

SINKHOLES AND KARST IN PUERTO RICO: PICTURESQUE AND PROBLEMATIC

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Abstract

The karst landscapes of Puerto Rico cover nearly 30% of the island, occurring on the north and south coasts and in small patches throughout the central part of the Commonwealth. The karst is expressed through dramatic inland and coastal landforms, extensive limestone aquifers, coastal wetlands and estuaries, and through the many caves and cave systems that drain the landscape. An important feature of Puerto Rico's karst are sinkholes which form from a variety of processes including dissolution of underlying strata, collapse of subterranean voids, and landslides. From a touristic perspective, sinkholes have served as major attractions in Puerto Rico e.g. Tres Pueblos Sinkhole, Arecibo Observatory telescope located within a large sinkhole, and the route of the Rio Tanama through a series of collapsed sinkholes. Analysis of sinkhole occurrence and density have shown that sinkhole development is a measure of karstification. However, despite touristic and academic interest, sinkholes pose major challenges to land development and are also subject to human impact. In the most extensive karst area, on the North Coast, it is reported that there are over 4,300 documented sinkholes, giving a sinkhole density of 5.4/km² with a mean sinkhole depth of 19 m. Improved availability of digital terrain, and other GIS data allow a fresh look at karstification of the island and the ever-growing impact of human development on the karst. Typical problems include groundwater contamination, foundation instability, and storm-induced road collapses.

Introduction

The karst landscapes of Puerto Rico cover nearly 30% of the island, occurring on the north and south coasts and in small patches throughout the central part of the Commonwealth (Figure 1). The karst is expressed through dramatic inland and coastal landforms, extensive limestone aquifers, coastal wetlands and estuaries, and through the many caves and cave systems that drain the landscape. An important feature of Puerto Rico's karst are sinkholes. They are an inherent part of the karstification process and contribute to the ruggedness of the terrain. Closed depressions, some of which may be classified as sinkholes, can form from a variety of erosional processes including dissolution of underlying strata, collapse of subterranean voids, collapse of cover sediments, and non-karst processes such as landslides, and wind excavation of blanket sands.

From a touristic perspective, sinkholes have served as major attractions in Puerto Rico e.g. Tres Pueblos Sinkhole, Arecibo Observatory telescope located within a large sinkhole, and the eco-tour route of the Rio Tanama through a series of collapsed sinkholes. At the same time, sinkholes pose a challenge to the installation and maintenance of human infrastructure. New sinkholes can form from the interaction of infrastructure on bedrock. Severe weather events can cause sinkhole flooding or formation of new sinkholes.

In the present paper an examination is made of the state of knowledge of Puerto Rican Karst, and human impacts on karst, specific to sinkholes, with concerns/case stud-

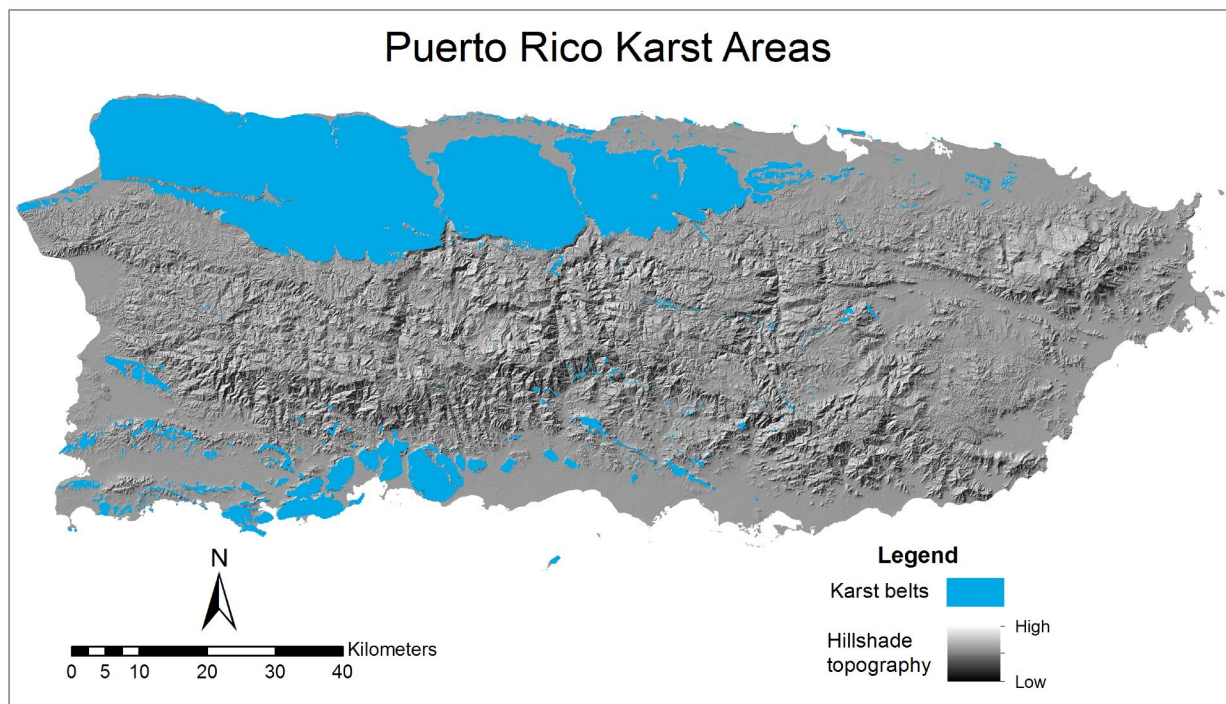


Figure 1. Karst areas of Puerto Rico. Derived from: Alemán González, 2010.

ies shared as well as frequency analyses of areas with deep sinkholes (those greater than 30 meters in depth).

Background

Geology

Puerto Rico can be divided into three basic geological provinces. The oldest rocks comprise a central volcanic-plutonic province which trends east-west and represents the higher terrains with elevations up to 1337 m. The central core rocks are from Late Jurassic to Early Cretaceous age and consist of serpentinite, and amphibolite, chert and basalt (Krushensky and Monroe, 1978; Volckmann, 1984a, 1984b, 1984c). Lower terrains on the north and south coasts consist primarily of carbonate lithologies, with lesser terrigenous beds, and ages from 34 to 14 million years before present (Ma), and thicknesses up to 1,220 m (Briggs, 1965; Monroe, 1980). These strata dip gently towards the coastlines. Blanket deposits ("blanket sands") of probable Pliocene age cover portions of the island, up to 30 meters thick (Briggs, 1965; Monroe, 1980). These infill many of the depressions in the limestone belt, and virtually bury lower elevations of the entire karst terrain.

Hydrology

Puerto Rico receives substantial annual rainfall, especially in the interior highlands where up to 100 inches (2540 mm) may fall (Figure 2). Climate and rainfall distribution on the karst belts are determined by the orographic effect. The north coast is the windward side of the island receiving 50-80 inches (1270-2030 mm) of rain per year on average. The leeward south coast receives only 30-60 inches (760-1520mm) of precipitation. The differences in climate result in different rates of karstification (Lugo et al., 2001).

Giusti (1978) conducted a detailed study of the hydrology of the Puerto Rico karst. The karst belts consist of aquifers that receive recharge via two different modes. Allogenic runoff from large catchment areas of the island's igneous core form surface rivers that dissect the north and south karst belts en-route to ocean base level. Some of the allogenic recharge sinks at or near the igneous-limestone contacts at the edges of the karst belts. Autogenic runoff from the karst belts recharges the underlying drainage systems which ultimately resurge into the surface rivers or possibly to submarine springs. The Atlantic Ocean and Caribbean Sea are the ultimate base levels on the north and south coasts respectively.

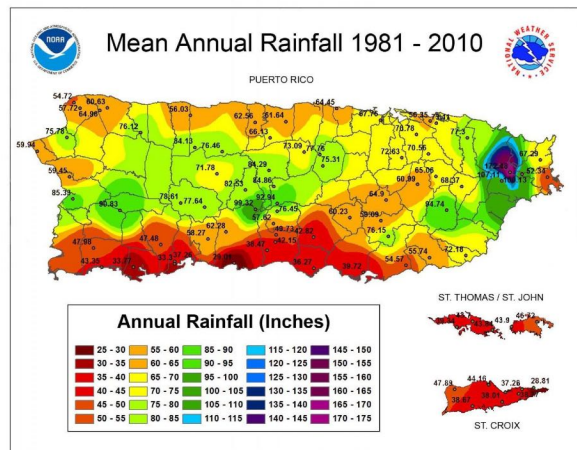


Figure 2. Map showing distribution of rainfall on Puerto Rico. Source: NOAA 2010.

The karst aquifers consist of relatively young and porous limestones separated by clay layers that act as confining units. This creates a stacked series of aquifers (Figure 3) both on the north and south coast, many of which are confined (artesian). The ultimate discharge for these waters is the ocean, but little is known about the submarine springs,

The overall pattern of groundwater flow is radial, away from the central highlands, as is typical in an island setting.

Geomorphology

The island of Puerto Rico contains a combination of karst and fluvial landforms (fluvio-karst). Initial observations were made by Monroe (1976) and Giusti (1978) who conducted much of the original karst research on Puerto Rico. The variety of landforms are a function of lithology and climate (Lugo et al. 2001).

The northern karst belt is composed of limestone units that generally strike east to west and with a dip of about 1-degree North and form linear cuestas that hold many sinkholes. The southern limestones are more structurally influenced with overall dips of 5 degrees or more, to the south. Sinkholes tend to be rare in these units. Remnants of Cretaceous-age carbonates are scattered throughout the interior of the island and represent relicts of past landscapes formed as erosion modified the hydrology of the region. Though the older carbonates tend to be more resistant to erosion than adjacent igne-

ous rocks, enclosed depressions of up to 50 m have been documented in some of the Cretaceous segments (Miller et al., 2009). A variety of geomorphic features characterize the various limestone units including cockpits, cone karst, dry valleys, mogotes and towers, zanjones and caves. (White 1988).

Sinkholes Overview

Puerto Rico has an abundance of sinkholes that are inherent features of the different karst landscapes. Naturally occurring sinkholes form by several different processes. Dissolution sinkholes form where aggressive water first contacts a soluble bedrock surface. Bedding planes, joints, and/or fractures focus water flow into the bedrock. Dissolution can also take place at the zone of water-table fluctuation where groundwater is in contact with the atmosphere.

Sinkhole occurrence and morphology are highly affected by the stratigraphic units on which they occur. (Lugo et al., 2001). Density of sinkhole development is a function of topographic relief which is exemplified on the North coast by areas of land located north of the Cibao Formation where sinkholes occur on 50% of the land surface (Lugo et al., 2001).

Bedrock collapse sinkholes, which are rare, occur when the ceiling of a cave collapses, exposing the cave passage to the surface. Bedrock collapse sinkholes develop as a function of the influence on the stability of bedrock, and are dependent on the geology of the area, including geologic structures, and the maturity of the process in relation to geologic time.

Cover-subsidence sinkholes can occur where covering sediments are permeable and contain sand cover. In areas where surface sediments are thicker or contain more clay, incipient cover subsidence sinkholes can go undetected for extended time periods.

Sinkhole formation can also be initiated or accelerated by human development and cover-subsidence sinkholes are the most common type associated with development. These sinkholes tend to impact infrastructure like roads and buildings. Triggers for these types of sinkholes include: 1) Weather events such as heavy rainfall, or drought followed by rain; 2) Changes in natural water-drainage patterns due to construction or new

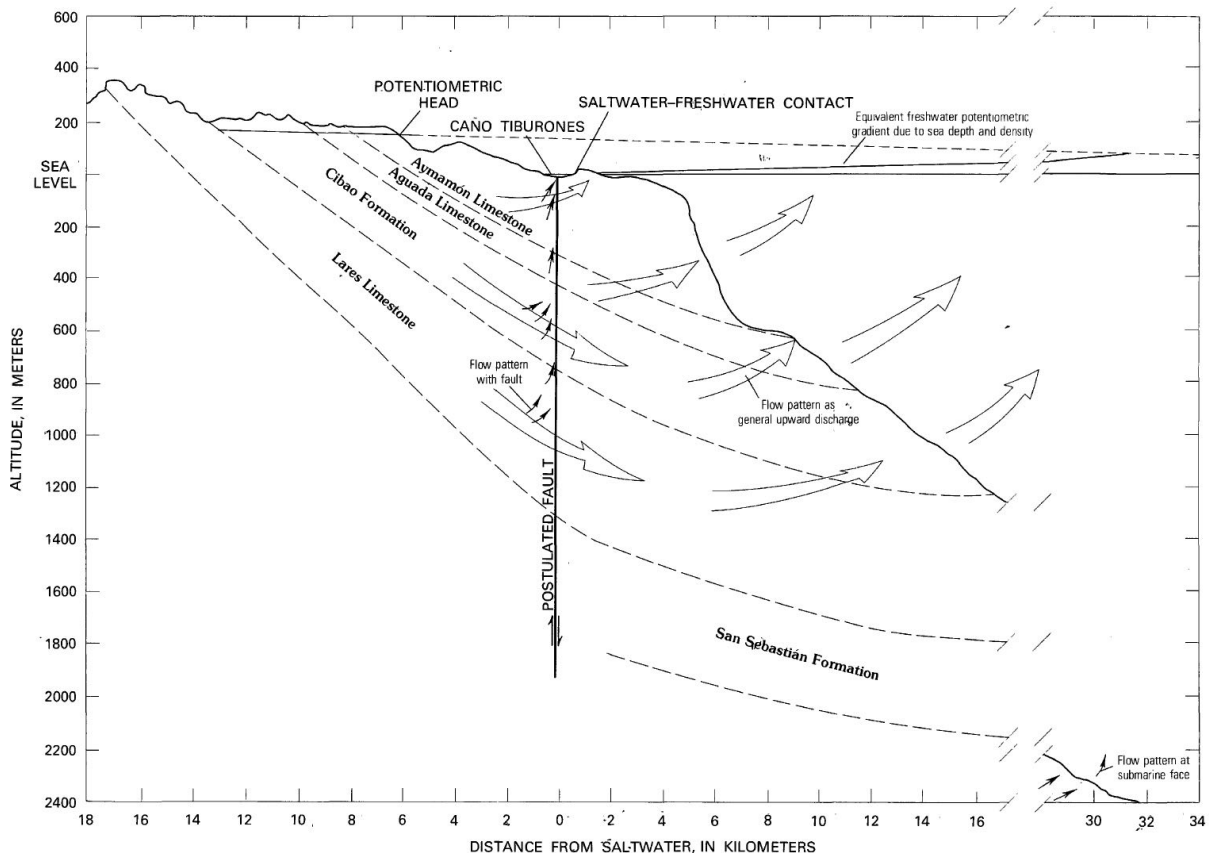


Figure 3. Cross section showing general configuration of aquifers in the north coast karst belt. 10x vertical exaggeration. From: Giusti, 1978.

water-diversion systems 3) Changes in load on the land surface such as when industrial and runoff-storage ponds are created, and when the substantial weight of the new material triggers an underground collapse of supporting material 4). Significant ground water pumping.

Digital terrain data (USGS National Elevation dataset) along with sinkhole data from the USGS National and Puerto Rican Karst Maps (Weary and Doctor 2014; Alemán González, 2010) provided an opportunity to examine the distribution of sinkholes on the island and their relationship to infrastructure (Figure 4). The Karst Map data sets contain georeferenced polygons for 1,172 sinkhole areas that commonly have sinkholes that are greater than 30 m in depth. A broader area has sinkholes 5-30 m deep. A dataset of individual sinkholes is not currently available. The distribution plot (Figure 5) shows that the majority of sinkhole areas having the deeper sinkholes are smaller than 8,000 m² or less, but that one area is over 430,000 m². Map overlays show the

interaction of population, karst and sinkholes, and major roads (Figure 4), which will be discussed further below.

Sinkholes Case Studies

Superfund site

The north coast of Puerto Rico has seen extensive commercial development, due to the presence of prolific aquifers throughout the region, as well as numerous historical tax incentives (both federal, section 936 of the US tax code, and Commonwealth of Puerto Rico) designed to lure industry to the island. The RCA del Caribe site (Figure 6) was a manufacturing facility located near the town of Barceloneta, approximately 30 miles (48 km) west of San Juan, and 5 miles (8 km) inland from the Atlantic Ocean, and within the North Coast Karst belt. Information in this section is drawn from the three volume Remedial Investigation Report for the facility (Nittany Geoscience, Inc., 1994). The primary site ac-

Puerto Rico Karst Areas

major roads, sinkhole distribution, high population density

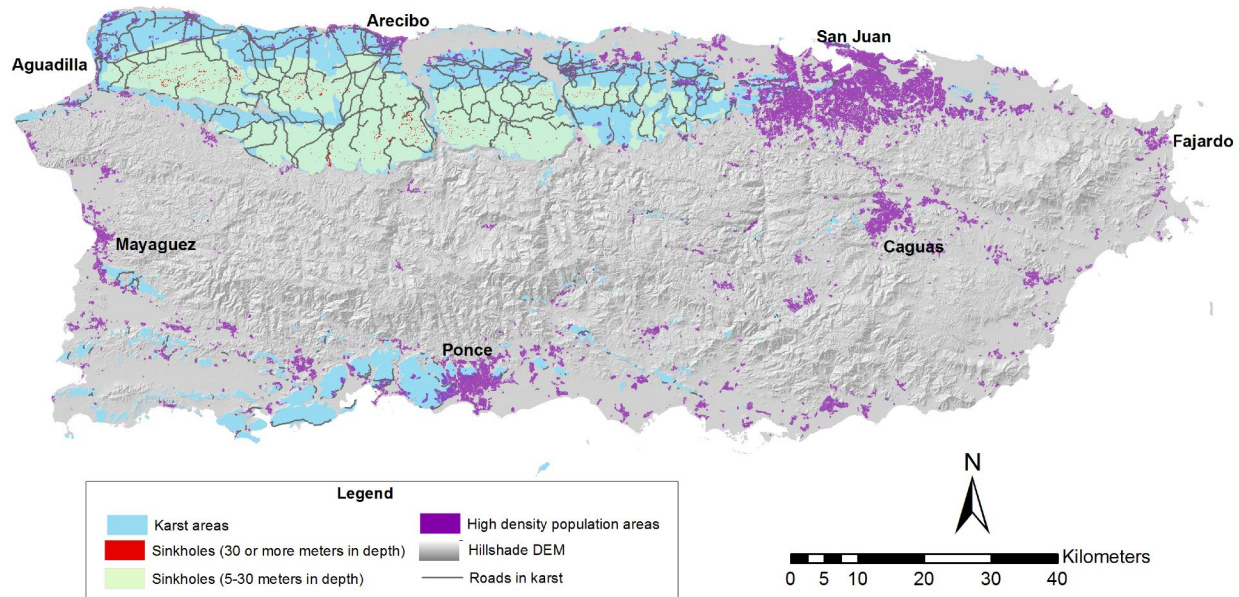


Figure 4. Map showing relation of Puerto Rico karst and dense sinkhole areas to high population density and major roads. Derived from Gould et al. 2008 and Alemán González, 2010.

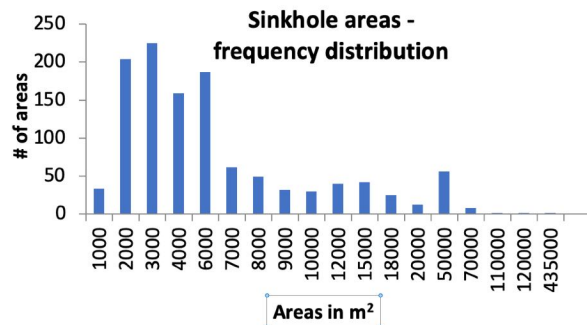


Figure 5. Frequency distribution of areas having many sinkholes > 30m deep. Based on data from Alemán González, 2010.

tivity was the manufacture of cathode ray tube aperture masks. In this process, sheets of metal were etched with a strong acid, and the excess ferric chloride solution was stored in 4 lined lagoons which had been constructed in the 1970s. Over an approximate three-year period from 1978 to December 1981, each of the lagoons failed due to sinkhole development beneath them, releasing approximately 1,000,000 gallons (3,800 m³) of extremely low pH metal-rich solution into the groundwater. This led to concerns about groundwater, spring, and drink-

ing water quality in the region. Additionally, wastewater treatment plant effluent was regularly discharged from 1971-1987 to an on-site natural sinkhole permitted for disposal. This sinkhole received about 490,000 gallons (1,850 m³) of effluent per day.

In December 1982 the site was placed on the National Priorities List (NPL, Superfund), and a remedial investigation was begun. The site underwent an extensive study which included review of the physical characteristics and facility background, the regional hydrogeology, and former manufacturing operations. Specific methods involved included analysis of topographic maps, soils investigation, an on-site hydrogeologic investigation which included monitoring well installation and repair of an artesian well, a karst hydrogeologic investigation which included aquifer and tracer tests, geochemical modelling, and a flow path investigation. Groundwater flow in the uppermost aquifer was determined to be in a northward direction, towards the Atlantic Ocean. However, conditions at the site were complicated by the presence of a 1,167 foot (356 m) deep supply well which had been drilled into the underlying artesian aquifer, the Montebello Member of the Cibao Formation.

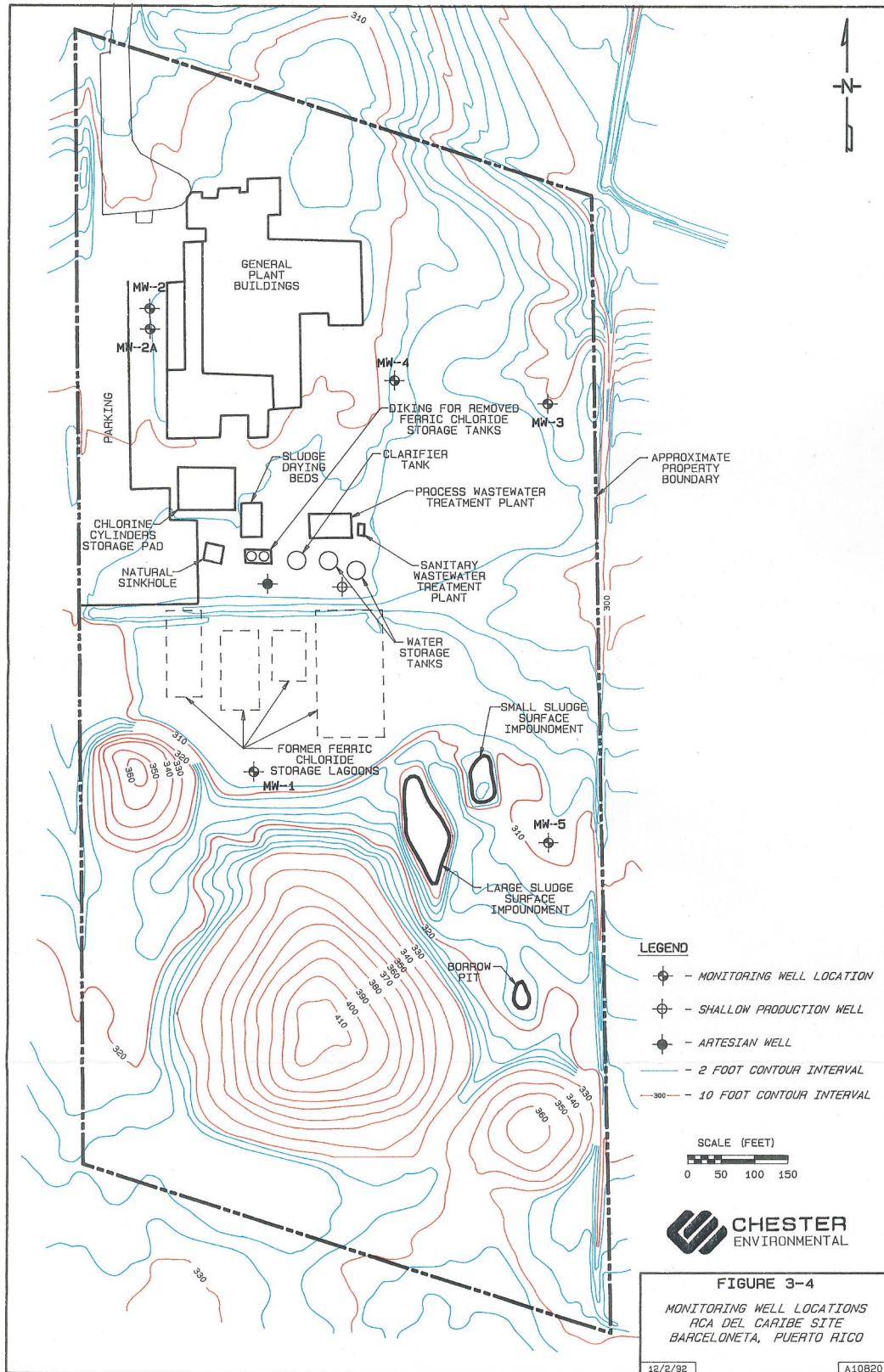


Figure 6. Plan map of the RCA del Caribe Barceloneta facility showing buildings, on-site sinkhole, and adjacent mogote topography. Source: Nittany Geoscience, 1994.

Failure of the well casing seal at the confining unit was allowing copious upward leakage of water from the artesian aquifer into the overlying water table aquifer; a >250 foot (>76 m) head difference was present. The uppermost aquifer is karstified, probably quite extensively, though no evidence of open conduits was found. The site is overlain by blanket deposits, and all of the karst cavities are infilled with sediments. From this perspective, the groundwater flow system was characterized as diffuse. Nevertheless, pore velocities as high as 10 to 100 feet (3 to 30 m) per day were determined from tracer tests. These were interpreted to be the result of highly conductive beds in the lower Aguada Limestone. However, the end result of the study revealed a surprisingly benign outcome.

Geochemical modeling showed that upon failure of the ferric chloride containments, the acidic solution came into contact with the limestone and was immediately neutralized. This rise in pH resulted in the precipitation of the metals from the solution, and their immobilization within the strata. Consequently, the only ongoing and off-site impact to groundwater was a benign diffuse chloride plume. The final decision for the site was that no further remedial action was necessary.

Coastal Cave Collapses

The well-known caves of the North Coast karst of Puerto Rico, and those within the Cretaceous blocks of limestones that are scattered through the central parts of the island, are either active or relict and fluvio-karstic in nature. An ongoing coastal karst inventory project (Miller et al., 2009) has revealed that there are also a significant number of coastal caves on the Atlantic and Caribbean coastlines of the island that have an origin as either littoral, flank margin (mixing zone), or flank margin overprinted by littoral processes. On the north coast, the caves occur at various elevations from sea level to the top edges of many of the rocky cliffs. Though most of the entrances open towards the major water bodies, many also have additional entrances formed by natural surface collapse into the voids (Miller et al., 2009).

During recent inventory field work a flank margin cave was discovered on the north coast of the island at approximately 60 m above sea level. Survey of the cave documented a main access point at the cliff line and sev-

eral collapses (sinkholes) inland of the cliff. Limestone overburden is less than 6 m. Construction equipment was observed to be clearing land less than 100 m from the section of the cliff containing the cave. A return visit six months later noted that a 3-story apartment complex had been built close to the cave-containing cliff. Coastal erosion is likely to result in more surface collapse into the cave which could pose future problems for the apartment infrastructure. This is just one example of commercial land development that has begun to encroach the coastal cliffs and pose a threat to the caves and to the overlying infrastructure. The construction of new beach house structures and resorts are having negative impact on the coastal karst resources of the island.

Storm Induced Cover Collapse

Many of Puerto Rico's main highways and roads traverse the north coast karst where naturally occurring sinkholes abound (Figure 4). (Soto and Morales 1984) However, it is the human-induced sinkholes that negatively impact development infrastructure in these areas.

The hurricanes of 2017 caused significant damage to Puerto Rico. Included among the geohazards triggered by the hurricanes were sinkhole collapses that damaged homes and road infrastructure (Thorne, 2017). One of the most notable sinkhole collapses occurred on Highway 2, which is a main artery between San Juan and Ponce. The heavy rains wrought by Hurricane Maria caused extensive flooding under the highway and resulted in a rupture of a water main. The water scoured away the sediment beneath the road forming a void which eventually collapsed forming a sinkhole 30 m long and 6 m deep that backed up traffic for miles.

The sinkhole was of the cover collapse variety, occurring entirely within the soil profile. These are the most common and catastrophic causes of ground failure in karst terrains (Waltham 2008). Cover collapse sinkholes are typically caused when some sort of ground disturbance due to engineering activity affects the natural drainage of an area (Waltham and Fookes, 2003). As hurricanes become more intense and frequent, cover collapse sinkholes will likely continue to wreak havoc on the roads traversing Puerto Rico's karst regions.

Summary

Sinkhole development has a complex history in Puerto Rico. The nature of the tropical karst produces landscapes that are defined by the dense distribution of sinkholes. The evolution of a carbonate coastline results in new sinkhole development from littoral and erosional processes. The growth of population and supporting infrastructure also induces increased sinkhole development. Severe weather, coupled with roads built across extensive karst regions bring catastrophic sinkhole collapses to what have become main travel arteries. Necessary remediation of sinkhole collapses adds to the growing economic challenges of the island.

References

- Briggs RP. 1965. Geologic map of the Barceloneta quadrangle, Puerto Rico. U.S. Geological Survey Investigations Map 1-42 1, 1 sheet, scale 1:20,000.
- Alemán González WB. 2010. Karst map of Puerto Rico: U.S. Geological Survey Open-File Report 2010-1104, 1 map sheet, scale 1:140,000, online at: <https://pubs.usgs.gov/of/2010/1104>.
- Giusti EV. 1978. Hydrogeology of the karst of Puerto Rico. USGS Professional Paper 1012, 68 p.
- Gould WA, Martinuzzi S, Ramos González OM. 2008. High and low density development in Puerto Rico. Scale 1: 260 000. IITF-RMAP-11. Río Piedras, PR: USDA Forest Service, International Institute of Tropical Forestry. <https://www.fs.usda.gov/detailfull/iitf/home/?cid=fseprd581486>
- Lugo A, Miranda-Castro L, Vale A, del Mar López T, Hernández-Prieto E, García Martínó A, Puente-Rolón AR, Tossas AG, McFarlane DA, Miller T, Rodríguez A, Lundberg J, Thomlinson J, Colón J, Schellekens JH, Ramos O, Helmer E. 2001. Puerto Rican karst – A Vital Resource. General Technical Report WO-65, US Department of Agriculture – Forest Service, 99 p.
- Miller TM, Kambesis PN, Lace M. 2009. Neighboring Countries: The Caribbean: Puerto Rico. In: Palmer AN, Palmer MV, editors. *Caves and Karst of the USA*. Huntsville, AL, National Speleological Society, p. 332-345.
- Krushensky RD, Monroe WH. 1978. Geologic map of the Penuelas and Punta Cuchara quadrangles. Puerto Rico. U.S. Geological Survey Miscellaneous Investigations Series Map 1-1042, 1 sheet, scale 1:20,000
- Monroe WH. 1976. The karst landforms of Puerto Rico. USGS Professional Paper 899, 69 p.
- Monroe WH. 1980. Some tropical landforms of Puerto Rico. USGS Professional Paper 1159, 39 p
- Nittany Geoscience, Inc. 1994. Remedial Investigation Report for RCA del Caribe, Inc., Barceloneta, Puerto Rico. 3 volumes, various page numbers.
- NOAA. 2010. Puerto Rico Mean Annual Rainfall, 1981-2010. https://www.weather.gov/images/sju/hydrology/2010_ncdc_precip_normals_PR_USVI.jpg
- Palm R, Hodgson M. 1993. Natural Hazards in Puerto Rico. *Geographical Review* 83 (3): 280-289.
- Soto AE, Morales W. 1984. Collapse Sinkholes in the Blanket Sands of the Puerto Rico Karst Belt. p. 143-152. In: Beck BF (editor), *Proceedings of the 1st Multidisciplinary Conference on Sinkholes*, Orlando, Florida AA Balkema, Rotterdam, p. 143-146.
- Thorne G. 2017. The 2017 Hurricanes didn't just hit Puerto Rico – they hit the Caribbean. *The Nation*, <https://www.thenation.com/article/the-2017-hurricanes-didnt-just-hit-puerto-rico-they-hit-the-caribbean/> retrieved October 1, 2019.
- Troester JW, White EL, White WB. 1984. A comparison of sinkhole depth frequency distributions in temperate and tropic karst regions. In: Bec BF (editor). *Proceedings of the First Multidisciplinary Conference on Sinkholes* (Orlando, Florida). AA Balkema, Rotterdam, p. 65-74.
- USGS National Elevation Dataset. Retrieved October 28, 2019, <http://ned.usgs.gov/>
- Volckman RP. 1984a. Geologic map of the Cabo Rojo and Parguera quadrangles, southwest Puerto Rico. U.S. Geological Survey Miscellaneous Investigations Series Map 1-1557. 1 sheet, scale 1:20,000.
- Volckman RP. 1984b. Geologic map of the San German quadrangle, southwest Puerto Rico. U.S.

Geological Survey Miscellaneous Investigations
Series Map 1-1558. 1 sheet, scale 1:20,000.

Volckman RP. 1984c. Geologic map of the Puerto
Real quadrangle, southwest Puerto Rico. U.S.
Geological Survey Miscellaneous Investigations
Series Map 1-1559, 1 sheet, scale 1:20,000.

White WB. 1988. Geomorphology and Hydrology of
Karst Terrains. New York, NY: Oxford University
Press. 464 p.

Waltham AC, Fookes PG. 2003. Engineering
classification of karst ground conditions.
Quarterly Journal of Engineering Geology and
Hydrogeology 36: 101–118

Waltham AC. 2008. Sinkhole hazard case histories in
karst terrains. Quarterly Journal of Engineering
Geology and Hydrogeology 41 (3):291-300.

Weary, D.J., and Doctor, D.H., 2014, Karst in the
United States: A digital map compilation
and database: U.S. Geological Survey Open-
File Report 2014–1156, 23 p., [http://dx.doi.
org/10.3133/ofr20141156](http://dx.doi.org/10.3133/ofr20141156).