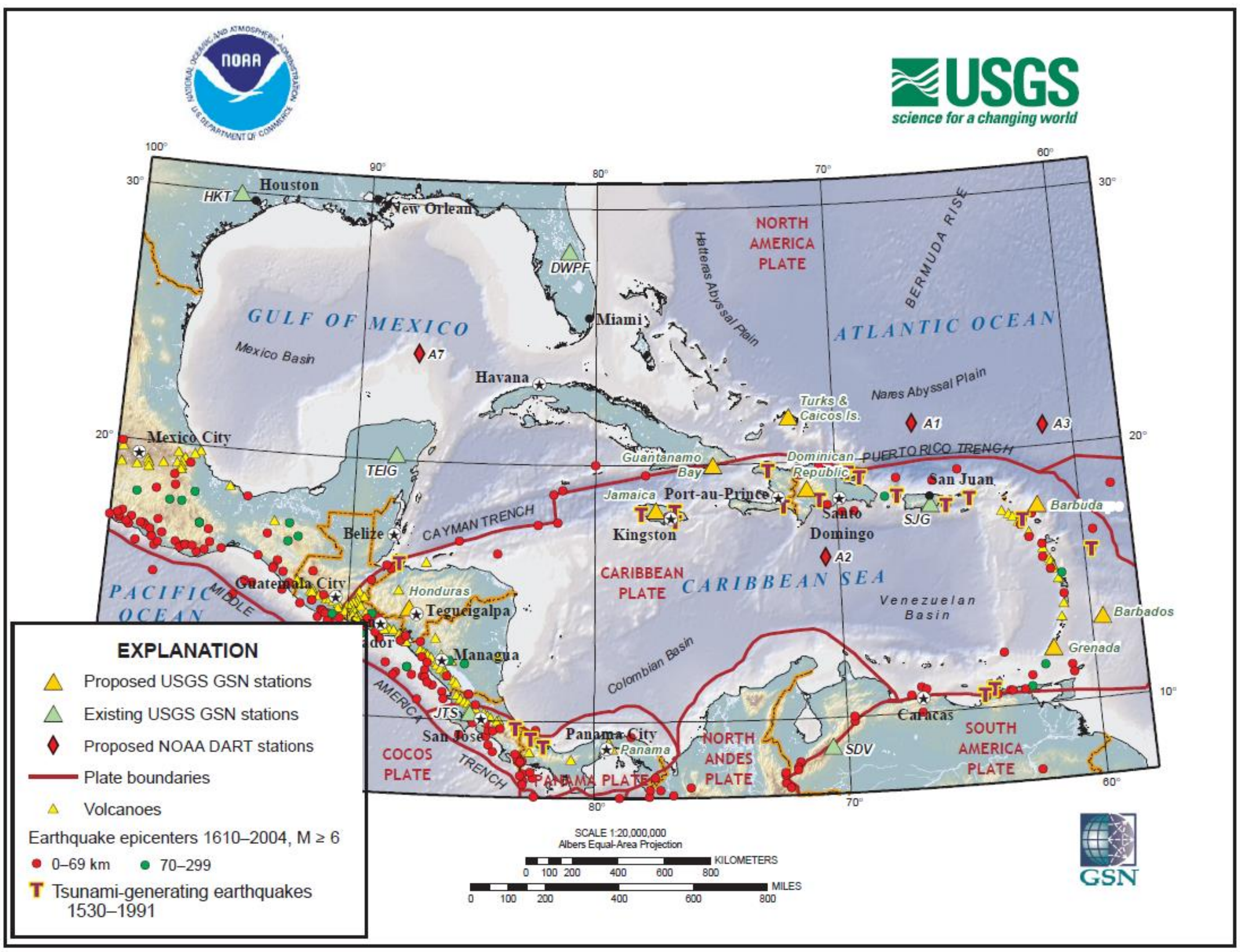

Figure 2. Simplified tectonic map showing plate boundaries, major geologic hazards, and locations of Panama, Puerto Rico, and Venezuela. Global Seismographic Network (GSN) and Deep-ocean Assessment and Reporting of Tsunamis (DART) stations are part of a U.S. federal agency hazard warning network. Source: McNamara et al. 2006. U.S. Geological Survey.

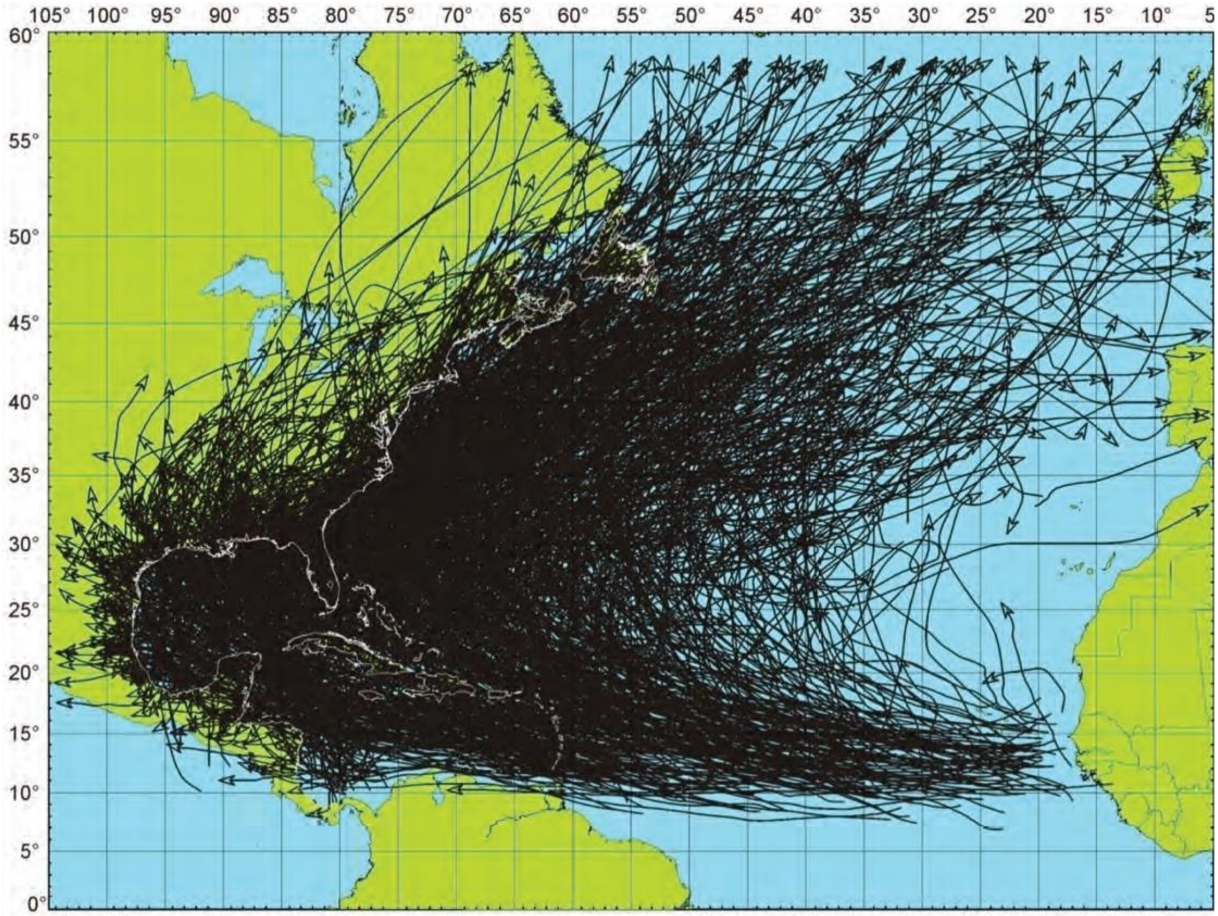

Figure 3. North Atlantic tropical storms and hurricanes, 1851-2006. Source: NOAA, 2009.

Figure 4. Unplanned community on steep unstable bedrock, Barrio Mameyes, Ponce, southern Puerto Rico. Photo source: R. Jibson, USGS, 1985. Hillslope failure killed 129 people (Jibson, 1989).

Figure 5. Vulnerability to debris flow hazard of homes and other structures at the base of steep hillslopes such as this one in Penuelas, southern Puerto Rico. Photo source: R. Jibson, USGS, 1985.

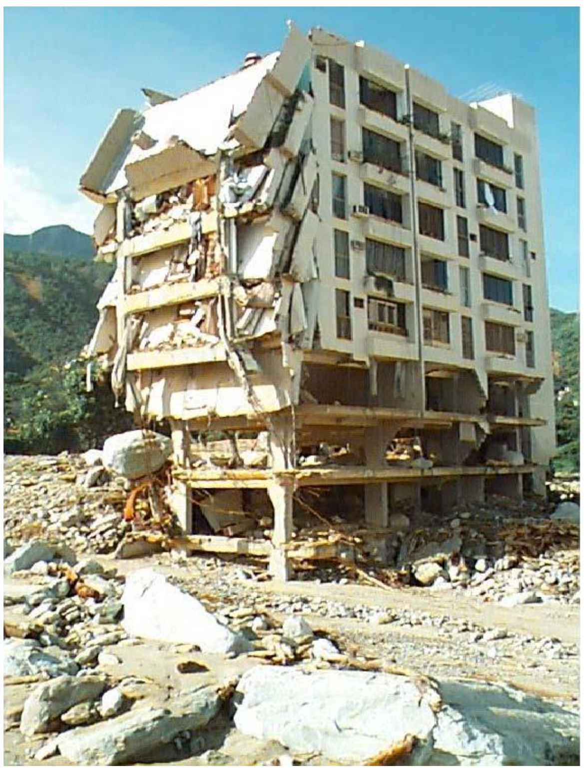

Figure 6. Apartment buildings damaged by debris flows and flash floods, 1999, Caraballeda, Vargas, Venezuela.
Photo source: M.C. Larsen, January 2000.

Figure 7. View to south, Vargas, Venezuela, showing numerous landslide scars on steep hillslopes and narrow river channel emanating from Sierra de Ávila mountain front onto highly developed coastal alluvial fan.
Note shoreline progradation resulting from massive quantity of sediment delivered onto and across alluvial fan.
Photo source: M.C. Larsen, January 2000.

Figure 8. Vargas state, Venezuela, view to east along Caribbean coast showing landslide scars and a series of highly developed alluvial fans at the mouths of multiple stream channels at Sierra de Ávila mountain front. Photo source: M.C. Larsen, January 2000.

Figure 9. Concrete-lined stream channel emerging from mountain front, Sierra de Ávila, Vargas, showing vertical barriers designed to reduce transport of debris flow material onto downstream alluvial fans.