National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Big Thicket National Preserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1779

ON THE COVER
The wide and shallow Neches River meanders across its floodplain. National Park Service photograph by Chuck Hunt in National Parks Conservation Association (2005).
THIS PAGE
Bald cypress swamp within Big Thicket National Preserve. National Park Service photograph in NPS (2014)

Big Thicket National Preserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1779

Trista L. Thornberry-Ehrlich

Colorado State University Research Associate
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

October 2018

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (https://www.nps.gov/im/publication-series.htm). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov

Please cite this publication as:

Thornberry-Ehrlich, T. L. 2018. Big Thicket National Preserve: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/1779. National Park Service, Fort Collins, Colorado.

NPS 175/148867, October 2018

Contents

Executive Summary ... **ix**
Products and Acknowledgments ... **xiii**
GRI Products ... xiii
Acknowledgments ... xiii
Geologic Setting and Significance ... **1**
Park Establishment ... 1
Geologic Setting and History ... 1
Geologic Significance and Connections to Human History ... 8
Geologic Features, Processes, and Resource Management Issues ... **13**
Geologic Resource Management ... 13
Oil and Gas Development and Production ... 14
Geologic Map Data ... **49**
Geologic Maps ... 49
Source Maps ... 49
GRI GIS Data ... 50
GRI Map Posters ... 50
Use Constraints ... 50
Literature Cited ... **53**
Additional References ... **57**
Geology of National Park Service Areas ... 57
NPS Resource Management Guidance and Documents ... 57
Climate Change Resources ... 57
Geological Surveys and Societies ... 57
US Geological Survey Reference Tools ... 57
Appendix A: Scoping Participants ... **59**
2008 Scoping Meeting Participants ... 59
2016 Conference Call Participants ... 59
Appendix B: Geologic Resource Laws, Regulations, and Policies ... **61**
Posters ... **in pocket**
Poster 1: Map of Big Thicket National Preserve
Poster 2: 1:250,000 scale geologic map of Big Thicket National Preserve (Texas Water Development Board 2007; bith_geology.mxd)
Poster 3: 1:24,000 scale geologic map of the Beaumont unit (Aronow 1982a; bmnt_geology.mxd)
Poster 4: 1:24,000 scale geologic map of the Beech Creek unit (Aronow 1982b; becr_geology.mxd)
Poster 5: 1:24,000 scale geologic map of the Big Sandy Creek unit (Aronow 1982c; bisa_geology.mxd)
Poster 6: 1:24,000 scale geologic map of the Lance Rosier unit (Aronow 1982d; lanr_geology.mxd)
Poster 7: 1:24,000 scale geologic map of the Little Pine Island Bayou corridor unit (Aronow 1982e; lpis_geology.mxd)
Poster 8: 1:24,000 scale geologic map of the Lower Neches River corridor unit (Aronow 1982f; lone_geology.mxd)
Poster 9: 1:24,000 scale geologic map of the Menard Creek corridor unit (Aronow 1982g; menc_geology.mxd)
Poster 10: 1:24,000 scale geologic map of the Neches Bottom and Jack Gore baygall unit (Aronow 1982h; necb_geology.mxd)
Poster 11: 1:24,000 scale geologic map of the Turkey Creek unit (Aronow 1982i; turc_geology.mxd)
Poster 12: 1:24,000 scale geologic map of the Upper Neches River corridor unit (Aronow 1982j; upne_geology.mxd)
Poster 13: 1:500,000 scale land resources map of Big Thicket National Preserve (Kier et al. 1977; bitl_geology.mxd)

Figures

Figure 1. Location map of Big Thicket National Preserve. xiv
Figure 2. Map of the physiographic provinces of Texas. 2
Figure 3. Map of regional geologic structures in Texas..... 3
Figure 4. Geologic time scale. 4
Figure 5. Paleogeographic maps of North America. 5
Figure 6A–C. Illustration of the evolution of the landscape and geologic foundation of Big Thicket National Preserve..... 6
Figure 6D–F. Evolution of the landscape and geologic foundation of Big Thicket National Preserve. 7
Figure 7. Generalized stratigraphic section..... 9
Figure 8. Three-dimensional view of the major geologic units at Big Thicket National Preserve. 10
Figure 9. Cross-sectional view of the fluvial corridors in Big Thicket National Preserve. 20
Figure 10. Illustrations and photographs of fluvial features associated with meandering rivers. 22
Figure 11. Photographs of rivers at Big Thicket National Preserve..... 23
Figure 12. Photograph at the confluence of Village Creek and the Neches River..... 24
Figure 13. Photograph of sand mound. 27
Figure 14. Photographs of common features at abandoned oil and gas sites..... 31
Figure 15. Photographs of disturbed lands and external development..... 33
Figure 16. Photograph of an oil pipeline exposed in Big Sandy Creek. 36
Figure 17. Maps of potential storm surge height and areal extent..... 38
Figure 18. Photograph of the LVNA saltwater barrier of the Neches River..... 39
Figure 19. Flood-inundation map of Pine Island Bayou for the August and September 2017 Hurricane Harvey-related flood event in southeastern Texas and southwestern Louisiana..... 39
Figure 20. Flood-inundation map of the upper reach of the Neches River for the August and September 2017 Hurricane Harvey-related flood event in southeastern Texas and southwestern Louisiana. 40
Figure 21. Flood-inundation map of the lower reach of the Neches River for the August and September 2017 Hurricane Harvey-related flood event in southeastern Texas and southwestern Louisiana. 41
Figure 22. Schematic illustrations of slope movements..... 43
Figure 23. Image of eroding shoreline at Menard Creek and Trinity River. 44
Figure 24. Map of probability of earthquakes with magnitude greater than 5.0 (moderate earthquake). 47

Tables

Table 1. Summary of resource management issues associated with oil and gas development and production. ... 16
Table 2. Summary of Big Thicket habitats and underlying geology. ... 19
Table 3. Summary of fluvial features and processes. ... 21
Table 4. Summary of features and processes associated with wetlands and lakes. ... 25
Table 5. Summary of features and processes associated with sand mounds and salt domes ... 26
Table 6. Summary of features and processes associated with sedimentary units and geologic exposures. ... 28
Table 7. Clastic sedimentary rock classification and characteristics. ... 29
Table 8. Summary of resource management issues associated with mitigation and restoration of abandoned mineral lands and other disturbed lands. ... 30
Table 9. Summary of resource management issues associated with external mineral, resource, and residential development. ... 32
Table 10. Summary of resource management issues associated with river meandering, erosion, and fluvial flooding. ... 34
Table 11. Summary of resource management issues associated with coastal resources, sea level rise, and climate change. ... 36
Table 12. Summary of resource management issues associated with slope movement hazards and risks. ... 42
Table 13. Summary of resource management issues associated with paleontological resource inventory, monitoring, and protection. ... 45
Table 14. Summary of resource management issues associated with seismic activity hazards and risks. ... 46
Table 15. GRI GIS data layers for Big Thicket National Preserve. ... 51
Table 16. Descriptions of land resources units. ... in pocket
Table 17. Considerations for use of land resources units. ... in pocket

Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2008 and a follow-up conference call in 2016 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Big Thicket National Preserve, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. Posters (in pocket) illustrate these data.

Considered the biological crossroads of North America, the Big Thicket, with its swampy lowlands, meandering rivers and creeks, and dense, diverse vegetation, has discouraged human habitation for thousands of years. Other than sporadic American Indian use, the Big Thicket was able to remain a million hectares (almost 2.5 million ac) of almost true wilderness until the timber, railroad, and oil and gas booms of the 1800s and early 1900s. Since that time, human use has fragmented the Big Thicket into smaller and smaller parcels in southeastern Texas. In 1974, Big Thicket National Preserve was authorized as one of the two first national preserves in the National Park System—dedicated to "preserving, conserving, protecting, and enhancing the integrity of the natural and ecological systems in the Big Thicket". Like pearls on a string, the preserve is composed of nine land units connected by six water corridor units, spread over a broad, relatively flat geographical area.

The preserve's landscape is a nearly level, slowly draining plain dissected by rivers and creeks that feed into the Gulf of Mexico where the coastline is dotted with barrier islands, marshes, bays, and estuaries. As a transition zone of four distinct vegetation types, the Big Thicket hosts incredible biodiversity. Flowing water and the geologic foundation of the area are primary controls on the biological system of the preserve.

For at least 250 million years, sediment has accumulated on the Gulf Coastal Plain of Texas. Most of this record is buried deep beneath the preserve but is relevant to the oil and gas history of the area. The oldest mapped geologic unit dates back to the Miocene more than 5.3 million years ago, when sea level was dropping and rivers meandered across a broad, marshy floodplain. Since that time, intermittently rising and falling seas inundated the coastal plain or exposed it to erosion, respectively. This history produced a complicated geologic record with units of different ages juxtaposed, overlapped, and interlayered across the landscape. At present, wind and water are constantly depositing and reworking the surficial geologic units at the preserve including alluvium (river deposits), colluvium (slope deposits), and eolian (windblown) sand.

The diversity of the geologic record and its physical properties directly support the biodiversity at Big Thicket. Well-drained, sandy soils in upland areas allow desert species and diverse forests to flourish there, whereas clay-rich, poorly drained soils underlie wetland savannahs and baygall wetlands—a term that stems from sweet*bay* magnolia and *gall*berry holly (two dominant plants in these wetlands). In some areas, the flood regime flushes away acid-forming organic debris; in other cases, organic debris breaks down in place, forming acid bogs.

This report is supported by GRI-compiled map data of the geology of Big Thicket National Preserve. There are multiple sets of map data that are further described in the "Geologic Map Data" section of this report:

- Small-scale (1:250,000) geologic mapping of the entire preserve by the Texas Water Development Board.
- Larger scale (1:24,000) geologic mapping of 10 of the 15 individual units of the preserve by geologists from Lamar University.
- Small-scale (1:500,000) land resources map data of the entire preserve by the Texas Bureau of Economic Geology.
- Oil and gas well locations (as of 2009) by the Railroad Commission of Texas.

Geologic features, processes, and resource management issues identified for the preserve during GRI scoping, literature research, and a follow-up conference call include the following:

- **Big Thicket Habitats and Underlying Geology**. Due in part to the to the complex interplay of geology, topography, hydrology, and climate, the biodiversity of the Big Thicket is one of the highest in North America with a close proximity of radically different ecosystems and habitats. The boundaries of the Big Thicket ecosystem are not well defined, but the preserve protects as much as 5% of the original area (prior to development).
- **Fluvial Features and Processes**. Flowing water is the unifying resource at the preserve. Major river systems are the Neches River and its tributaries: Little Pine Island Bayou, and Village Creek. Menard Creek flows into the Trinity River. All of the preserve's water ultimately ends up in the Gulf of Mexico. Fluvial features, past and present, include meandering channels, oxbow lakes, point bars, natural levees, backswamps, and terraces. The location of these fluvial features controls the vegetation in those areas. Similarly, the rise and fall of river stages and flows, as well as their timing and duration, set the rhythm of the preserve's water-dependent habitats.
- **Wetlands and Lakes**. The preserve protects diverse lakes and wetlands, which are transitional areas between land and water bodies, where water periodically floods the land or saturates the soil. Preserve examples include freshwater baygall wetlands or wetland shrub bogs, swamp cypress wetlands, acid bogs, and brackish-water estuarine wetlands near the coast. Wetlands function as nutrient sources, sinks, or transformers, and are sensitive to minute changes in water flow regimes and climate. Open-water lakes (as opposed to smaller wetlands) are typically oxbows, formed as river bends were abandoned for another course during channel meandering. Lacustrine features such as oxbow lakes are still forming along the preserve's rivers. Lakes often contain valuable deposits of pollen and other organic materials that can be used as proxy records of paleoclimates.
- **Sand Mounds and Salt Domes**. Also known as "pimple", "mima", or "prairie" mounds, sand mounds are enigmatic in origin and occur on sandy surficial deposits in the preserve area. Theories as to their origin range from wind-blown erosion to burrowing rodents. Salt domes are high ground areas underlain by buoyant salt deposits that bulged upward. Salt domes influence local hydrology, can produce salt licks for wildlife, were sources of sulfurous springwater, and are indicators of potential oil and gas resources. At least 14 salt domes are mapped in the preserve area.
- **Sedimentary Units and Geologic Exposures**. All of the geologic map units at the preserve are clastic sedimentary; that is they are the products of weathering, erosion, transportation, and deposition of rock fragments. Features within these units provide clues as to their depositional environment. Geologic exposures are not common on the low-relief landscape of the preserve, but at least 25 mapped exposures occur within the Upper Neches River corridor, Turkey Creek, and Menard Creek Corridor units of the preserve.
- **Oil and Gas Development and Production**. Oil and gas development and production are among the top natural resource management concerns at the preserve. Oil and gas activities, including vehicle use; drilling and detonation; and construction, maintenance, and use of roads, wellpads, production facilities, flowlines and pipelines have the potential negatively impact preserve resources. Activities may increase surface runoff; increase soil erosion, rutting and compaction; affect the permeability of soils (and other soil characteristics); and could negatively affect the growth and regeneration of vegetation. The preserve's oil and gas management plan, developed in 2006, established a framework for managing the development of nonfederal oil and gas over a 15 to 20 year time frame. Oil and gas issues include impacts from current production, abandoned sites, contamination risks, and future development, directional drilling, and hydraulic fracturing.
- **Mitigation and Restoration of Abandoned Mineral Lands and Other Disturbed Lands**. Prior to establishment of the preserve, much of the landscape was impacted by logging (including tram roads and canals), railroads, and oil and gas development. Abandoned and active oil and gas sites are the primary abandoned mineral land within the preserve. Other disturbed features include sand pits, iron ore gravel pits or scraped areas, and sand mines. A comprehensive inventory is needed to manage these features. With such a long boundary, adjacent land use is diverse and presents many challenges for resource management. Preserve staff actively seek to conserve land along its boundaries whenever possible.
- **River Meandering, Erosion, and Fluvial Flooding**. The fluvial system is a uniting feature of the preserve, connecting the land units with narrow river corridors. Channel migration causes rivers to move in and out of the preserve's jurisdiction. The morphology of a stream channel is integral to the fluvial and riparian ecosystem. Human modifications

to the streambanks and floodplain areas including dredging, dam construction, armoring, and oil and gas activities have altered the natural system affecting discharge, sediment supply, and erosional resistance of the banks. Flooding accelerates the rate of river meandering and could undermine streambank stability. Much of the rivers' natural flow is diverted for urban, industrial, and agricultural use. As this report was in final review in late summer 2017, Hurricane Harvey—"the most significant rainfall event in United States history in scope and rainfall totals since rainfall records began during the 1880s (Watson et al. 2018, p. 7)"—inundated southeastern Texas and caused significant flooding in the preserve.

- **Coastal Resources, Sea Level Rise, and Climate Change**. The coastal area of the preserve is limited to narrow stretches of the Beaumont and Little Pine Island-Island Bayou Corridor units south of the saltwater barrier. Shaped by waves, tides, wind, and geology, coastal natural resources are located in a transition zone between terrestrial and marine environments. Coastal features will be in flux with predicted climate change-induced sea level rise. The coastal areas are highly altered (dredged) to protect shipping capabilities for the Port of Beaumont. In 2003, a saltwater barrier north of Beaumont replaced temporary structures that were causing coastal erosion. Predicted local sea level rise (as much as +23.5 cm [+0.77 ft] by 2050) will continue to inundate low-lying, coastal areas with saltwater intrusion. Climate change is a dominant factor driving the physical and ecologic processes affecting the preserve. The effects extend to the preserve's fluvial system as well because models predict increased temperatures and frequency of strong storms. This may increase water temperature, sediment load, and channel morphology affecting dependent ecosystems. As this report was in final review in late summer 2017, Hurricane Harvey struck southeastern Texas and caused widespread flooding.
- **Slope Movement Hazards and Risks**. Relief in the preserve is generally low, but in certain areas along the Neches River slopes up to 12% exist. These and other steep bluffs along the preserve's rivers and creeks are possible settings for slope movements. Mapped deposits of colluvium and alluvial fans mark areas that experienced slope movements or the downslope transfer of earth material. These areas may have the potential for future slope failures.
- **Paleontological Resource Inventory, Monitoring, and Protection**. The shallow marine, nearshore, and fluvial paleoenvironments that flourished in Big Thicket's past supports a rich paleontological record today at the preserve. This evidence of ancient life is now protected as fossil resources in the preserve. Plant, invertebrate, and vertebrate fossils are weathering out of bluffs along the rivers and washing up on preserve shores. Of particular interest are Pleistocene megafauna fossils such as mammoths and rhinoceros. Preserve fossils may also be found in cultural contexts. Weathering out from river bluffs, fossils from Big Thicket National Preserve may be subject to theft and degradation. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation. To achieve this goal, a field-based, preserve-specific paleontological resource survey could be completed.
- **Seismic Activity Hazards and Risks**. The preserve is not located near an active seismic zone; however, seismic activity is still possible as a 1960s earthquake attests. Most faulting in the region is associated with sediment deposition and movement into the Gulf of Mexico basin and movement of salt diapirs. Earthquakes can directly damage preserve infrastructure, or trigger other hazards such as liquefaction or slope movements that may impact preserve resources or visitor safety.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey, state geological surveys, local museums, and/or universities developed the source maps and reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

Review

Jason Kenworthy (NPS Geologic Resources Division)
Eddie Collins (Texas Bureau of Economic Geology)
Martha Segura (NPS Gulf Coast Network)
Joe Meiman (NPS Cumberland Piedmont Network)
Dusty Pate (NPS Big Thicket National Preserve)
Herbert Young, Jr. (NPS Big Thicket National Preserve)
Jeremiah Kimbell (NPS Geologic Resources Division)

Editing

Michael Barthelmes (Colorado State University)

Report Formatting and Distribution

Jason Kenworthy (NPS Geologic Resources Division)
Michael Barthelmes (Colorado State University)

Source Map Authors and Agencies

Saul Aronow (Lamar University)
Texas Water Development Board
Bureau of Economic Geology, University of Texas at Austin
Railroad Commission of Texas

GRI GIS Data Production

Heather Stanton (Colorado State University)
John Gilbert (Colorado State University)
Stephanie O'Meara (Colorado State University)
Ethan Schaefer (Colorado State University)
James Chappell (Colorado State University)
Dave Green (Colorado State University)

GRI Map Posters Design

Chase Winters (Colorado State University)
Georgia Hybels (Colorado State University)

GRI Map Posters Editing

Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Michael Barthelmes (Colorado State University)
Jason Kenworthy (NPS Geologic Resources Division)

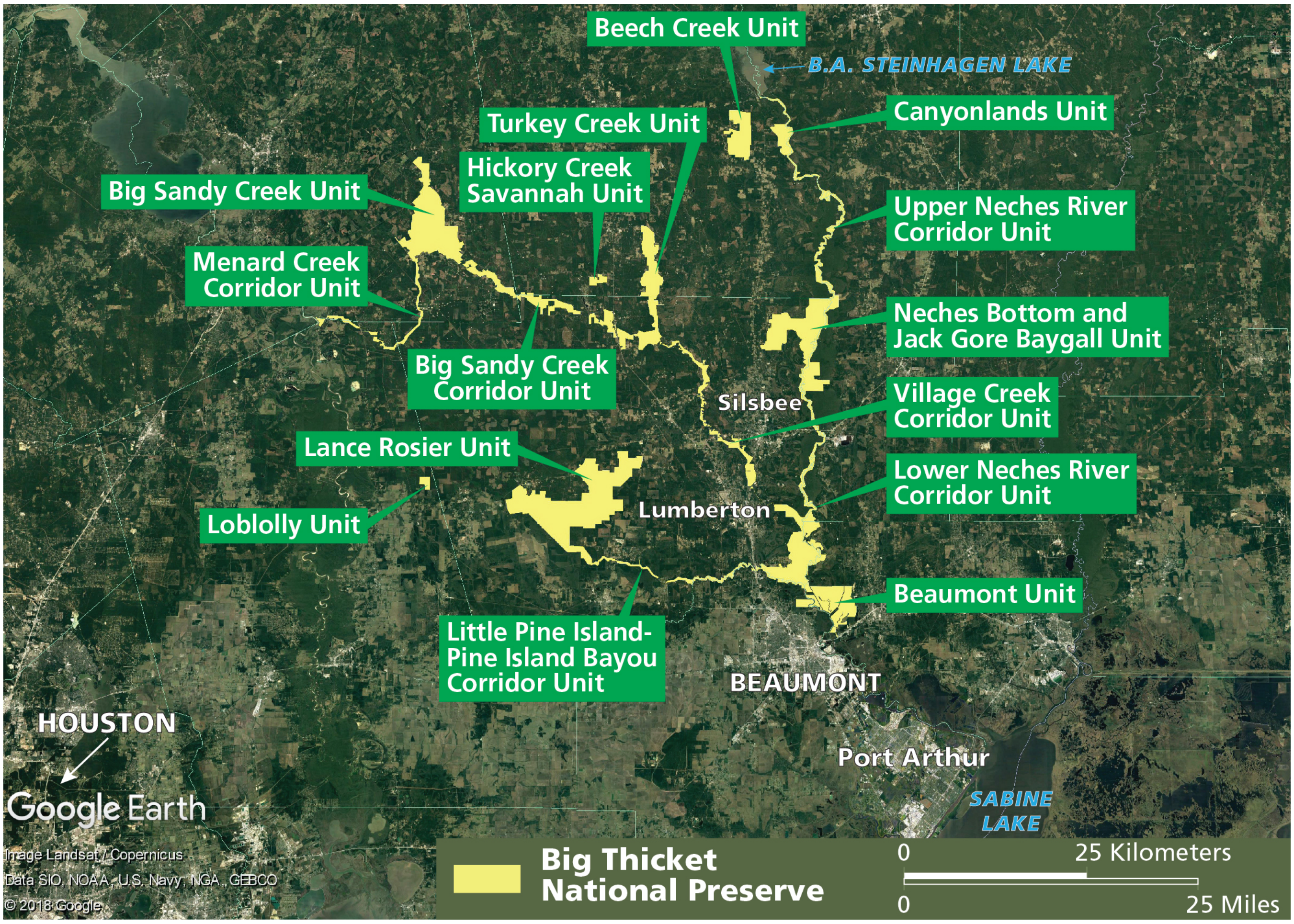


Figure 1. Location map of Big Thicket National Preserve.
Six river corridor units (Upper Neches River, Big Sandy Creek, Little Pine Island-Pine Island Bayou, Lower Neches River, Menard Creek, and Village Creek corridor units) and nine land units (Beech Creek, Turkey Creek, Big Sandy Creek, Loblolly, Lance Rosier, Hickory Creek Savannah, Neches Bottom, Jack Gore Baygall, and Beaumont units) make up Big Thicket National Preserve in southeastern Texas. A more detailed map is included as map 1 (in pocket). Map by Jason Kenworthy (NPS Geologic Resources Division) using Google Earth imagery (accessed 20 August 2018) from Landsat/Copernicus with date from SIO, NOAA, U.S. Nave, NGA, GEBCO; © 2018 Google.

Geologic Setting and Significance

This chapter describes the regional geologic setting of the preserve and summarizes connections among geologic resources, other preserve resources, and preserve stories.

Park Establishment

Big Thicket National Preserve was authorized on October 11, 1974 as one of the two first national preserves in the National Park System. The preserve contains remnants of the Big Thicket of Texas, an area of originally more than 1 million ha (3 million ac). Now the Thicket encompasses only about 120,000 ha (300,000 ac), one-tenth of its former area. The preserve protects as much as 5% of the original Big Thicket. The purpose statement for Big Thicket National Preserve states the preserve "is dedicated to preserving, conserving, protecting, and enhancing the integrity of the natural and ecological systems in the Big Thicket." (Public Law 93-439). More than 100,000 people visit the preserve annually.

Big Thicket is the biological boundary area at the southwestern edge of the southeastern US, humid subtropical in climate, geologically and hydrologically complex, rich in species (60 mammals, 92 reptiles and amphibians, more than 1,800 invertebrates, 97 fish, at least 176 bird, and more than 1,300 vascular plant species in 11 different plant communities), and characterized by a loblolly pine-white oak-beech-magnolia forest with many associated and often very distinct vegetation types (National Park Service 2014). Big Thicket was designated an international biosphere reserve in 1981 (National Park Service 2014). The Big Thicket area is a transition zone of four distinct vegetation types—the eastern hardwood forest, the southeastern swamp or Gulf coastal plain, the central or Midwest prairie, and the southwestern desert (National Park Service 2014).

Big Thicket National Preserve encompasses more than 45,778 ha (113,121 ac) in Polk, Tyler, Jasper, Liberty, Hardin, Jefferson, and Orange counties, near Beaumont, Texas, 120 km (75 mi) northeast of Houston. The preserve s includes nine land units and six water corridors across a 9,100 km^2 (3,500 mi^2) area of southeastern Texas near the Louisiana border (fig. 1 and poster 1 [in pocket]). The units of the preserve are within four watersheds: the lower reaches of the main stem of the Neches River, Big Sandy, Village Creek, and Pine Island Bayou. With the exception of Menard Creek corridor unit (part of the Trinity River watershed), water within the preserve will flow through the Neches River into the marshes below Beaumont and ultimately into the Gulf of Mexico (National Park Service 2014).

Relief in Big Thicket National Preserve is generally low, with elevations ranging from 1.5 m (5 ft) in the Beaumont unit to 111 m (365 ft) at the northern tip of the Big Sandy Creek unit, more than 90 km (54 mi) to the northwest. The steepest slopes (as much as 12%) occur in the Neches Bottom and Jack Gore Baygall, Turkey Creek, Big Sandy Creek, and Beech Creek units where the rivers have cut into sandy uplands and terraces (Sobczak et al. 2010).

The preserve's significance is summarized in five significance statements in the foundation document (National Park Service 2014) that identify the following resources and values:

- Extraordinary combination and habitats and species and their scientific value,
- Flowing water and dependent systems,
- National and international designations,
- Visitor experience, and
- Cultural resources.

From those significance statements, the preserve identified the following fundamental resources and values (National Park Service 2014):

- Visitor experience in a natural setting,
- Free-flowing water and dependent systems,
- Biodiversity,
- Compositional diversity,
- Structural diversity,
- Processes and functional diversity,
- Scientific value, and
- The Thicket.

Cultural resources are considered an "other important resource and value" in the foundation document.

Geologic Setting and History

Geological features and processes form a foundation upon which the globally significant biodiversity of the Big Thicket flourishes and evolves. The preserve is part of the Coastal Prairies region of the Gulf Coastal Plain physiographic province characterized by a nearly level, slowly draining plain dissected by rivers and creeks that feed into the Gulf of Mexico (figs. 2 and 3; Wermund 1996). Barrier islands, marshes, bays, and estuaries dot the south Texas coastline. Ewing (2016) provides a valuable reference on the geology, landscapes, and resources of Texas.

Figure 2. Map of the physiographic provinces of Texas.
Big Thicket National Preserve (green star) is located within Gulf Coastal Plains province and Coastal Prairies subprovince, which contains the youngest geologic units in the state. Bold line through San Antonio separates the Gulf Coastal Plains provinces from the inland provinces. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after map by Wermund (1996). Basemap by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 12 December 2015).

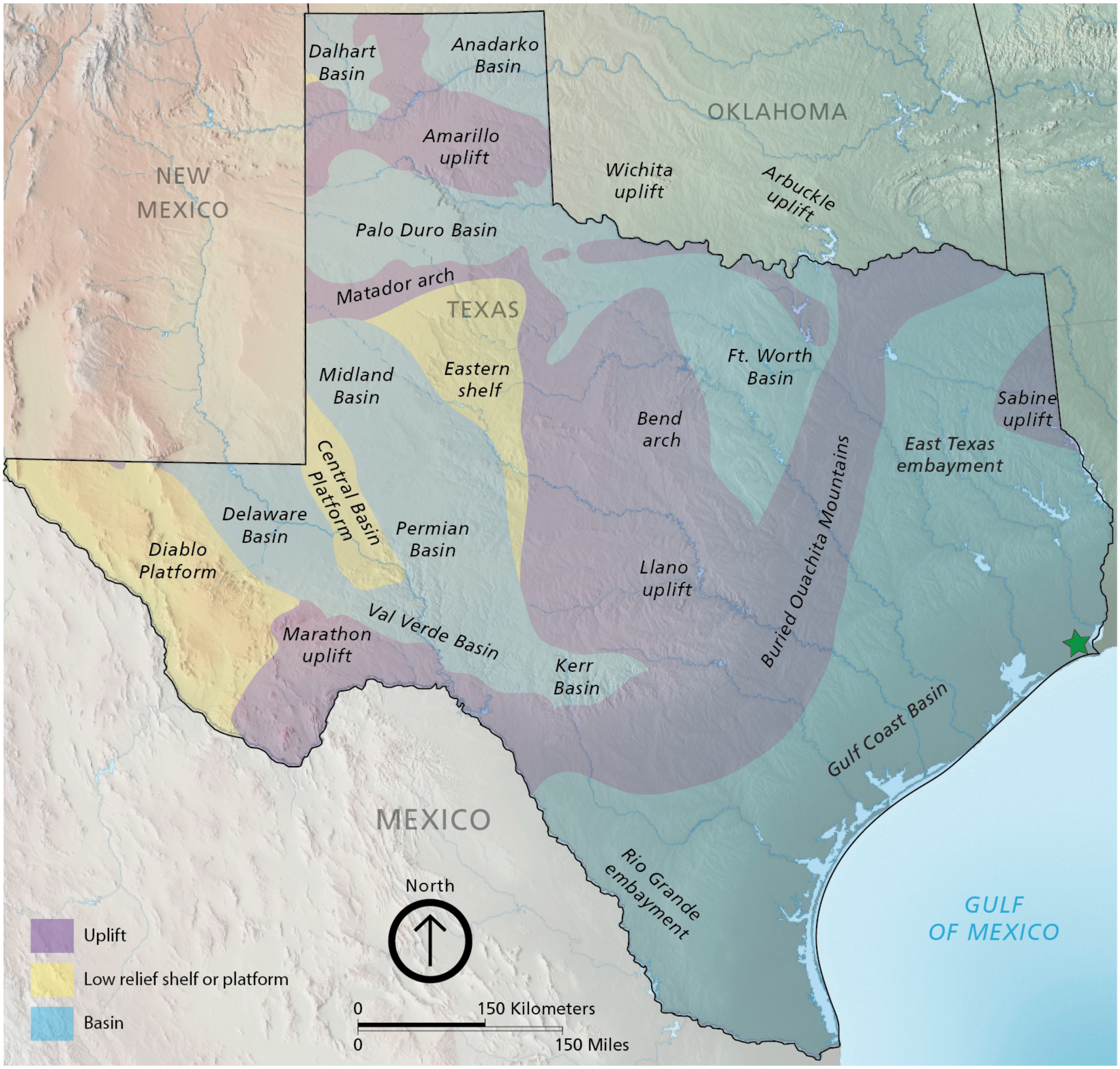


Figure 3. Map of regional geologic structures in Texas.
The preserve (green star) is along the southern edge of the Gulf Coast basin. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Spearing (1991, p. 27). Base map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 12 December 2015).

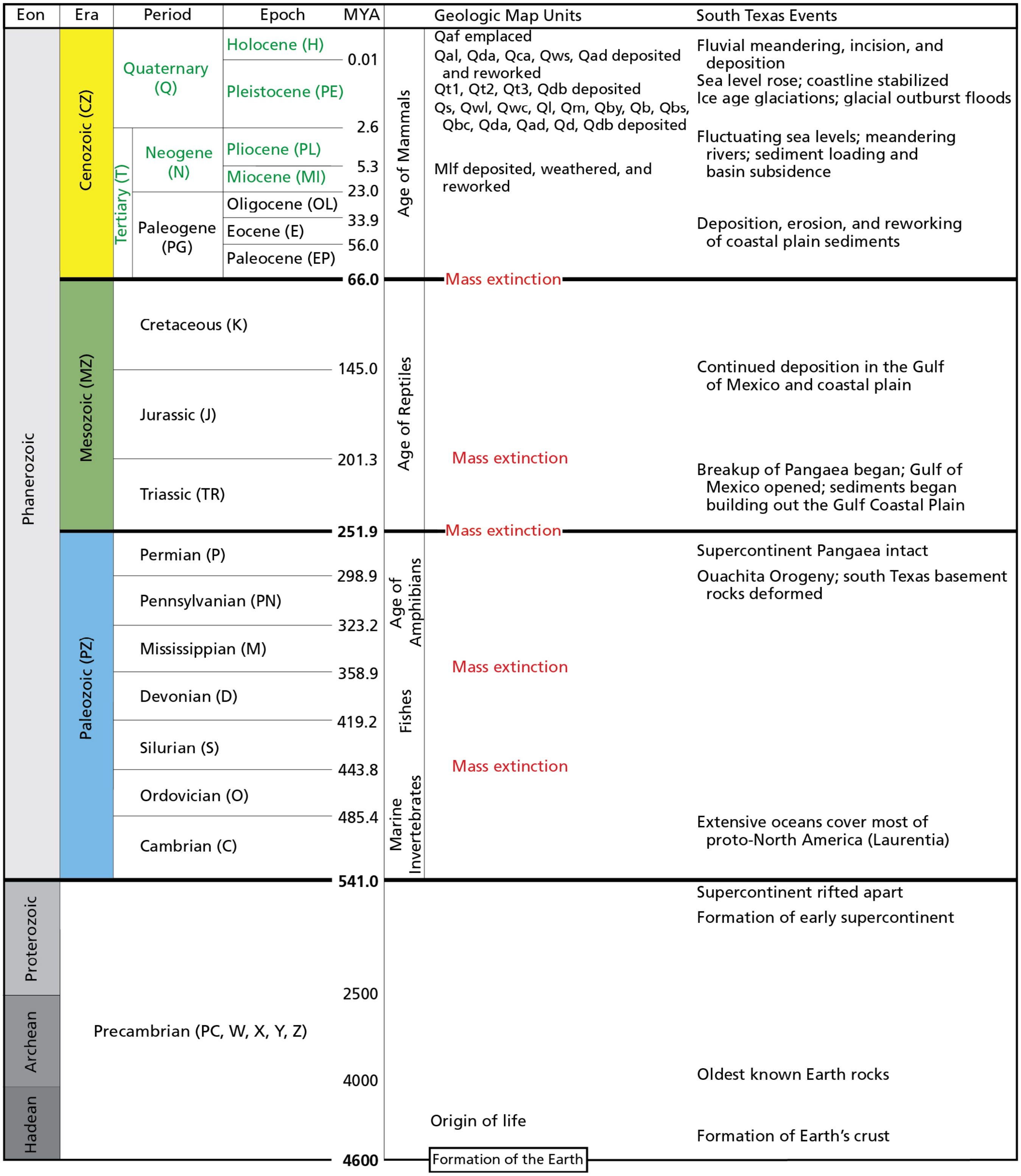


Figure 4. Geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). Units mapped in the preserve are quite young and range from the Miocene through the Pleistocene and Holocene (all labelled in green). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 7 May 2015.

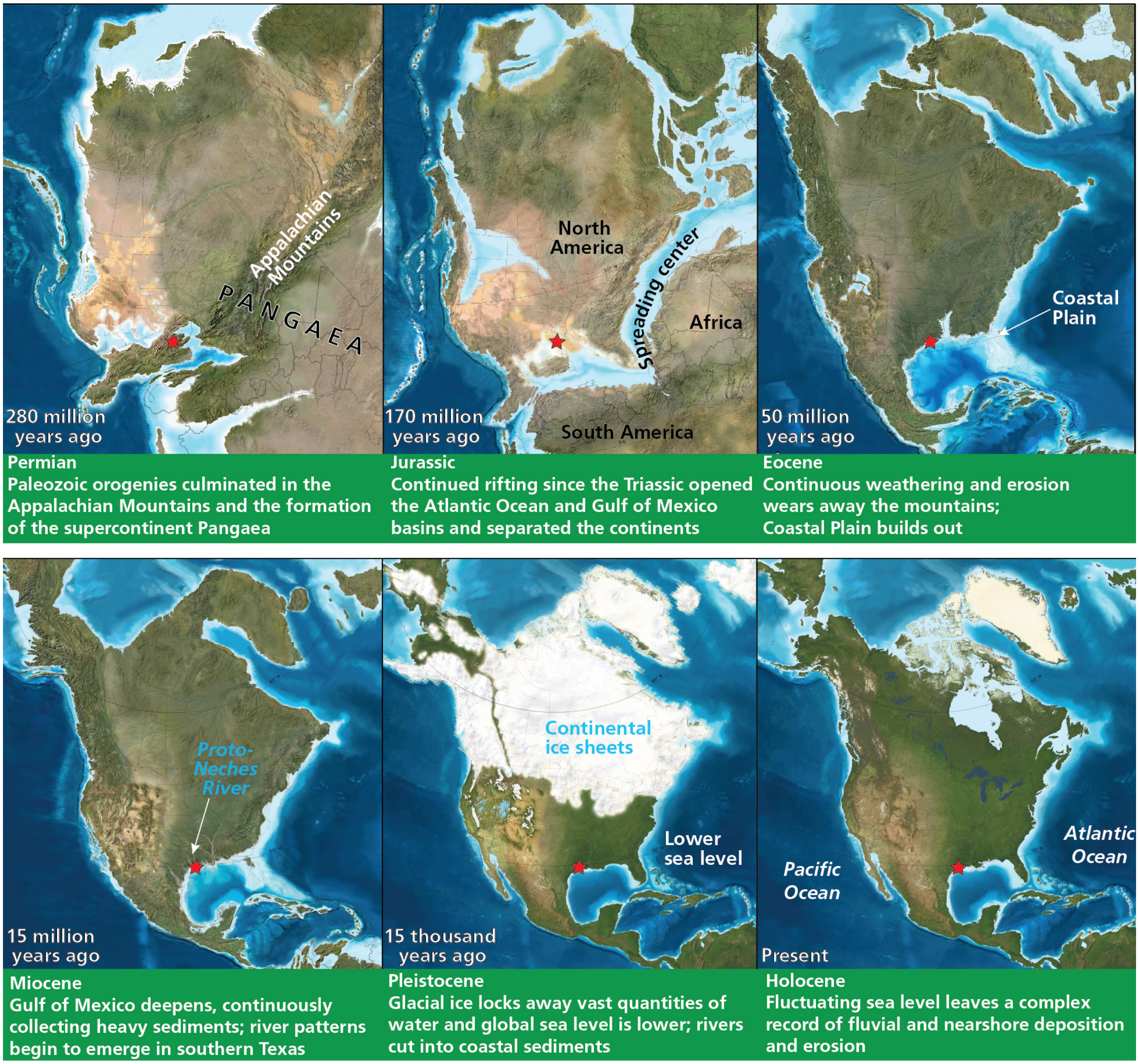


Figure 5. Paleogeographic maps of North America.
The red star indicates the approximate location of Big Thicket National Preserve. Graphic complied by Trista L. Thornberry-Ehrlich (Colorado State University). Basemaps are from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems, Inc; used under license. Refer to http://deeptimemaps.com/ for additional information.

An exceptionally deep accumulation of sediments (15,000–18,000 m [50,000–60,000 ft, or about 11 miles]) underlies the Gulf Coastal Plain of Texas. Sediments have been deposited in this area since the Triassic Period, for at least 250 million years (figs. 4, 5, and 6A). During the Triassic, the Gulf of Mexico Basin (and the Atlantic Ocean basin) formed as basement rocks downwarped or sagged as the supercontinent Pangaea was pulled apart (Byerly 1991; Chowdhury and Turco 2006). Below this pile of coastal plain sediments is a foundation of crystalline rocks hundreds of millions of years old that formed and were deformed during the Ouachita Orogeny (Baker 1995)—a Late Paleozoic mountain building event that created the Ouachita and Marathon Mountains and was associated with construction of the Appalachian Mountains and the assembly of Pangaea.

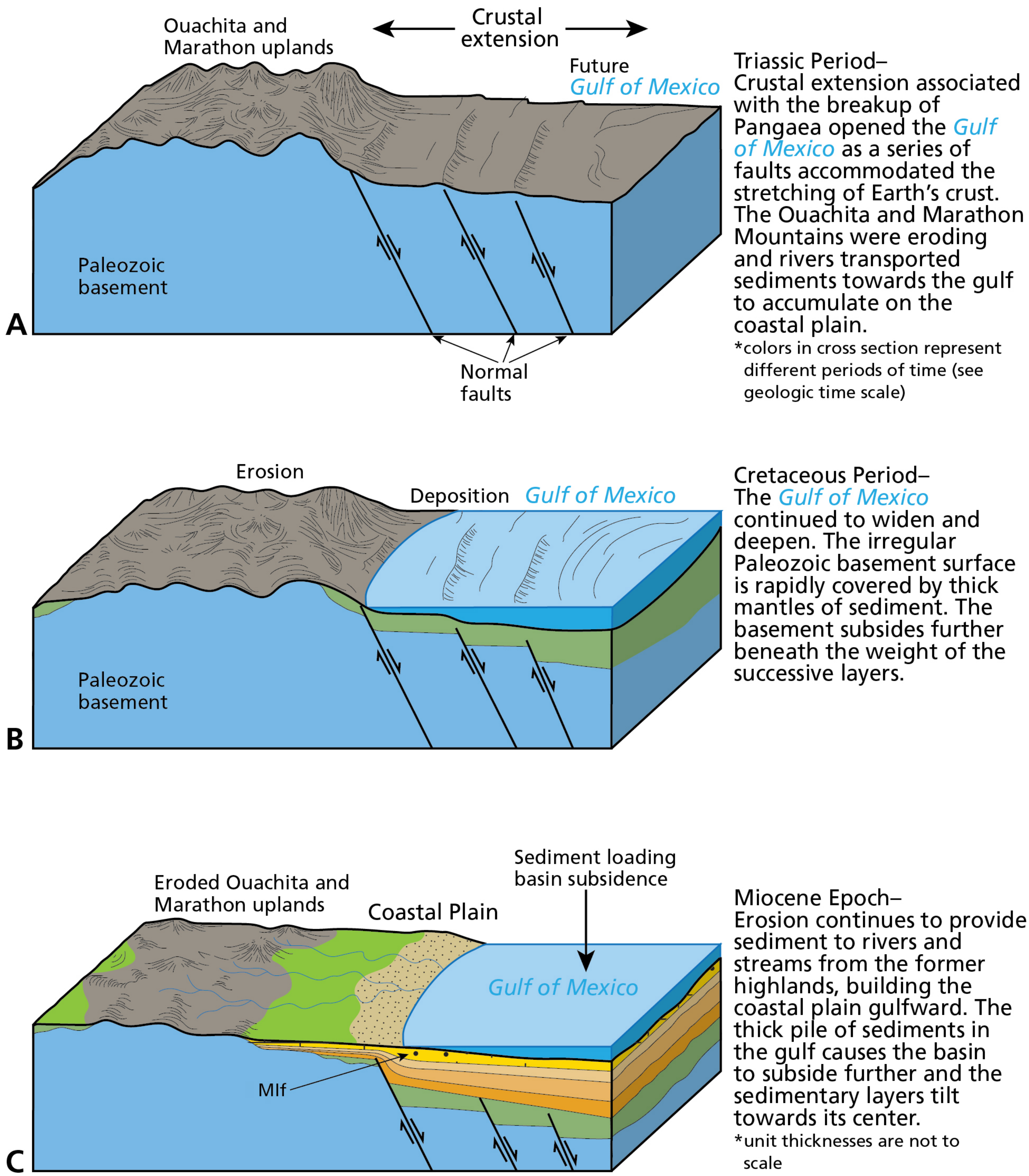
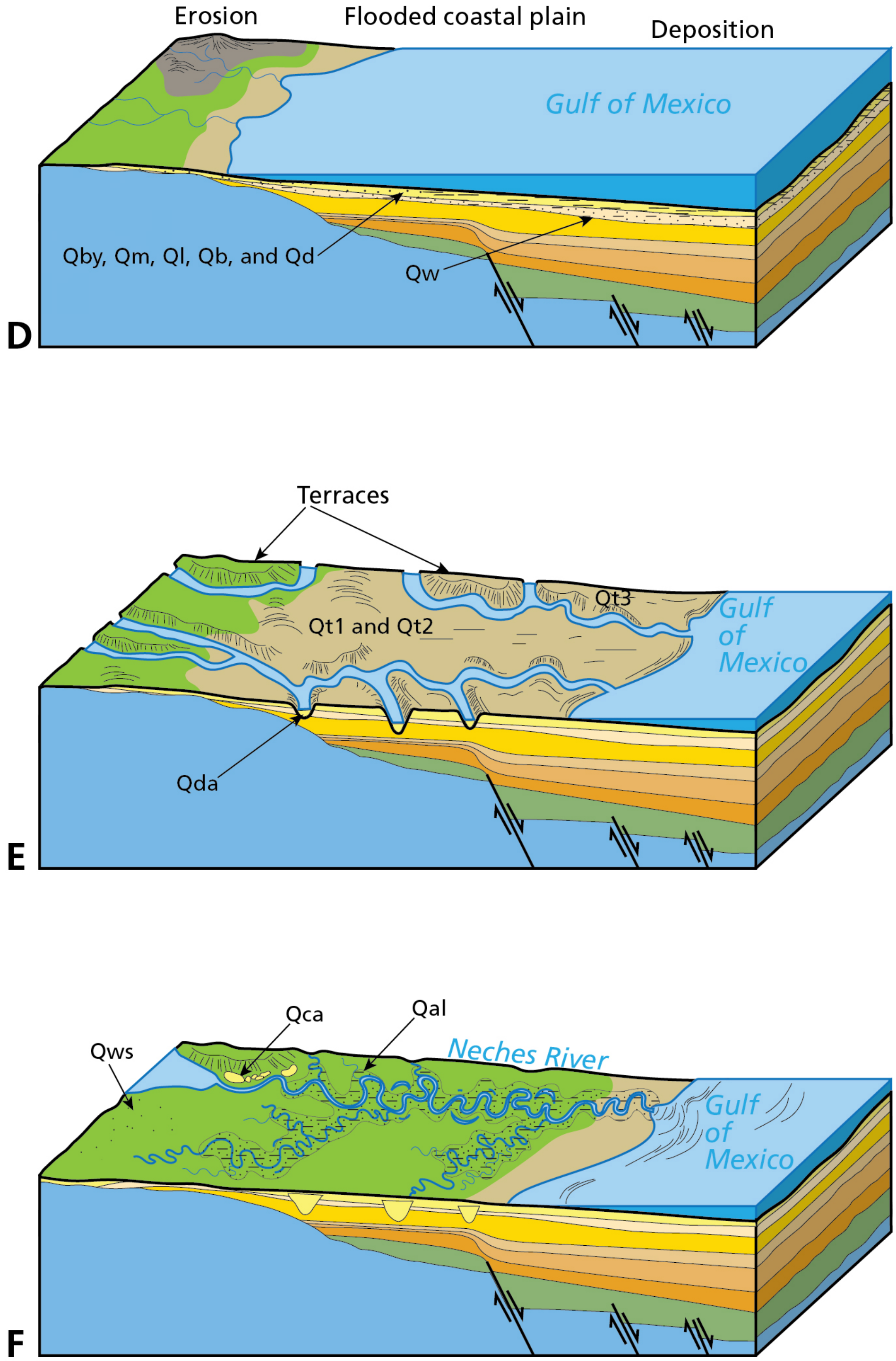


Figure 6A–C. Illustration of the evolution of the landscape and geologic foundation of Big Thicket National Preserve.
Continued on next page. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors other figures in this report. Map symbols are included for some of the geologic map units mapped within the park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Aronow (1981) and Sobczak et al. (2010).



Pleistocene Epoch–
During times between glaciations, global sea level was relatively high, the Gulf Coast flooded, and marine and nearshore deposits accumulated in the Big Thicket area.

End of Pleistocene Epoch–
During ice ages, glaciers entrained vast quantities of water, lowering global sea level. Rivers cut through the thick fluvial, nearshore, and marine sediments; scattered terraces mark former river levels.

Holocene Epoch–
Sea level approached modern levels; river patterns were established; wind, rivers, creeks, and sloughs reworked sediments across the landscape. As sea level continues to rise, coastal settings will shift landward.

Figure 6D–F. llustration of the evolution of the landscape and geologic foundation of Big Thicket National Preserve.
Continued from previous page. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the figures in this report. Map symbols are included for some of the geologic map units mapped within the park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Aronow (1981) and Sobczak et al. (2010).

Most of this ancient sedimentary record is deeply buried below the Big Thicket. The oldest formation mapped in the preserve is the Fleming Formation, which dates back only to the Miocene between 23 million and 5.3 million years ago, (geologic map unit **Mlf**; figs. 7, 6C, and 8; Aronow 1981; Sobczak et al. 2010). The Fleming Formations was deposited on an intermittently flooding plain drained by meandering rivers during a time when sea level was dropping (Chowdhury and Turco 2006). Throughout the Pleistocene Epoch (2.6 million to 11,700 years ago), sea level alternately dropped during ice ages, when vast amounts of water were contained in glacial ice, and rose during interglacial warm periods (figs. 6D and 6E). The fluctuations inundated or exposed the coastal plain, each inundation leaving behind a formation of sediments and each exposure eroding them. Four formations mapped in Big Thicket span the transitional climates of the Pleistocene: the Deweyville (**Qda**, **Qad**, **Qd**, and **Qdb**) deposited in levees, channels, and backswamps; the Beaumont (**Qb**, **Qbs**, and **Qbc**) deposited in levees, deltas, and lagoons; the Lissie (**Ql**, **Qm**, and **Qby**) deposited in streams and deltas; and the Willis (**Qs**, **Qwl**, and **Qwc**) deposited in channels and point bars (Rigsby 1980; Aronow 1981; Chowdhury and Turco 2006). The geologic legacy of these changes is represented by a complex sedimentary record of discontinuous beds of sand, silt, clay, and gravel.

When the Holocene (11,700 years ago to present) coastline stabilized, a mix of clayey and sandy soils covered the lower reaches of the coastal plain. Fluvial (river) and eolian (wind) processes continue to rework the sediments (fig. 6F). Meandering rivers and creeks such as the Neches, Village, Turkey, Big Sandy, and Menard deposited alluvium (**Qal** and **Qda**) along their channels (Aronow 1981; 1982j). Terraces (**Qt3**, **Qt2**, **Qdb**, and **Qt1**) mark former river levels perched above the modern floodplains (Aronow 1982a, 1982b, 1982c, 1982f, 1982g, 1982i, 1982j; Texas Water Development Board 2007). Colluvium and alluvial fan deposits (**Qca**) accumulate at the base of modest slopes (Aronow 1982j). Winnowed, windblown sand (**Qws**) forms small mounds (Aronow 1982i). In areas of quiet or standing water are organic-rich, fine-grained swamp deposits (**Qad**; Aronow 1982a, 1982f, 1982h, 1982j). Humans are modifying landforms in the preserve area, in some cases on a scale large enough to appear on geologic maps as artificial fill (**Qaf**; Texas Water Development Board 2007).

Weathering of geologic units contributes to the development of soils. Soil resources are not covered in this geologic report, but a soil resources inventory product for Big Thicket National Preserve is available at https://irma.nps.gov/App/Reference/Profile/2190427 (accessed 9 December 2015).

In addition to the geologic map units, the GRI GIS data also include a land resources map with the following six types of units (tables 16 and 17; in pocket):

- geohydrologic units (areas of groundwater recharge to aquifer systems),
- physical properties units (where substrate composition is the dominant physical feature),
- geomorphic units and features (where topography or landform is the dominant physical characteristic),
- process units (areas of significant dynamic processes),
- biologic units (areas dominated by biologic habitation, activity, and productivity), and
- man-made units or features (human alteration of the environment).

Geologic Significance and Connections to Human History

The interplay of geology, topography, climate, water, and soils supports the world-class biodiversity of the preserve (Sobczak et al. 2010). During the Pleistocene, when the climate was much colder, the area was a refuge for many plant species driven southward by advancing ice and colder climates. Forest species now typical of the northeast are found today in the preserve with xeric species more typical of the southwest, and where swamp species from Florida and the southeast flourish with prairie and desert species now found on Texas and Oklahoma plains to the northwest (Callicott et al. 2006). With such diverse ecosystems represented, the Big Thicket contains a wealth of natural resources. From the earliest American Indians to modern oil and gas operations, humans have long used and altered the resources and environments of the Big Thicket.

Prior to the early 1800s, the wilderness of the thicket was sparsely populated by American Indians for at least 8,000 years. These peoples tended to live on the margins of the Big Thicket, only entering the Thicket for hunting (National Parks Conservation Association 2005; Callicott et al. 2006; National Park Service 2014). Archeologists have identified at least 91 sites within the preserve attesting to sporadic prehistoric and historic American Indian presence (National Parks Conservation Association 2005). The historic Alabama Trace—an American Indian trail which passed through four Alabama village sites in the Texas counties of Angelina, Tyler, and Polk—bisects the Big Sandy Creek unit (National Park Service 2014). Sand ridges provided areas of relatively high and dry ground and as such

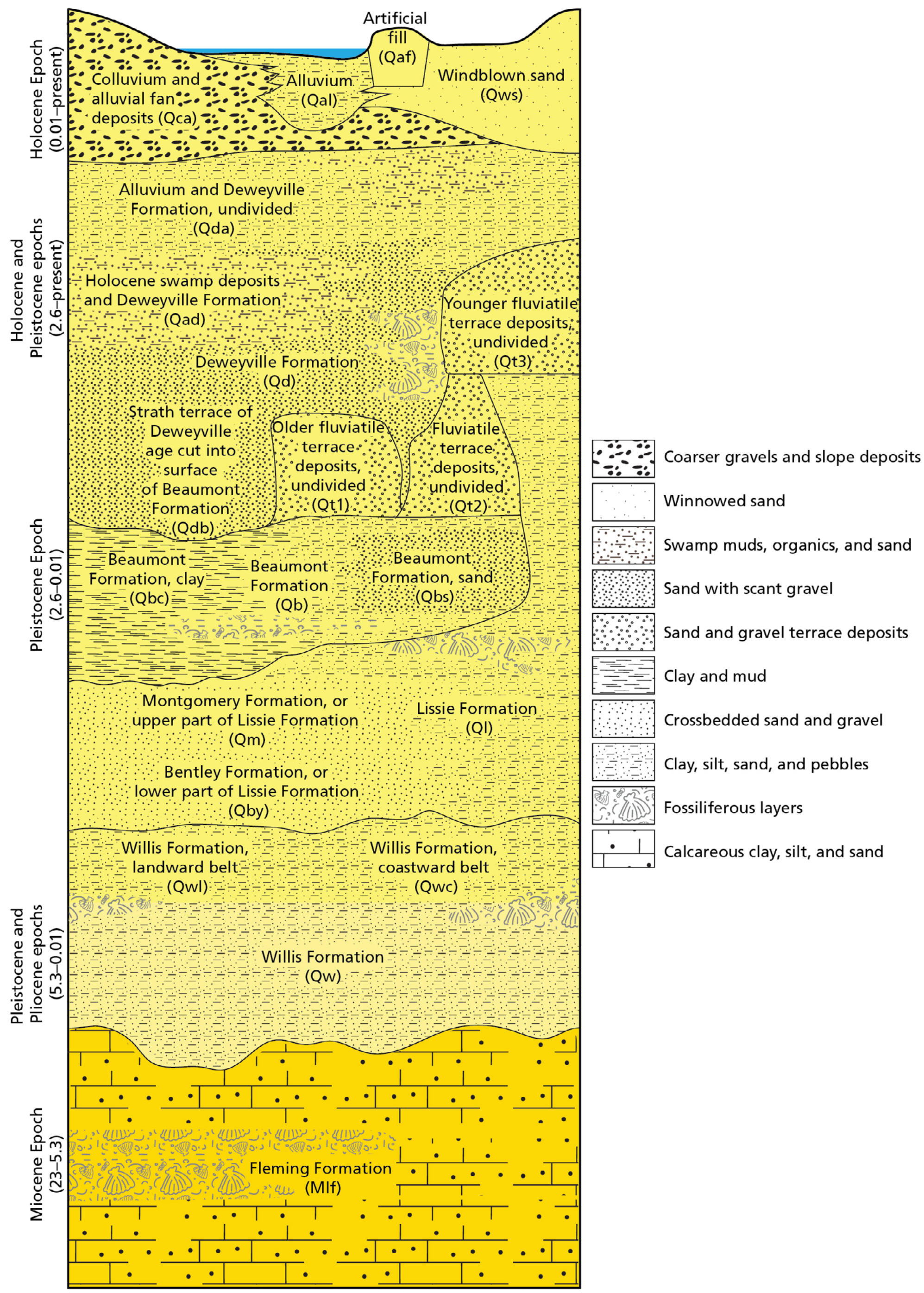


Figure 7. Generalized stratigraphic section.
Miocene, Pliocene, and Pleistocene sediments underlie most recent Holocene surficial deposits. Vertical placement is representative of age only and not necessarily spatial proximity. Units in this part of Texas are discontinuous and their spatial distribution is complicated. Unit names follow the GRI source maps. However, the nomenclature for the different units varies between Louisiana and Texas and both nomenclatural systems were used by the agencies that published the source maps used by GRI. Refer to the "Sedimentary Units and Geologic Exposures" section (table 6) for additional information. Only units that are mapped within the preserve in the GRI GIS data are included. Unit colors are according to US Geological Survey standards for geologic time periods. Section is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Aronow 1981; Aronow 1982b, 1982g; Texas Water Development Board 2007).

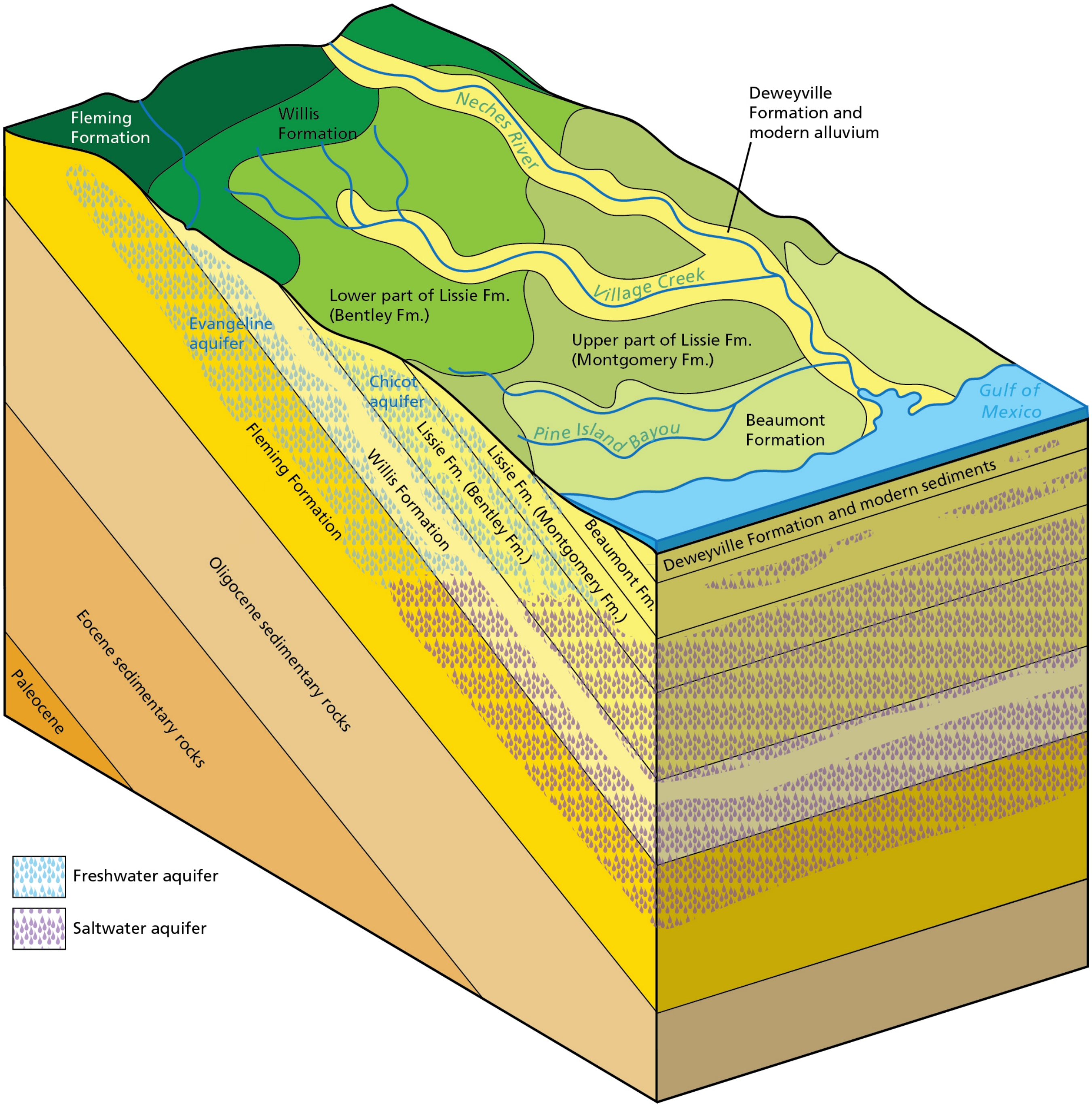


Figure 8. Three-dimensional view of the major geologic units at Big Thicket National Preserve. Sedimentary layers tilt towards the Gulf of Mexico deposited in layers during incremental sea level rises. During periods of low sea level, the sediments were eroded. The surficial expression of most of these units are as belts or bands that roughly parallel the modern coastline and become progressively older further inland. Locally significant aquifers of the greater Gulf Coast aquifer are included: the deeper Evangeline and shallower Chicot aquifers. Smaller, discrete aquifers are also common throughout the preserve area within sandy layers or lenses of the geologic units. Unit colors (in cross-section view) are according to US Geological Survey standards for geologic time periods. Graphic is not to scale and some geologic units, including the most recent surficial deposits were omitted for clarity. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 5 in Sobczak et al. (2010).

supported villages, fire hearths, and stone-working areas in or near Little Pine Island Bayou (Lance Rosier unit), and the Beech Creek, Neches Bottom and Jack Gore Baygall, and Lower Neches River Corridor units (National Park Service 1980). American Indians made pottery from local clays along banks in the Turkey Creek unit (National Park Service 1980). They used surface "oozes" of crude oil for medicinal purposes (National Parks Conservation Association 2005). Lithic flakes and pottery sherds have also been found on high ground near bluffs south of Evadale on the Neches River.

The marshy lowlands, sandy soils, winding streams, bayous, and nearly impenetrable forests characteristic of the Big Thicket discouraged substantial settlement during the colonial period. During the mid-19th century, the thicket harbored outlaws, fugitives, and the occasional agriculturist (Callicott et al. 2006). It was not until the early 1890s that the population swelled when cattle ranching, timber companies, and railroads encroached on the area (Callicott et al. 2006; National Park Service 1980, 2014). The preserve is dotted with homesteads, hunting camps, ferry crossings, steamboat landings, cemeteries, and other structures from the various periods of settlement throughout its history (National Park Service 1980; National Park Service 2006). The logging industry felled large swaths of forest making way for other exploration.

The Big Thicket would be changed forever in 1866 when Lynis T. Barrett of the Melrose Petroleum Company drilled an oil well at Nacogdoches and tapped into the relatively shallow oil reserves (National Park Service 2006). Oil was relatively easy to find in the preserve area using salt dome mounds and surface oozes of gases and sludge as clues. Salt domes form by underground movement of buoyant salt at depths of several thousands of meters. Hydrocarbons accumulate above and on the flanks of these domed subsurface salt structures (National Park Service 2006). The preserve is between the Coastal Salt Dome Province (Spindletop oil field) and the East Texas Basin Salt Dome Province (Fay 2009) that produce from many units and at depths of more than 7,000 m (23,000 ft) below the surface (National Park Service 2006).

The early effort at Nacogdoches preceded the east Texas oil boom (1901–1903) when Spindletop (home of the Lucas gusher) in Beaumont, Batson-Old in Batson, and Hooks 7 in Saratoga came into production. The spectacularly productive, but ephemeral, Sour Lake strike occurred at this time as well (Callicott et al. 2006; National Park Service 2014). By 1902, 285 active oil wells were operating at Spindletop (National Parks Conservation Association 2005). This boom caused a rush of new settlers to Hardin, Polk, and Tyler counties and rapid development of cities and infrastructure to support the influx of people and the extraction, transportation, and refining of petroleum. The Beaumont-Port Arthur area became the oil refining capital of the world in the decades that followed (Sobczak et al. 2010). By the 1950s, between 125 and 155 wells were drilled within the boundary of the future preserve (National Parks Conservation Association 2005).

Both the early timber and oil booms had drastic effects on the ecosystems at Big Thicket National Preserve. The use of steam skidders for tram logging gouged and compacted the topsoil, created furrows in the landscape, and damaged tree seedlings and understory vegetation. After the old growth forests were cut, the forests regrew, but with a nearly complete shift in forest composition from longleaf pine to loblolly (Callicott et al. 2006). Oil explosively blew out of the early drill holes, coated the surrounding biota, and seeped into the surficial deposits and percolated down into the groundwater; noxious gases polluted the air. Briny (salt-rich) water that came out of the wells along with petroleum products was flushed into the nearest stream and devastated freshwater ecosystems. Initially, the Big Thicket wells were so productive that there were simply not enough barrels available to store all the oil, so producers put it anywhere they could (e.g., in leaky wooden containers or pits dug in the ground). During the 20th century, increased awareness of the environmental impacts of such practices lead to new regulations. Oil and gas deposits continued to be discovered and developed in the Big Thicket and throughout the 20th century, and operations continue within the preserve today. New wells and pipelines are being installed next to the rusting infrastructure of the first oil boom causing resource management challenges at Big Thicket National Preserve (see "Geologic Resource Management Issues" section; Callicott et al. 2006).

People keep coming to the Big Thicket not only to develop its resources but also now to enjoy recreation in its remaining natural areas. The preserve's challenge is to protect the biodiversity, educate the public, and work with stakeholders to responsibly utilize and manage the many resources of the Big Thicket.

Geologic Features, Processes, and Resource Management Issues

These geologic features and processes are significant to the preserve's landscape and history. Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

Flowing water and dependent systems are among the preserve's fundamental resources and values (National Park Service 2014). They underlie and alter the preserve's globally significant ecosystems. Therefore, the majority of the features, processes and issues identified for the preserve are connected to the river systems and its changes over time. The preserve also contains significant geologic heritage features beyond the river systems, including sand mounds, salt domes, and paleontological resources. Given the low relief and typically muted topography of southeast Texas, the geologic exposures found within the preserve are rare and significant.

Big Thicket National Preserve is fragmented into scattered land units, connected by units of narrow riparian corridor. The preserve has more than 983 km (611 mi) of boundary dispersed over 4,882 km^2 (1,885 mi^2) of southeast Texas (National Parks Conservation Association 2005; Herbert Young, Jr., chief of resource management, Big Thicket National Preserve, written communication, 30 March 2017) and is in the process of acquiring new lands (Conference call participants, 1 February 2016). The preserve faces development pressures from urban, suburban, and exurban sprawl, as well as impacts from timber, and oil and gas industries (Callicott et al. 2006). Some of the last remaining parcels of original Big-Thicket diverse forests are protected within preserve boundaries (National Parks Conservation Association 2005). For these reasons, some consider Big Thicket National Preserve among the most endangered of all lands under the jurisdiction of the National Park Service (Callicott et al. 2006). Because oil and gas development and production is a complex and comprehensive issue at the preserve, a detailed narrative accompanies the summary table (table 1).

Geologic Resource Management

The National Park Service considers geologic resources within three areas:

- geologic heritage,
- active processes and hazards, and
- energy and minerals management.

Contact the NPS Geologic Resources Division (http://go.nps.gov/grd) for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs (Geoscientists-in-the-Parks and Mosaics in Science). Park staff can formally request assistance via https://irma.nps.gov/Star/.

The Geoscientists-in-the-Park (GIP) and Mosaics in Science (MIS) programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. Completed projects are available on the GIP website: http://go.nps.gov/gip. Products created by the program participants may be available on that website or by contacting the Geologic Resources Division. Eight GIP and MIS participants have completed projects at Big Thicket National Preserve from 2003 through 2016. GIPs or Mosaics in Science program participants may be utilized to address the potential action items listed in the tables of this chapter.

The preserve's Foundation Document (National Park Service 2014), Natural Resource Foundation Document (Sobczak et al. (2010), Natural Resource Condition Assessment (Nadeau et al. 2016), and Oil and Gas Management Plan (National Park Service 2006) are primary sources of information for resource management. Additional sources of information are listed on the following tables.

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

Refer to the Geologic Map Data chapter for full citations of the geologic maps and land resources maps included in the GRI GIS data set

During the 2008 scoping meeting (see Fay 2009) and 2016 conference call, participants (see Appendix A) identified the following features, processes, and resource management issues. Each is described in a table that provides basic information, park examples, additional resources, and potential action items.

- Oil and Gas Development and Production (table 1)
- Big Thicket Habitats and Underlying Geology (table 2)
- Fluvial Features and Processes (table 3)
- Wetlands and Lakes (table 4)
- Sand Mounds and Salt Domes (table 5)
- Sedimentary Units and Geologic Exposures (tables 6 and 7)
- Mitigation and Restoration of Abandoned Mineral Lands and Other Disturbed Lands (table 8)
- External Mineral, Resource, and Residential Development (table 9)
- River Meandering, Erosion, and Fluvial Flooding (table 10)
- Coastal Resources, Sea Level Rise, and Climate Change (table 11)
- Slope Movement Hazards and Risks (table 12)
- Paleontological Resource Inventory, Monitoring, and Protection (table 13)
- Seismic Activity Hazards and Risks (table 14)

Oil and Gas Development and Production

Big Thicket National Preserve is one of 12 NPS areas with active oil and gas operations. Oil and gas development and production are among the top natural resource management concerns at the preserve. The park's oil and gas management plan (National Park Service 2006) is the primary reference for all oil and gas operations in the park. It established a 15–20-year framework for managing the development of nonfederal oil and gas at Big Thicket National Preserve. Resources and concerns evaluated in the plan include geologic resources (and soils), floodplains, and wetlands, all of which are considered under one or more "Fundamental Resources" (see table 1 and National Park Service 2014).

According to issue statements for geologic resources, presented in National Park Service (2006), oil and gas activities, including off-road vehicle (ORV) use; shothole drilling and detonation; and construction, maintenance, and use of roads, wellpads, production facilities, flowlines, and pipelines have the potential to increase surface runoff; increase soil erosion, rutting and compaction; affect the permeability of soils (and other soil characteristics); and could negatively affect the growth and regeneration of vegetation. Per that description of the issue, the Big Thicket National Preserve Oil and Gas Management Plan (1) identifies resources and values most vulnerable to adverse impacts from oil and gas operations; (2) establishes performance standards and impact mitigation measures to protect preserve values and resources; (3) establishes performance standards and mitigation measures to avoid or minimize impacts on human health, safety, and recreation; and (4) provides pertinent information to oil and gas operators to facilitate planning and compliance with National Park Service and other applicable regulations (National Park Service 2006; Sobczak et al. 2010).

The preferred alternative defines special management areas in each unit, performance standards, and mitigation measures to protect specific resources and values in Big Thicket National Preserve, consistent with the purposes and values of the preserve and state and federal resource protection mandates (National Park Service 2006).

National Park Service regulations at 36 CFR Part 9, Subpart B (the "9B" regulations) require the owners/operators of nonfederally owned oil and gas rights to (1) demonstrate bona fide title to mineral rights on lands administered by the NPS; (2) submit an Operations Permit application to the NPS that describes where, when and how they intend to conduct the proposed oil and gas activities; (3) prepare/submit a reclamation plan; and (4) submit financial assurance in an amount sufficient to cover the reasonable cost of reclamation by a third party.

The National Park Service works with adjacent land managers and other permitting entities to help ensure that National Park System resources and values are not adversely impacted by mineral exploration and development. Additional and continued drilling in the preserve could create the following issues:

- Surface and groundwater impacts related to loss of casing integrity;
- Reductions in streamflow and groundwater levels from operational water requirements;
- Air quality degradation from internal combustion engines;
- Introduction of exotic species;
- Erosion and/or siltation;
- Excess dust from equipment transportation;
- Disruption of solitude and night skies from operational lights or flaring;
- Impacts to cultural resources, including archeological structures, as a result of vibrations from transportation and drilling; and

- Visitor safety concerns and impacts to wildlife associated with the necessary transportation to support oil and gas operations.

The NPS Energy and Minerals website, http://go.nps.gov/energyandminerals, provides additional information.

The Railroad Commission of Texas, through its Oil and Gas Division, regulates the exploration, production, and transportation of oil and natural gas in Texas. Its statutory role is to (1) prevent waste of the state's natural resources, (2) to protect the correlative rights of different interest owners, (3) to prevent pollution, and (4) to provide safety in matters such as hydrogen sulfide. Refer to http://www.rrc.state.tx.us/oil-gas/ for additional information.

Current Production

Subsurface oil and gas rights were retained by the State of Texas when Big Thicket National Preserve was established. Therefore, the NPS works with operators to allow access to develop mineral rights while minimizing impacts to the preserve's other resources. As of July 2018, 46 wells by 14 operators were active within preserve boundaries. All of these wells are subject o the 9B Regulations' legal and policy requirements. A complete inventory of current and abandoned oil and gas operations at Big Thicket National Preserve is ongoing. According to GRI scoping meeting participants (Fay 2009), there were 217 well sites at the preserve. Other estimates are as high as approximately 226 abandoned oil and gas wells within preserve boundaries (Sobczak et al. 2010).

In addition to the wells, there are at least 71 oil and gas pipeline segments and associated rights-of-way in the preserve. These structures total 163 km (101 mi) over 238 ha (589 ac) of all units except Loblolly and Beech Creek (National Parks Conservation Association 2005; Sobczak et al. 2010). The pipelines cross nearly every waterway in the preserve. According to National Park Service (2006), trans-park oil and gas pipelines have their point of origin and end point outside parks, and, are not typically supporting nonfederal oil and gas operations in parks. As a result, they are not subject to the 9B Regulations; however, if a nonfederal oil and gas operation in the preserve connects to such a pipeline by a flowline or gathering line, then that portion of the flowline or gathering line crossing the preserve would be subject to the 9B Regulations. However, no statutory authority exists for granting new pipeline rights-of-way within preserve boundaries (Sobczak et al. 2010).

Some of the aging pipeline infrastructure at the preserve is cause for resource management concern (Sobczak et al. 2010). Erosion in stream channels and in terrestrial settings has exposed these pipelines (see tables 1, 8, and 10; figs. 14 and 16). Continued erosion could potentially compromise the integrity of the pipes.

Abandoned Site Issues

Most oil and gas operations within the preserve are now plugged and abandoned. However, the reported numbers of abandoned sites in the preserve vary widely. Sobczak et al. (2010) reported approximately 226 abandoned oil and gas wells within the preserve. Of the 858 oil and gas features with a 250 m (820 ft) buffer in the GRI GIS data (original source Texas Railroad Commission), 121 are adjacent to or are enclosed by the NPS boundary. It is unclear how many of these are abandoned. The NPS comprehensive inventory and assessment of abandoned mineral lands (AML; Burghardt et al. 2014) lists 52 AML features at 44 sites, all of which are related to oil and gas.

AML oild and gas sites commonly include fill material, cleared areas, well and production pads, drainage ditches, buried drilling mud and cuttings pits, petroleum- and salt-contaminated soils, structure foundations, abandoned equipment and debris, unreclaimed access roads, mud pits, and small blow-down pits (fig. 14; Michael Baker Jr., Inc. 2006; Fay 2009). Fill and other ground disturbances impacts hydrologic and fluvial processes, can exacerbate erosion, compact soils, introduce invasive species, and cause localized deposition (Fay 2009). Soils compacted by foot or vehicle use typically show reduced permeability (especially clay-rich soils), change surface drainage patterns, and can obstruct the growth of plant roots (National Park Service 2006).

A Radian Corporation 1985 natural resource site assessment at 125 abandoned oil and gas wells and 24 km (15 mi) of abandoned access roads in the preserve noted many of the abandoned sites and roads required restoration action, including (1) removal of imported fill material (e.g., crushed oyster, gravel, etc.) and debris (e.g., pipes, drums, cable, concrete footings, treated lumber, etc.); (2) aerating and treating compacted soils; (3) remediating contaminated soils; (4) and reestablishing natural contours and vegetation (Sobczak et al. 2010). A 1987 study focusing on the impacts of oil and gas development on vegetation and soils determined the presence of foreign material (e.g. boards, plastic, crushed shell) on 12 of the 45 sites investigated was a primary impediment to the reestablishment of native vegetation.

Some of these abandoned sites are situated near meandering streams and rivers. Bank erosion and stream channel migration (see tables 1 and 10) have exposed oil and gas well casing of at least three

Table 1. Summary of resource management issues associated with oil and gas development and production.

Resource management issue	Oil and Gas Development and Production
Description	• Primary concerns from active operations include contamination from hydrocarbon or other hazardous material spills or releases, as well as activities that accelerate erosion or compaction of soils that impact growth and regeneration of vegetation. • Abandoned sites require reclamation or mitigation of hazards including unreclaimed access roads, drainage ditches, buried drilling mud and cuttings pits, petroleum- and salt-contaminated soils, and abandoned equipment (piping and tanks), debris, and foundations for structures (Baker 2006). • Future development may include directional drilling and hydraulic fracturing.
Related map units and/ or preserve examples	• 46 active oil and gas wells within the preserve. All are subject to the 9B Regulations. • Hundreds of active oil and gas wells surround the preserve (see GRI GIS data for 2009 well locations). • 163 km (101 mi) of pipeline crosses 238 ha (589 ac) of preserve land. • Hundreds of abandoned oil and gas wells within preserve and surrounding area. • Stream erosion is exposing pipelines and capped (abandoned) wells.
Related fundamental resources	• Free-flowing water and dependent systems. • Structural diversity. • Processes and functional diversity. • The thicket. • Cultural resources.
Potential action items	• All operations within the preserve must follow the Oil and Gas Management Plan and Environmental Impact Statement (National Park Service 2006) until a revised oil and gas inventory and management plan is produced. • Develop oil and gas operator's handbook (for mitigation measures); separate from a national plan; this is considered a medium priority planning need in the foundation document. • Develop a jurisdictional compendium for oil and gas pipelines to understand jurisdictional issues prior to, or in the event of, a spill, and to protect preserve resources; this is considered a low priority data need in the foundation document. • Determine if the US Geological Survey is tracking oil and gas reserves in the area and updating their maps; deep resources are a particularly preserve interest • Continue to assess soil and water contamination at abandoned oil and gas sites; as of 2005, only four sites had been tested. • Identify additional oil and gas sites that are in need of reclamation or restoration. • Use GRI GIS data and field checks to determine where meandering rivers may be impacting oil and gas infrastructure (i.e. determine which way meanders are moving, which wells are at risk, and proximity of wells to all creeks). • Develop interpretive materials to share with visitors the important oil and gas history of the preserve (and southeast Texas), as well as modern efforts to reduce environmental impacts of oil and gas extraction and improve visitor safety.
Primary references	• Oil and Gas Management Plan and Environmental Impact Statement: National Park Service (2006). • GRI scoping meeting summary: Fay (2009). • Natural resources foundation report: Sobczak et al. (2010). • Resources management plan: National Park Service (1980). • State of the Parks Report: National Parks Conservation Association (2005). • Texas General Land Office manages state lands and natural resources: http://www.glo.texas.gov/. • Railroad Commission of Texas-Oil and Gas Division regulates the exploration, production, and transportation of oil and natural gas in Texas: http://www.rrc.texas.gov/. • Report on focused site investigations: Michael Baker Jr., Inc. (2006). • NPS Geologic Resources Division, Energy and Minerals Branch for technical and policy expertise and assistance https://www.nps.gov/orgs/1088/contactus.htm. • NPS Geologic Resources Division Disturbed Lands Restoration program http://nature.nps.gov/geology/dlr/. • US Geological Survey Oil and Gas Basin Assessments (Gulf Coast Basins): http://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment/USBasinSummaries.aspx?provcode=5047.

abandoned wells in the preserve, meaning the wells are now in the river. Bank erosion is also exposing previously buried segments of active oil and gas pipelines that traverse the preserve (Sobczak et al. 2010). GRI scoping meeting participants expressed concern that abandoned roads, rights-of-way, or other easements could potentially provide unpermitted access to the preserve for illegal off-road vehicle (ORV) use, wildlife poaching, and cultural artifact theft or vandalism (Fay 2009).

Spills and Contaminated Runoff

As noted by participants in the GRI scoping meeting, spills of oil or release of gas or other hazardous materials associated with oil and gas operations, from both in-preserve and adjacent operations, have affected and are likely to continue affecting park resources (Fay 2009). Spills can impact park resources in two ways: (1) direct contamination of soil or water and (2) indirect contamination by runoff through a contaminated area, transporting hazardous material downstream. Either of these scenarios can affect animals or plants. There are 14 permitted industrial discharges within the preserve's watershed; most of these are a result of oil and gas production (Meiman 2012). Salty brine spills are particularly challenging. Saltwater is difficult to remediate as it moves readily through the groundwater system of layered, artesian aquifers (see fig. 8) and can damage or kill vegetation. For example, until the 1960s, the traditional disposal process at Saratoga Field was to drain saltwater and other oil and gas wastes into a large lagoon impounded by asphalt-hardened sand. The now-breached levee system that separated the lagoon from Little Pine Island Bayou (approximately 30 ha [80 ac] within the Lance Rosier unit) resulted in a large saltwater plume that created what is called an "oil wasteland", killing vast tracts of vegetation (National Park Service 2006; Fay 2009). However, the frequency of contaminant releases at active sites within the preserve has diminished due to frequent monitoring of producing sites and strict application of the 9B Regulations (Sobczak et al. 2010).

Hydrogen sulfide, a highly toxic gas, is associated with some oil and gas reservoirs. The gas, being heavier than air, tends to accumulate in low areas such as pits, ditches, and gullies. Most of the hydrocarbon reservoirs targeted at Big Thicket National Preserve do not have associated hydrogen sulfide with the possible exception of the Sour Lake area (Patrick O'Dell, Petroleum Engineer, NPS Geologic Resources Division, written communication, 24 February 2009 as presented in Fay 2009). Even if hydrogen sulfide is naturally present, the gas is not released during normal drilling operations unless the casing is compromised. It is standard procedure to monitoring for hydrogen sulfide during for oil and gas drilling operations (Fay 2009).

Future Development, Directional Drilling, and Hydraulic Fracturing

Oil and gas development will likely continue at Big Thicket National Preserve (Sobczak et al. 2010). Seismic surveys from the 1990s and 2000s revealed very deep (>4,600 m [15,000 ft]) oil potential (see table 3.6 in National Park Service [2006] for deep reservoir units; conference call participants, 1 February 2016). Schenk et al. (1999) highlighted potential oil-producing geologic formations buried deep below the preserve surface: Upper Cretaceous Tuscaloosa Formation, Upper Cretaceous Austin Chalk (Austin Group), the Paleocene-Eocene Wilcox Group, the Eocene Yegua Formation and other sandstones of the Claiborne Group, the Oligocene Vicksburg Formation, and the Oligocene Frio Formation. These formations compose two oil and gas "plays" (local group of oil fields or prospects controlled by the same set of geological circumstances) were developed and described—the Tertiary Oil and Gas Play, and the Upper Cretaceous Gas Play (Schenk et al. 1999). Conservative estimates state Big Thicket may contain 1.15 million barrels of oil in undiscovered oil fields, 3.21 billion cubic feet (bcf) of associated gas, 32.92 bcf of gas in undiscovered gas fields, and approximately 1 million barrels of condensate in undiscovered gas fields as allocated from the Tertiary Oil and Gas Play; Big Thicket may contain 33.98 bcf in undiscovered gas fields, and approximately 1 million barrels of condensate in undiscovered gas fields as allocated from the Upper Cretaceous Gas Play (Schenk et al. 1999). These numbers have likely changed with the advances in deep drilling, directional drilling, and hydraulic fracturing (see below; Conference call participants 1 February 2016).

Improvements in directional drilling and hydraulic fracturing have spurred renewed industry interest in many areas of the US, including southeast Texas. Horizontal drilling typically involves drilling vertically to or near the top of a target geologic formation and then turning the drill bit horizontally into the target formation in order to expose more of the production zone to the well bore and intersect vertical fractures or other structures to increase crude production (Just et al. 2013; KellerLynn 2016). Directional drilling allows extraction from beneath the preserve to be based from an external surface location; this would be particularly prevalent in the narrow corridor management units in stream floodplains of the preserve (Sobczak et al. 2010). Oil and gas production is further enhanced by multiple-stage hydraulic fracturing during which a liquid, typically water, is mixed with sand and chemicals and then injected at high pressure into a wellbore to create artificial fractures in the surrounding reservoir rock. After the artificial hydraulic pressure is removed from the wellbore, the sand acts as a "proppant," and holds open the new fractures to allow oil and gas to migrate into the wellbore (Just et al. 2013; KellerLynn 2016).

When oil and gas activities occur adjacent to the preserve, the National Park Service works closely with representatives of the oil and gas industry to help insure that operations are conducted in concert with NPS management goals and objectives and in a manner that, if possible, minimizes impacts on preserve resources and visitor experience. If an activity outside park boundaries destroys, causes the loss of, or injures National Park System unit resources, the National Park Service has authority to seek recoveries for response costs and damages from a responsible party under "System Unit Resource Protection Act" at 54 U.S.C. §100721–100725 (formerly the Park System Resources Protection Act, 16 U.S.C. §19jj). This is a strict liability statute. All oil and gas activity within the boundary of the preserve is subject to the 9B Regulations as enacted in December 2016.

Table 1 summarizes the geologic resource management issues, including oil and gas development and production. The table connects to the preserve's foundation document's fundamental resources, presents references and resources, as well as suggested action items.

Table 2. Summary of Big Thicket habitats and underlying geology.

Geologic Feature or Process	Big Thicket Habitats and Underlying Geology
Description	• Big Thicket's incredible biodiversity is due in part to the interplay of geology, topography, hydrology, and climate (fig. 9), which is humid subtropical with mean annual temperatures of 21°C (70°F) and rainfall of about 135 cm (53 in). • How water flows through and over underlying sand, silt, clay, and gravel are key factors in determining local features and habitat (fig. 9). • Fluvial features and processes alter the flow of water and distribution of sediments in Big Thicket (table 3). • Pine uplands and arid sand hills were among the components determined to be of "significant concern" in the natural resource condition assessment.
Related map units and/ or preserve examples	• The higher hill country and older, sandy, more permeable Willis and Bentley formations (geologic map units **Qw**, **Qwl**, **Qwc**, and **Qby**) support longleaf pine uplands in the northern areas of the preserve. • The younger, clay-rich, nearly impermeable Montgomery and Beaumont formations (**Qm**, **Qb**, **Qbs**, and **Qbc**) support pine savannah wetlands in the southern two-thirds of the preserve (Sobczak et al. 2010). • Primary habitats found in the Big Thicket include bottomlands, backwater slough, low ridges, oxbow lakes, terraces, sandy uplands, baygall wetlands, and acid bogs (fig. 9). These features and habitats are located on low active floodplains, stable floodplains, and terraces, which are increasing in elevation above the active river channels.
Related fundamental resources	• Free-flowing water and dependent systems. • Biodiversity. • Structural diversity. • Processes and functional diversity. • The Thicket. • Cultural resources.
Related resource management issues	• River Meandering, Erosion, and Fluvial Flooding (table 10). • Coastal Resources, Sea Level Rise, and Climate Change (table 11). • Oil and Gas Development and Production (table 1). • Mitigation and Restoration of Abandoned Mineral Lands and Other Disturbed Lands (table 8).
Potential action items	• Support studies proposed to define the Big Thicket in terms of its extent, former extent, flora, fauna, and landforms. • Support research efforts to restore vegetation communities and ecosystems. • Continue to support research into how resources respond to disturbances. • Support research to understand the threats of fragmentation and habitat loss, as well as adjacent land-use practices in an effort to prioritize management objectives and focus efforts to maintain health and integrity of the preserve ecosystem. • Prepare a resource stewardship strategy to serve as a bridge between qualitative statements of desired conditions for resources and measurable goals; this was identified as a medium priority planning need in the preserve's foundation document. • Use topography and GRI GIS data to 1) target rolling hilltop areas with sandy soils for pine uplands inventory updates and monitoring, 2) to identify gently sloping areas with fine sand and sandy loams for slope forest research, including forest age class structure, and 3) to define extremely well-drained sandy soils associated with old stream terraces and river bluffs for arid sand hills management and surveys.
Primary references	• Big Thicket National Preserve Foundation Document (National Park Service 2014). • Many references provide information about the complex biodiversity of the Big Thicket, including a flora overview by Diggs et al. (2006), an overview of the thicket and biocomplexity by Callicott et al. (2006), and a forest overview by Marks and Harcombe (1981). Lists of species by county are available from Texas Parks and Wildlife Department: http://tpwd.texas.gov/gis/rtest/. • Resources management plan: Big Thicket National Preserve by National Park Service (1980). • Sobczak et al. (2010) lists stakeholders who have an interest in the Big Thicket as well as laws and policies that apply or provide guidance. • Natural Resource Condition Assessment: Nadeau et al. (2016). • State of the Parks Report: National Parks Conservation Association (2005).

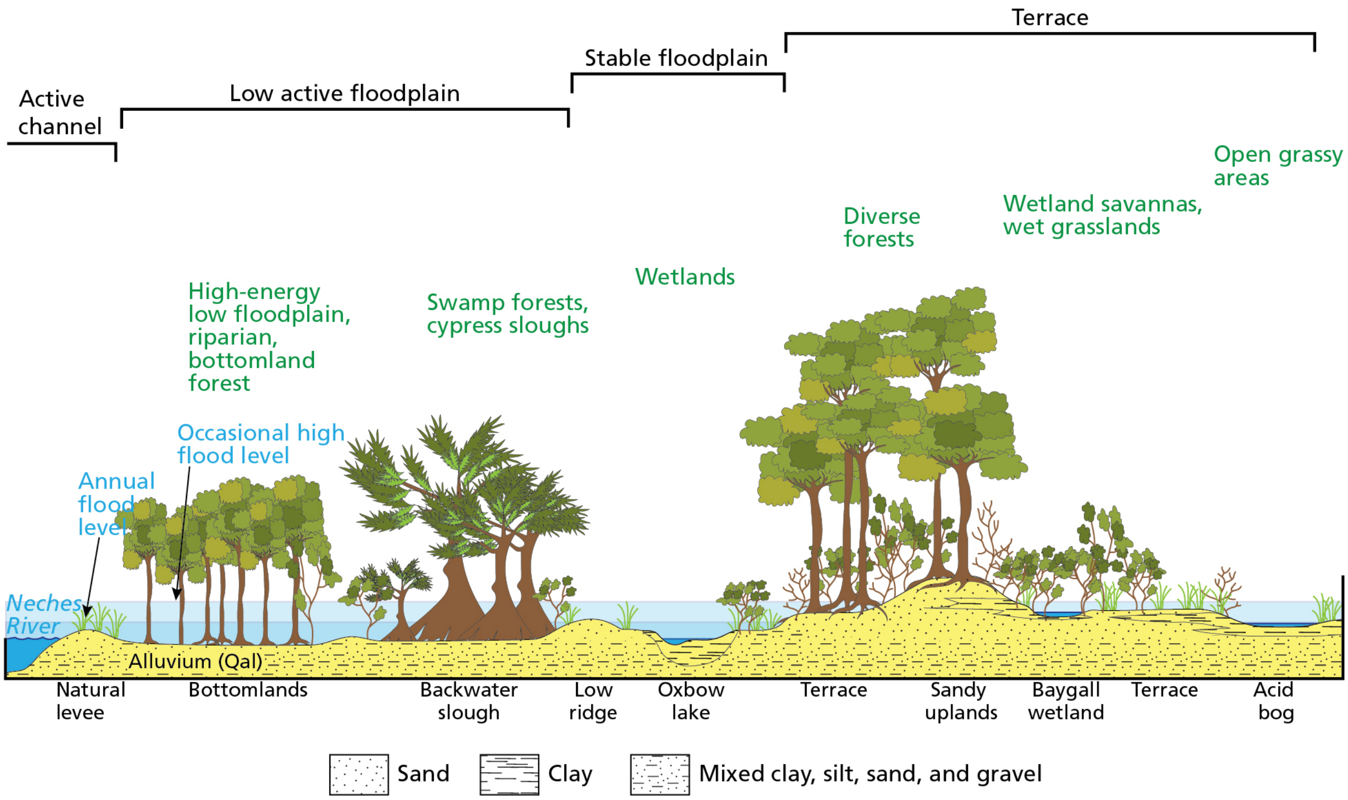


Figure 9. Cross-sectional view of the fluvial corridors in Big Thicket National Preserve.
Water stage and flow, sediment load, flood duration, and topography all play vital roles in maintaining the structure, function, diversity, and integrity of the ecosystems present in the preserve. Uplands and sloped areas typically have better drainage than flatlands underlain by clay-rich sediments. The highest areas are terraces or former river levels, perched above the modern floodplain. Bottomlands are flooded for most of the year. Bottomland forests occur closest to the river's edge where frequent floods scour the forest floor. Swamp forests of cypress and tupelo trees (cypress sloughs) are above bottomland forests and have almost perennial water, but regular flooding flushes organic material away, keeping the water fresh and not acidic. Sloughs are creeks or sluggish bodies of water in a bottomland or other marshland. They retain water for most of the year, but regular flooding flushes away acidic organic debris. Wetland savannas or wet grasslands are higher than sloughs and occur on claypan (clay-rich) substrates where rainwater is retained, but dries frequently; they are higher than sloughs. Wetland pine savannahs contain the richest biological diversity in the preserve. The preserve's wetland savannas occur, where flat terrain and tight, clay-rich substrates retard the infiltration of surface water; this creates a system that limits the growth of woody plants compared to surrounding upland areas. Baygall wetlands are higher on the floodplain and are characterized by forested swamps thick with evergreen shrubs that form where seep-fed creeks drain bogs. The name "baygall" comes from sweetbay magnolia and gallberry holly (two dominant plants in these wetlands). The highest topographic features—sandy uplands—support many forest types and even desert species, and exhibit good drainage for non-swamp conditions. A bog or seep forms where water, percolating downward through the sandy alluvium, flows atop a relatively impermeable clay layer and seeps out at the surface. Leaching of the soils by the percolating water creates acidic conditions, which support open, grassy acid bogs or seeps. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using figure A in Sobczak et al. (2010).

Table 3. Summary of fluvial features and processes.

Geologic Feature or Process	Fluvial Features and Processes
Description	• Fluvial processes create landforms through deposition and erosion (fig. 10). • Examples of common fluvial features in the Big Thicket include meandering river channels with point bars and cutbanks (including scarps), oxbow lakes, natural levees, backswamp areas, and terraces (fig. 10). • The characteristic meandering channels in Big Thicket are a result of a low gradient (slow flow) and moderate to high sediment load. • Old stream and river terraces have excellent drainage that supports desert species. • Hydrology was among the components determined to be of "significant concern" in the natural resource condition assessment; stressors to hydrology include dams, saltwater barrier, saltwater intrusion, pipelines, erosion, bank stabilization, and channel dredging.
Related map units and/ or preserve examples	• **Qal, Qca, Qda, Qad, Qt3, Qt2,** and **Qt1** are wholly, or in part, alluvial or terrace deposits. • Relict streams are mapped in Turkey Creek unit as part of the GRI GIS data in **Qt3**. • Fluvial patterns are mapped as part of the GRI GIS data east of the Lower Neches River Corridor unit in **Qb**. • Land Resources map units formed by fluvial processes include **D-3** (terraces), **D-4** (inactive alluvial fan and slopewash deposits), and **E-1** (flood prone areas). • The preserve contains 930 km (578 mi) of waterways, 386 km (240 mi) of which are major streams. • Major river systems are Neches River (fig. 11A) and its tributaries: Little Pine Island Bayou (fig. 11B, and Village Creek (figs. 11C and 12; fed by Turkey [fig. 11D] and Big Sandy creeks). Menard Creek flows into the Trinity River. • The preserve manages over 90% of the main stem of Village Creek; most of the headwater of Beech Creek, and 12 km (7.5 mi) of the lower segment of Turkey Creek. • The riparian corridor units are considered "brownwater" (larger, more turbid) or "blackwater" (smaller, slower, high organic content). • Most of the land within the preserve either contains or is directly adjacent to perennial streams, the majority of which are free flowing and nonchannelized. • The Texas Water Development Board identified virtually all of the major streams in the preserve for consideration as ecologically unique stream segments.
Related fundamental resources	• Free-flowing water and dependent systems. • Biodiversity. • Compositional diversity. • Structural diversity. • Processes and functional diversity. • The Thicket.
Related management issues	• River Meandering, Erosion, and Fluvial Flooding (table 10). • Coastal Resources, Sea Level Rise, and Climate Change (table 11) • Mitigation and Restoration of Abandoned Mineral Lands and Other Disturbed Lands (table 8)
Potential action items	• Use historic maps and aerial photographs to document how the Neches River has migrated and changed through time. • Conduct a wild and scenic river suitability study; this was identified as a medium-priority planning need for the preserve in the foundation document. • Prepare a watershed management plan; this was identified as a low-priority planning need in the foundation document.
Primary references	• Lord et al. (2009) presented methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. • Big Thicket National Preserve Foundation Document: National Park Service (2014). • Summary of water quality data and trends: and Bourdon (1985). • Water quality status and summary: Meiman (2012). • Natural resources foundation report: Big Thicket National Preserve by Sobczak et al. (2010). • Natural Resource Condition Assessment: Nadeau et al. (2016). • Lower Neches River Valley Authority (LNVA) http://www.lnva.dst.tx.us/. • State of the Parks Report National Parks Conservation Association (2005). • Stream habitat and land use: Moring (2003). • Texas Water Development Board: http://www.twdb.texas.gov/index.asp.

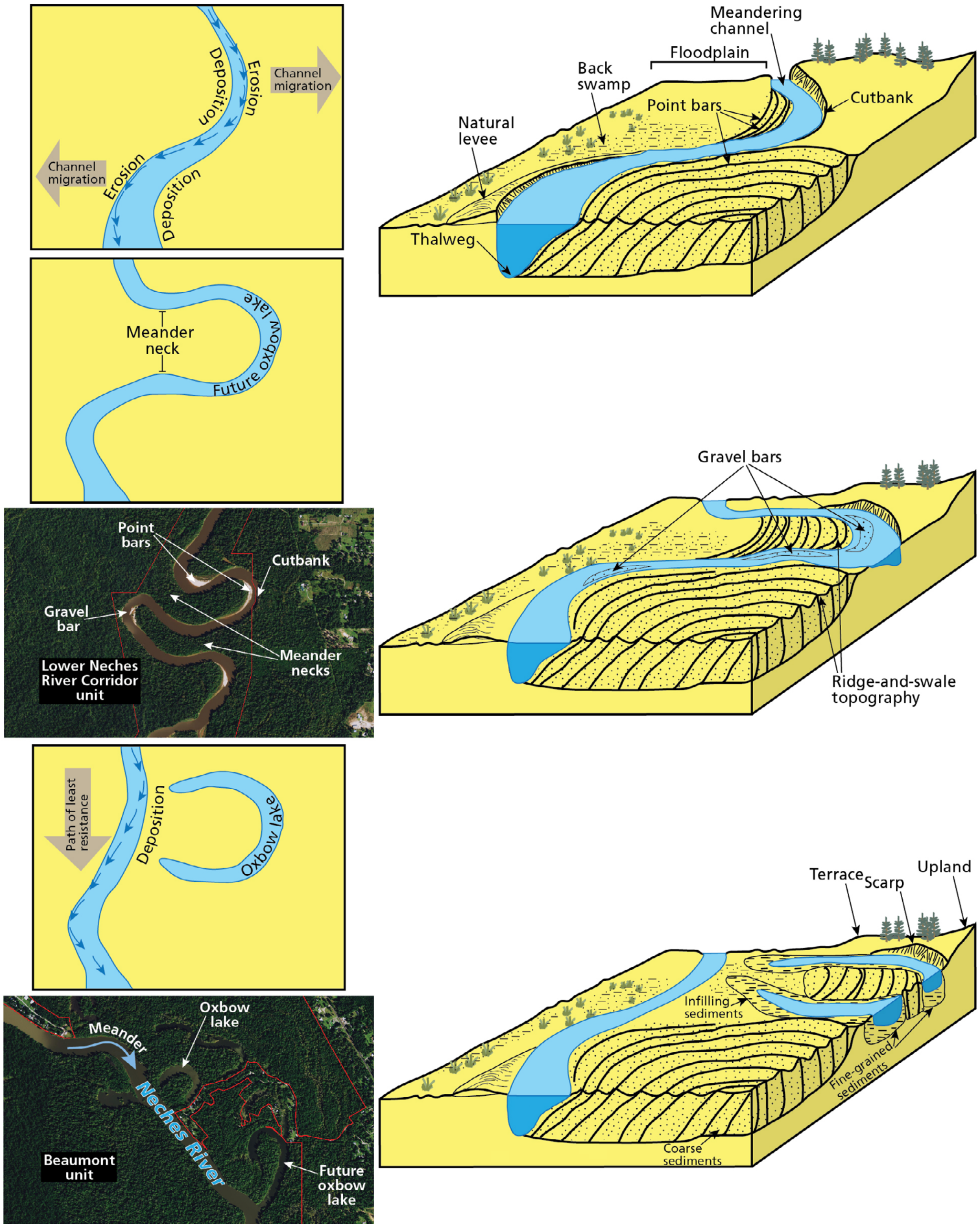


Figure 10. Illustrations and photographs of fluvial features associated with meandering rivers. As a river flows around curves the flow velocity (and thus erosive energy) is greatest on the outside of the bend. The river erodes into its bank on the outside of a curve, creating a cut bank or scarp. On the inside of the meander, where velocity is slower, a point bar (crescent-shaped ridge of sand, silt, and clay) is deposited. As the process continues, the outside bend retreats farther, while the inside bend migrates laterally, thus creating migrating meanders as illustrated above. As meander bends migrate, the "neck" of land between two bends narrows and eventually may be cut through. Then, the meander is abandoned by the stream leaving "oxbow" lakes. Natural levees form adjacent to river channels during floods, when sand and silt is deposited as the river overtops its banks. These deposits represent the relatively coarse-grained component of a river's suspended sediment load and form a high area on an alluvial region's land surface. Backswamps are low-lying areas that retain water during floods or high flow and are commonly separated from the river channel by natural levees. Terraces are level or near-level areas of land, above a river and separated from it by a steeper slope. A river terrace was made by the river at some time in the past when the river flowed at a higher level. Thick red line on photographs is the preserve boundary. Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from Allen (1964) using ESRI World Imagery basemap (accessed 16 May 2016)

Figure 11. Photographs of rivers at Big Thicket National Preserve.
A) Neches River at Lakeview. Here, the river is wide, navigable, and heavily used by visitors. B) Little Pine Bayou, facing upstream. The bayou is much shallower, with nearly still, sediment-laden, organic-rich water. C) Village Creek at McNeely Road Bridge. Here, the stream is relatively shallow and narrow, incising its channel into the adjacent floodplain. D) Turkey Creek and Gore Store Road Bridge. Flow is above normal causing minor flooding and turbid, sediment-laden flows. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using photographs from Meiman (2012) taken in summer 2006, spring 2009, spring 2010, and spring 2009, respectively.

Figure 12. Photograph at the confluence of Village Creek and the Neches River.
During above normal flows, the tannin-stained waters of Village Creek, mix with the turbid, sediment-laden (muddy) flow of the Neches River. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using photograph presented as figure 8 from Meiman (2012) taken in summer 2006.

Table 4. Summary of features and processes associated with wetlands and lakes.

Geologic Feature or Process	Wetlands and Lakes
Description	• Wetlands are common in Big Thicket National Preserve and include marshes, swamps, seeps, pools, and bogs. Four primary types of wetlands in the preserve are palustrine, riverine, lacustrine, and estuarine. Wetlands may be covered in shallow water most of the year, or be wet only seasonally. Underlying materials (e.g., sand, silt, clay) control local drainage and therefore support, or limit, wetland formation. • Palustrine wetlands are inland freshwater, non-tidal wetlands characterized by trees shrubs, and emergent vegetation. • Riverine wetlands consist of wetlands and deepwater habitats within stream channels. • Lacustrine wetlands are larger than 8 ha (20 ac) situated in dammed river channels or topographic depressions with vegetative cover less than 30%. • Estuarine wetlands are brackish and have regular or sporadic access to tidally influenced water. • Bogs or seeps occur when water percolating through sandy soils hits an impermeable clay layer and flows along the top of it to emerge at the surface. Soil leaching causes acidic conditions. • Baygall wetlands occur where seep-fed creeks draining bogs flow into dense thickets or evergreen-shrub forested swamps. • Wetland savannahs or wet grasslands occur on claypan soils that trap rainwater, but dry out during dryer summer months. • Oxbow lakes form as abandoned meanders of rivers (see fig. 10 and table 3). • Perennial, still-water bodies such as lakes often contain valuable pollen and organic records of past climate conditions.
Related map units and/ or preserve examples	• Land Resources map units **F-1** and **F-2**. • At least 40% of the land within preserve boundaries is considered wetlands. These are primarily palustrine and riverine (Lower Neches River Corridor, and Neches Bottom and Jack Gore Baygall units) wetlands, with less area of lacustrine (two examples) and estuarine wetlands (only in Beaumont unit). • Baygall wetlands or wetland shrub bogs are most extensive along the broad floodplain of the Neches River or in the Lance Rosier unit forming in depressions left by abandoned channels on terraces. • Swamp cypress wetlands occur within the Turkey Creek and Village Creek Corridor units. • Acid bogs occur in the open, grassy areas where terrace-level tributary streams enter a main drainage. • Undrained or intermittently drained depressions are part of the GRI GIS data for Lance Rosier, Little Pine Island-Pine Island Bayou Corridor, Beech Creek, Big Sandy Creek, and Turkey Creek units. • An oxbow lake is in the process of forming in the Lower Neches River Corridor unit, just north of Wiess Bluff. • A series of small lakes were part of the resort settlement at Sour Lake in the 1830s. • Lakes within the preserve include Sally Withers, Tater Patch, Sand Lot, Franklin, Cooks, and Ard lakes, and Lake Bayou.
Related fundamental resources	• Free-flowing water and dependent systems. • Biodiversity. • Compositional diversity. • Structural diversity. • Processes and functional diversity. • The Thicket.
Related management issues	• River Meandering, Erosion, and Fluvial Flooding (table 10). • Coastal Resources, Sea Level Rise, and Climate Change (table 11).
Potential action items	• The preserve's wetland area is likely underestimated; a wetlands inventory (contact NPS Water Resources Division) would provide detailed information and mapping of wetlands within the preserve. A detailed inventory was identified as a high-priority data need in the preserve's foundation document. • Landcover data could be used to determine how the wetlands have changed over time. Data are available at https://irma.nps.gov/DataStore/Reference/Profile/2167026.
Primary references	• Contact NPS Water Resources Division (https://www.nps.gov/orgs/1439/index.htm) for wetlands assistance. • NPS wetlands website: https://www.nps.gov/subjects/wetlands/index.htm. • Wetlands distribution Master's Thesis for Big Thicket: Zygo (1999). • Big Thicket National Preserve Foundation Document: National Park Service (2014). • State of the Parks Report National Parks Conservation Association (2005). • Natural resources foundation report: Big Thicket National Preserve by Sobczak et al. (2010). • Oil and Gas Management Plan and Environmental Impact Statement: National Park Service (2006).

Table 5. Summary of features and processes associated with sand mounds and salt domes

Geologic Feature or Process	Sand Mounds and Salt Domes
Description	• Sand mounds (fig. 13) are also known as "pimple mounds" or "Mima mounds" or "prairie mounds." • Regionally, sand mounds occur in and on sandy surficial deposits. Their origin is enigmatic and has been attributed to eolian (windblown) processes, burrowing rodents, or erosion during floods. • Mounds formed during the late Pleistocene and early Holocene epochs and each mound took 300 to 500 years to form (National Park Service 2006). • Salt domes are high ground areas underlain by salt deposits that are less dense than surrounding rock and have bulged upward, deforming overlying sedimentary layers. • Salt domes can produce salt licks which attract wildlife and "curative sulfurous water" associated with salt dome fueled the resort industry at Sour Lake in late 1800s and early 1900s. • Salt domes can indicate the presence of oil and gas (e.g., Spindletop and Sour Lake) and were the source of great interest to geologists and oil companies. • Mounds and other high ground areas are of high probability for finding cultural artifacts.
Related map units and/ or preserve examples	• The highest concentration of sand mounds in the preserve is in the Lance Rosier unit; some are also present in the Neches Bottom and Jack Gore Baygall unit. • Mounds are typically found on **Qm** and **Qby**, but also on **Qb**, **Qbs**, and **Qbc**. • Mounds occur on approximately 1,600 ha (4,000 ac) of the preserve; recent, high resolution LiDAR surveys revealed mounds are present in preserve units previously considered devoid of mounds. • Individual mounds range in height from 15 to 150 cm (6 to 60 in, are elliptical to circular in shape, and can vary in diameter from 2 to 55 m (6 to 180 ft). • At least 14 salt domes are mapped within the seven-county preserve area including High Island, Hall Dome, Spindletop, and Sour Lake. • Some 3-m (10-ft) high mounds found northwest of the preserve are not natural. They were constructed by the Caddoan Mound Builder Culture.
Related fundamental resources	• Biodiversity. • Compositional diversity. • Structural diversity. • Processes and functional diversity. • Scientific value. • The Thicket.
Related management issues	• Oil and Gas Development and Production (table 1). • Mitigation and Restoration of Abandoned Mineral Lands and Other Disturbed Lands (table 8).
Potential action items	• Inventory sand mounds within preserve boundaries to determine potential areas for cultural resource assessment, as well as areas to avoid for infrastructure development. • Use recent LiDAR surveys to delineate the exact locations of sand mounds; some topography available at https://irma.nps.gov/DataStore/Reference/Profile/2224684. FEMA may be obtaining LiDAR for entire preserve.
Primary references	• Comprehensive history of the Big Thicket and its preservation: Cozine (2004). • Natural resources foundation report: Big Thicket National Preserve by Sobczak et al. (2010). • Resources management plan: Big Thicket National Preserve by National Park Service (1980). • Oil and Gas Management Plan and Environmental Impact Statement: National Park Service (2006).

Figure 13. Photograph of sand mound.
Sand mounds or ridges provide well-drained substrates for specific plant varieties at Big Thicket National Preserve. In a landscape of such low relief, areas of relative high land were inherently drier and supported more human activity that adjacent swamps. National Park Service photograph is an unnumbered figure from National Parks Conservation Association (2005).

Table 6. Summary of features and processes associated with sedimentary units and geologic exposures.

Geologic Feature or Process	Sedimentary Units and Geologic Exposures

Description	• In areas of typically low relief, such as Big Thicket, exposures of underlying geologic units are uncommon and therefore significant.
	• Some geologic map units were named for exposures in the Big Thicket area (e.g., Beaumont Formation from Beaumont and Fleming Formation from a site in Tyler County, east of Corrigan).
	• The names associated with the Quaternary age geologic units in southeast Texas and western Louisiana vary depending on geographic area, mapping agency, and interpretation. The following was summarized by Aronow (1981 [included with GRI GIS data as an attached PDF in bith_geology.pdf]) and Eddie Collins (geologist, Texas Bureau of Economic Geology, review comments, 4 May 2017):
	  ○ In Texas, the Quaternary units are, from, oldest to youngest, Willis, Lissie, and Beaumont formations. This nomenclature is used on the small scale GRI GIS map of the entire preserve (Texas Water Development Board 2007; bith_geology.mxd)
	  ○ The large scale GRI GIS map data of individual units (maps by Aronow 1982) use nomenclature that splits the Lissie into the Bentley (older) and Montgomery (younger) formations.

Related map units and/ or preserve examples	• All of the geologic map units in the GRI GIS data are clastic sedimentary, meaning they are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." Clastic sedimentary rocks are named after the size of clasts (see table 7 and bith_geology.pdf in GRI GIS data). They were deposited primarily by water (rivers, coastal settings) or wind. Colluvium represents slope movement deposits. Artificial fill deposits (**Qaf**) are human-constructed "sedimentary" deposits. • Units deposited primarily by water: **Qal, Qca, Qda, Qda, Qad, Qt3, Qd, Qt2, Qdb, Qb, Qbs, Qbc, Qt1, Ql, Qm, Qby, Qw, Qwl, Qwc, Mlf**. • Units deposited primarily by wind: **Qws**. • Units primarily associated with slope movements: **Qca**. • Beaumont (**Qbs**, **Qbc**) and Lissie (**Ql**) formations are the predominant geologic units mapped in the preserve area. • Older units are generally exposed inland and overlying, younger units crop out seaward. • Outcrops are mapped in the GRI GIS data: 17 of **Qw** and **Mlf** occur in Upper Neches River Corridor unit; one of **Qby** in Turkey Creek unit; one of **Qby** in the Neches Bottom and Jack Gore Baygall unit; one of **Mlf** in Menard Creek Corridor unit; one of **Qdb** in Lower Neches River Corridor unit; three in **Qd** in the Beaumont unit; one in **Qw** just outside the Big Sandy Creek unit. • Wild and Scenic River designation for the Neches River was supported by its significant geologic exposures, particularly those from the Town Bluff Dam to Interstate-10 divided by the 96 Bridge and the Saltwater Barrier, as well as in the Big Sandy Creek, Pine Island Bayou, Village Creek, Turkey Creek, and Menard Creek units.
Related fundamental resources	• Biodiversity. • Compositional diversity. • Structural diversity. • Processes and functional diversity. • Scientific value.
Related resource management issues	• Slope Movement Hazards and Risk (table 12). • Oil and Gas Development and Production (table 1).
Potential action items	• Deposits in the GRI GIS data are generally not well consolidated and are subject to slope movements where exposed on scarps or steep slopes. Target scarps or steep slope areas for monitoring.
Primary references	• US Geological Survey GEOLEX database contains information about each geologic map unit including type section, age, and significant publications: http://ngmdb.usgs.gov/Geolex. • Geologic description of the Gulf Coast aquifer: Chowdhury and Turco (2006). • Texas geologic database: Texas Water Development Board (2007). • Geologic map data and descriptions: Aronow (1981, 1982a–j). • Geology of outstanding resource values: Turky (1943 to Village Creek) by Cantu (2012a); PIB by Cantu (2012b); Neches-Dam to 96 Bridge by Cantu (2012c); Menard (Boundary to the Trinity) by Cantu (2012d); Neches-96 Bridge to SWB by Cantu (2012e); Neches-SWB to I-10 by Cantu (2012f); Big Sandy (770 to Neches) by Cantu (2012g); Village Creek by Cantu (2012h).

Table 7. Clastic sedimentary rock classification and characteristics.

Note: Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale." In the case of the units at Big Thicket National Preserve, they are not yet fully lithified to be solid rock, but instead are still recognizable by their clastic components.

Rock Name	Clast Size	Example of Depositional Environment	Big Thicket National Preserve Example (may represent multiple depositional environments)
Conglomerate (rounded clasts) or Breccia (angular clasts)	>2 mm (0.08 in) [larger]	flowing water in rivers (higher energy environments)	Layers in **Ql, Qwl, Qwc**
Sandstone	1/16–2 mm (0.0025–0.08 in)	Stream channels and point bars	**Qws, Qbs, Qal,** layers in **Qd, Qb, Ql, Qby, Qw, Qwl, Qwc,** and **Mlf**
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)	Natural levees and floodplains	**Qal,** layers in **Qd, Qb, Qbs, Ql, Qw, Qwl, Qwc,** and **Mlf**
Claystone	<1/256 mm (0.00015 in) [smaller]	stagnant water in swamps (lower energy environments)	**Qbc, Qal,** layers in **Qb, Qbs, Ql, Qd, Qw, Qwl, Qwc,** and **Mlf**

Table 8. Summary of resource management issues associated with mitigation and restoration of abandoned mineral lands and other disturbed lands.

Resource management issue	Mitigation and Restoration of Abandoned Mineral Lands and Other Disturbed Lands
Description	• Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations (described in the "Oil and Gas Development and Production" section). • AML features are commonly targets for mitigation, reclamation, or restoration to reduce hazards and impacts to natural and/or cultural resources. • Prior to establishment of the preserve, much of the landscape was impacted by logging (including tram roads and canals), railroads, and oil & gas development. • Mitigation measures are required as part of new permits to reduce or eliminate erosion, sedimentation, contamination, and other impacts that could affect geologic resources. • Residential development now represents one of the most potent drivers of landscape change in southeast Texas.
Related map units and/ or preserve examples	• Areas of artificial fill are mapped as geologic unit **Qaf**. • The preserve contains 52 AML features at 44 sites (Burghardt et al. 2014). • None of the AML features within the park have already been mitigated and 30 additional features at 25 sites are in need of mitigation. Of those that require mitigation, nine are classified as high priority, one medium, and 20 are low priority (Burghardt et al. 2014). • Village Creek Corridor unit has fine washed sand that is marketable and more likely to have been mined regionally. • 16 total sand pits are located in the GRI GIS data for Neches Bottom and Jack Gore Baygall, Beaumont, and Lower Neches River Corridor units. • 9 iron ore gravel pits or "scraped areas" are located in the GRI GIS data for Menard Creek Corridor, Big Sandy Creek, and Beech Creek units. • Logging may continue on private land within preserve's authorized boundary. • ORV use throughout the preserve denudes or crushes vegetation, impacts saturated and hydric soils, and causes compaction and accelerated erosion; ORV use is prevalent in the Lance Rosier unit.
Related fundamental resources	• Free-flowing water and dependent systems. • Structural diversity. • Processes and functional diversity. • The Thicket. • Cultural resources.
Potential action items	• Complete or update inventory and documentation of all AML features. These should be recorded in the Servicewide AML Database. An accurate inventory identifies human safety hazards and contamination issues, and facilitates closure, reclamation, and restoration of AML features. • Complete cultural landscape inventories for all preserve units. • Continue sandy uplands habitat restoration.
Primary references	• NPS Abandoned Mineral Lands website: http://go.nps.gov/aml. • Abandoned mineral lands in the National Park System: comprehensive inventory and assessment by Burghardt et al. (2014). • GRI scoping meeting summary: Fay (2009). • Aronow (1982a, 1982b, 1982c, 1982f, 1982g, 1982h). • Big Thicket National Preserve Foundation Document: National Park Service (2014). • Natural resources foundation report: Sobczak et al. (2010). • Comprehensive history of the Big Thicket and its preservation: Cozine (2004). • Resources management plan: Big Thicket National Preserve by National Park Service (1980). • Oil and Gas Management Plan and Environmental Impact Statement: National Park Service (2006). • Overview of the thicket and biocomplexity: Callicott et al. (2006). • Drilling permits and completion statistics; pipeline damage reporting; oil and gas well reporting; GIS data: Railroad Commission of Texas http://www.rrc.texas.gov/. • Socioeconomic atlas for Big Thicket National Preserve: McKendry et al. (2004). • State of the Parks Report: National Parks Conservation Association (2005). • Stream habitat and land use: Moring (2003). • Texas General Land Office http://www.glo.texas.gov/. • NPS Disturbed Lands Restoration http://go.nps.gov/grd_dlr

Figure 14. Photographs of common features at abandoned oil and gas sites within the Neches Bottom and Jack Gore Baygall unit.
A) Thin, stunted, and invasive or exotic vegetation regrows on areas disturbed or contaminated by oil and gas development. B) Abandoned, capped wells, valves, and pipelines are present in the preserve. C) Some shallowly buried pipelines are leaking and contaminating adjacent soil. D) Well pads do not immediately revegetate and may harbor exotic species. E) Flooded pits at sites may contain hazardous materials. F) Some pipelines are not buried and are at the surface of well pads. Images are photographs 1, 4, 13, 12, 10, and 6, respectively from Michael Baker Jr., Inc. (2006) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

Table 9. Summary of resource management issues associated with external mineral, resource, and residential development.

Resource management issue	External Mineral, Resource, and Residential Development
Description	● Resource extraction and residential development adjacent to the preserve may impact resources within the preserve. ● Timber companies are selling timber lands to developers and real-estate speculators; it is difficult to keep up with zoning changes and proposed developments.
Related map units and/ or preserve examples	● Land resources map units include basic information about development potential. Units **A-1**, **A-4**, **C-1**, **C-5**, **D-3**, **D-4**, **E-1**, **F-1**, and **F-2** are mapped in and adjacent to the preserve. See tables 16 and 17 (in pocket), poster 13 (in pocket) and Kier et al. (1977). ● Sand mining operations near the preserve include near Ross Ridge, off FM-787 near the Menard Creek Corridor unit, and several small mines near Village Creek Corridor unit. ● Commercial and private forest lands account for approximately 95% of the land area adjacent to the preserve however more than 2 million acres surrounding the preserve have been up for sale by the timber industry since 2002 (National Parks Conservation Association 2005). ● The preserve only protects about 1.6% of the entire Neches River watershed. ● Residential subdivisions occur along 19 km (12 mi) of preserve boundary (fig. 15) adjacent to Big Sandy Creek, Hickory Creek Savannah, Pine Island Bayou-Little Pine Island Bayou Corridor, and Beaumont units. ● Rural homesite developments occur along 42 km (26 mi) of preserve boundary. ● Appliances, abandoned cars, and other trash are often discarded on the riverbanks by adjacent residents, or dumped into the preserve's rivers and creeks intentionally (fig. 15). ● The percentage of land development in the drainage areas upstream from the preserve's blackwater streams correlates negatively with habitat stability for aquatic biota.
Related fundamental resources	● Free-flowing water and dependent systems. ● Structural diversity. ● Processes and functional diversity. ● The Thicket. ● Cultural resources.
Potential action items	● Collaborate with adjacent land managers and other permitting entities to help ensure that National Park System resources and values are not adversely impacted by external development, including linear infrastructure projects (oil-pipeline crossings, electrical transmission lines, and fiber optic network lines). ● Callicott et al. (2006) presented a model to predict how ecosystem processes and services would respond to development. This and further dynamic models may provide tools to determine how the landscape and ecosystem might respond to management decisions. ● McKendry et al. (2004) compiled a socioeconomic atlas for park management that includes land-use layers that may be useful in analysis of land-use changes and ecosystem response. ● Complete a comprehensive baseline inventory and updates of neighboring land uses as described in the natural resource condition assessment. ● Continue seeking funds and approval to work with land owners and cooperators to conserve land along preserve boundaries. ● Continue cooperation with the Texas Department of Transportation to ensure resource impacts are minimized during roads construction, maintenance, or expansion. ● Accurately mark and cyclically remark preserve boundaries; this was identified as a high priority planning need by the preserve's foundation document. ● Compile right-of-way access and easements; these data were identified as a high priority need in the foundation document.
Primary references	● Land resource maps: Kier et al (1977) is included in GRI GIS data. ● Resources management plan: Big Thicket National Preserve by National Park Service (1980). ● Natural Resource Condition Assessment: Nadeau et al. (2016). ● Disturbed Lands Restoration http://go.nps.gov/grd_dlr.

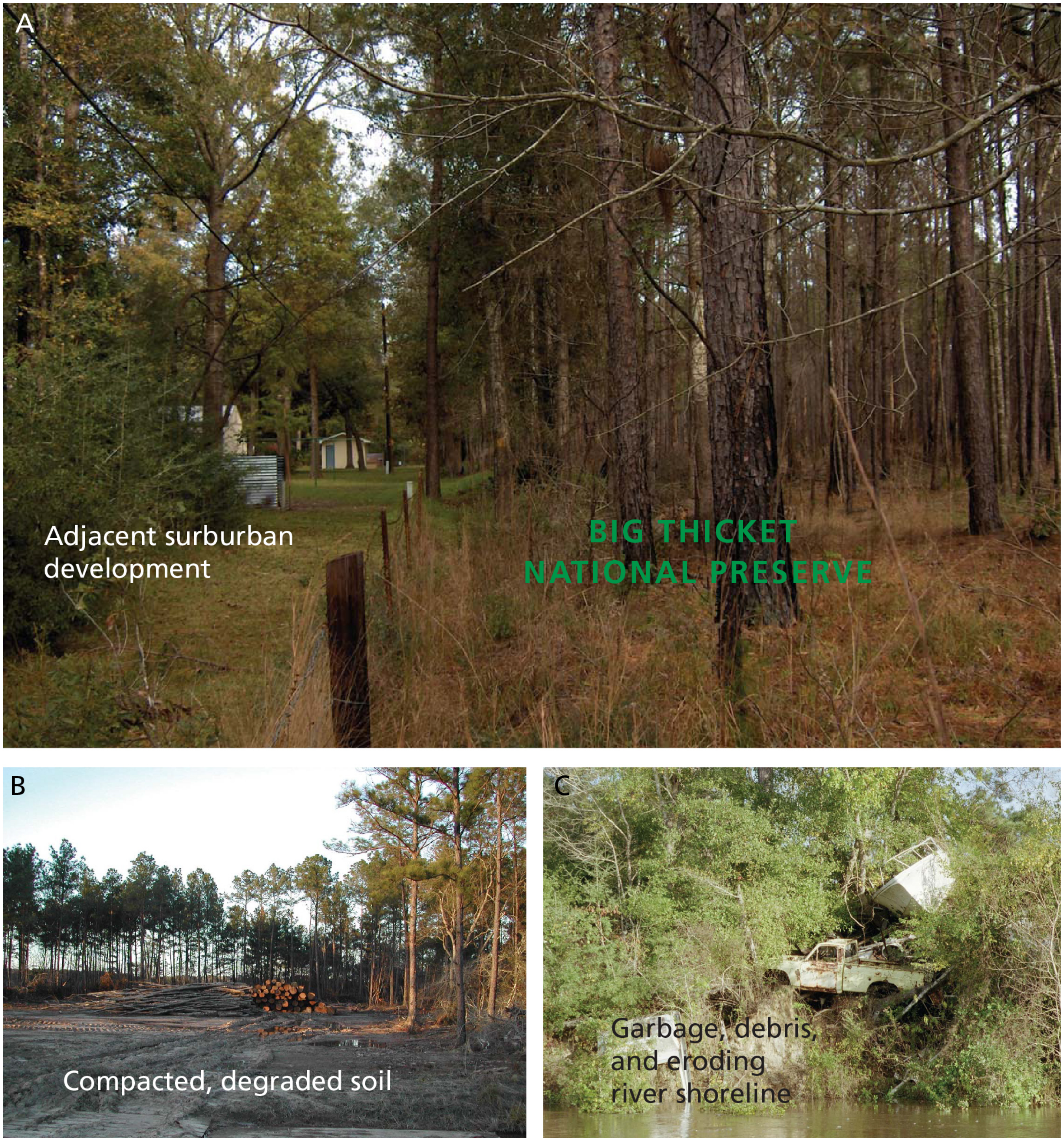


Figure 15. Photographs of disturbed lands and external development.
A) Isolated units connected by long narrow corridors is characteristic of the preserve. This situation means the preserve shares many kilometers of boundary with adjacent landowners. Impacts and potential impacts from adjacent land use is a major resource management issue at the preserve. B) Logging is ongoing in the preserve area. Effects from previous logging include compacted soils, degraded vegetative communities, and accelerated erosion. C) Dumping continues to occur along the Neches River and other preserve waterways. It also includes debris from prior floods. This dumping damages river shorelines, increases erosion locally, and may introduce contaminants. Images are unnumbered figures from National Parks Conservation Association (2005) annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

Table 10. Summary of resource management issues associated with river meandering, erosion, and fluvial flooding.

Resource management issue	River Meandering, Erosion, and Fluvial Flooding
Description	• Meandering rivers characteristic of the Big Thicket area (table 3) create a variety of resource management issues. • Channel migration (meandering) in narrow corridors creates scenarios where river flows in and out of the preserve's boundary. • Streambank erosion and channel migration threaten infrastructure and abandoned oil and gas sites (fig. 16); may cause adjacent property damage; presents navigational hazards; and can increase the risk of exposing preserve resources to contamination. • Flooding accelerates the rate of river meandering and erosion; flood pulses also increase suspended sediment and turbidity in river flows, which in turn will impact aquatic habitats and increase sedimentation downstream. • Erosion may expose, damage, or destroy cultural artifacts, particularly at sand ridges or mounds. • Flooding occurs more commonly in summer during tropical storms. For example, rainfall from Hurricane Harvey in 2017 caused extensive flooding in and around the preserve (figs. 20-22). Harvey was the most significant rainfall event in United States history in scope and rainfall totals since rainfall records began during the 1880s (Watson et al. 2018, p. 7). Rainfall totals in the Neches basin ranged from about 48 cm to 132 cm (18 in to 52 in) within the Neches Basin for the duration of the event (Watson et al. 2018). Hurricane Harvey rainfall totals in the Pine Island Bayou Subbasin ranged from about 61 cm to 112 cm (24 in to 44 in; Watson et al. 2018). For comparison the subbasin's average annual rainfall is approximately 114 cm (45 in; Watson et al. 2018, citing NOAA 2014) • Flood peaks are attenuated by the preserve's characteristic broad flat valleys that produce slow-moving, long-duration floods. • Flooding effects are exacerbated by river aggradation and floating debris. • The Neches River's flow is controlled and diverted by Sam Rayburn Dam, Town Bluff Dam, Neches River Saltwater Barrier, and the LNVA Canal to provide flood control, satisfy water rights, generate electricity, prevent saltwater intrusion, deliver water to the estuary, and create recreational opportunities. • Releases of water from dams create temporary flooding and may increase erosion and channel incision. These events and may occur with little or no warning to preserve managers. • Development outside the preserve increases impervious surfaces (e.g., parking lots), which increase surficial runoff into the preserve's river systems.
Related map units and/ or preserve examples	• Geologic map units **Qal, Qca, Qda, Qad, Qt3, Qt2,** and **Qt1** are all associated with modern rivers or floodplain. • Flood-prone areas are mapped as unit E-1 on the Land Resources Potential Development map. • Poor drainage associated with clay-rich geologic units (e.g., Qbc) exacerbates flooding following storms. • The National Park Service does not own the Neches River or its bed; the beds of navigable streams are owned by the state, in trust for the public. • Near the Edgewater day use area, homeowners are using fill dirt, tires, concrete, and other materials to armor the river banks in an attempt to prevent river encroachment. • In the northern part of the Neches Bottom and Jack Gore Baygall unit, the Neches River has migrated, exposing at least 3 abandoned well casings, pipelines have been exposed in Neches River and Big Sandy Creek (fig. 17). • Frequency and duration of saltwater intrusion events can be expected to increase as demand for freshwater in the greater Beaumont area increases and the Sabine-Neches Waterway is deepened and widened.
Related fundamental resources	• Free-flowing water and dependent systems. • Processes and functional diversity.

Resource management issue	River Meandering, Erosion, and Fluvial Flooding
Potential action items	• Identify areas where channel meander or shoreline erosion may coincide with oil and gas operations, infrastructure, sand ridges or mounds to potentially protect or preserve natural and cultural resources. • Research alternative means of bank stabilization and how bank modifications affect habitat for important preserve species as described in the natural resource condition assessment. • Measure flooding frequency and duration, drought frequency and duration as detailed in the natural resource condition assessment. • Photomonitoring of meander bends near oil and gas operations, cultural resources, or other important infrastructure is one option to provide quantitative data on rates of erosion for management decisions. • Collaborate with, or utilize data from studies of, hydrologic changes associated with flood pulses from upstream dams along Neches River (University of North Texas and Rice University). • Continue to work with the Texas Water Development Board concerning potential new dam and reservoir projects (e.g., increase height of Town Bluff Dam, construction of Fastrill Reservoir and Rockland Dam). • As appropriate, collaborate with US Geological Survey on accretion and erosion monitoring study proposed for the Neches River.

Primary references	• FEMA flood hazard mapping: http://www.fema.gov/national-flood-insurance-program-flood-hazard-mapping.
	• FEMA GIS flood hazard data viewer http://fema.maps.arcgis.com/home/webmap/viewer.html?webmap=cbe088e7c8704464aa0fc34eb99e7f30.
	• Peak stream flows and flood inundation maps associated with Hurricane Harvey: Watson et al. (2018).
	• Natural resources foundation report: Big Thicket National Preserve by Sobczak et al. (2010) explains history, status, and impacts of dam projects on the fluvial system of the preserve; also explains the flood-pulse concept model that links hydrology, biogeochemistry, and ecology of large rivers with extensive floodplains.
	• Lord et al. (2009) presented methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.
	• Natural Resource Condition Assessment: Nadeau et al. (2016).
	• GRI scoping meeting summary: Fay (2009).
	• Summary of water quality data: Wells and Bourdon (1985).
	• Summary of water quality data: Meiman (2012).
	• Resources management plan: Big Thicket National Preserve by National Park Service (1980).
	• Overview of the thicket and biocomplexity: Callicott et al. (2006).
	• A variety of state and federal agencies provide guidance or support for rivers and floodplains in Texas, including the following:
	  ○ Lower Neches Valley Authority http://www.lnva.dst.tx.us/.
	  ○ Texas Department of Parks and Wildlife http://tpwd.texas.gov/.
	  ○ Texas Commission on Environmental Quality http://www.tceq.state.tx.us/
	  ○ Texas Water Development Board: http://www.twdb.texas.gov/index.asp.
	  ○ US Geological Survey https://www.usgs.gov/science/science-explorer/Water.
	  ○ Federal Emergency Management Agency http://www.fema.gov/.
	  ○ Bureau of Reclamation http://www.usbr.gov/.
	  ○ US Forest Service http://www.fs.fed.us/.
	  ○ Railroad Commission of Texas http://www.rrc.texas.gov/.
	  ○ State Soil and Water Conservation Board https://www.tsswcb.texas.gov/.
	  ○ Texas General Land Office http://www.glo.texas.gov/.
	  ○ NPS Water Resources Division http://www.nature.nps.gov/water/.

Figure 16. Photograph of an oil pipeline exposed in Big Sandy Creek.
The pipeline is exposed during low flows, but could also pose a navigational hazard during higher flows. Image is facing downstream from the FM 1276 bridge. Photograph by Joe Meiman (National Park Service) in summer, 2006; figure 4 in Meiman (2012).

Table 11. Summary of resource management issues associated with coastal resources, sea level rise, and climate change.

Resource management issue	Coastal Resources, Sea Level Rise, and Climate Change
Description	● 7.6 km (4.7 miles) of shoreline are mapped within the preserve (Curdts et al. 2011). ● The coastal areas are tidally influenced wetlands or reaches of the Neches River in the Beaumont unit. Little Pine Island-Pine Island Bayou Corridor unit also includes coastal features and tidally influenced wetlands. ● Saltwater intrusion (and associated impacts to freshwater ecosystems and municipal water supplies) will be an increasing issue as sea level rises (fig. 17). ● Lower Neches Valley Authority (LNVA) constructed a saltwater barrier just south of Beaumont. ● As climate changes, storm patterns may also change. Higher intensity storms and storm surge (fig. 17) are an increasing risk; droughts may increase in frequency and duration.
Related map units and/ or preserve examples	● Flood-prone areas are mapped as unit **E-1** on the Land Resources Potential Development map. As sea level rises, floods may become more common. ● A saltwater barrier installed by the LNVA in 2003 (fig. 18) protects freshwater intakes for municipal and agricultural uses from saltwater intrusion. The saltwater barrier replaced temporary steel sheet-pile barriers that were installed 36 times from 1940 to 2000 and caused shoreline erosion in the preserve; the new barrier mitigated the erosion problems of the temporary structures. ● The US ACOE plans to deepen the navigational channel to the Port of Beaumont from 12 to 15 m (40 to 48 ft); this will magnify the influence of tides and salinity on the estuarine wetlands. ● From 1958 to 2014, the rate of local sea level rise is +0.53 cm/year (+0.21 in/year) (Caffrey 2015). ● Predictions for future sea level rise indicate a local change of as much as +23.5 cm (+0.77 ft) by 2050 or +66.1 cm (+2.17 ft) by 2100 (Caffrey 2015). ● Between 1842 and 2014, 20 tropical storms, depressions, and subtropical storm paths occurred within 16 km (10 mi) of the preserve (Caffrey 2015). ● Hurricanes Rita (category 5) in 2005 and Ike (category 4) in 2008 caused extensive blowdown in the preserve, which increases susceptibility to erosion and slope movements); storm surge associated with Hurricane Ike in 2008 breached the saltwater barrier. In August 2017, while this report was in final review and formatting, rainfall from Hurricane Harvey inundated the preserve causing widespread flooding and myriad resource impacts (e.g., Watson et al. 2018; figs. 19-21). ● At least one category 1 hurricane is predicted to reach the preserve over the next century.
Related fundamental resources	● Processes and functional diversity. ● The Thicket.

Resource management issue	Coastal Resources, Sea Level Rise, and Climate Change
Potential action items	● Climate change scenario planning (contact NPS Climate Change Response Program) can provide preserve-specific actions. ● A coastal vulnerability index (CVI) assessment is another potential planning tool. CVIs use tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea-level rise to create a relative measure of the coastal system's vulnerability to the effects of sea-level rise. ● Prepare a parkwide natural resources restoration plan taking into account potential impacts of climate change and management actions to mitigate impacts; this was identified as a high priority planning need in the preserve's foundation document.
Primary references	● The Coastal Adaptation Strategies Handbook (Beavers et al. 2016) summarizes the current state of NPS climate adaptation and key approaches currently in practice or considered for climate change adaptation in coastal areas in order to guide adaptation planning in coastal parks. The chapters focus on policy, planning, cultural resources, natural resources, facility management, and communication/education. The handbook highlights processes, tools and examples that are applicable to many types of NPS plans and decisions. ● Regional climate change impacts are summarized for the United States by Melillo et al. (2014). ● GRI scoping meeting summary: Fay (2009). ● Sea level and storm trends for the preserve: Caffrey (2015). ● Peak stream flows and flood inundation maps associated with Hurricane Harvey: Watson et al. (2018). ● Natural Resource Condition Assessment: Nadeau et al. (2016). ● Big Thicket water quality status report: Meiman (2012). ● Natural resources foundation report for Big Thicket National Preserve (Sobczak et al. 2010) discusses how climate change will affect freshwater supplies, river ecosystems, freshwater habitats, and biological resources at the preserve. ● Twilley et al. (2001) describes the potential risk of climate change to Gulf Coast ecosystems. ● NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction provides guidance for parks with boundaries that may shift with changing shorelines (available at http://www.nps.gov/applications/npspolicy/DOrders.cfm). ● Summary of Preserving Coastal Heritage workshop in 2014 (https://sites.google.com/site/democlimcult/). ● Bush and Young (2009) described methods and vital signs for monitoring the following coastal features and processes: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion. ● The NPS Climate Change Response Program https://www.nps.gov/orgs/ccrp/index.htm. ● NPS Water Resources Division http://www.nature.nps.gov/water/. ● NPS Water Resources Division, Ocean and Coastal Resources Branch http://www.nature.nps.gov/water/oceancoastal/. ● Texas Water Development Board: http://www.twdb.texas.gov/index.asp. ● US Geological Survey coastal vulnerability index (CVI) website: http://woodshole.er.usgs.gov/project-pages/nps-cvi/. ● Intergovernmental Panel on Climate Change: http://www.climatechange2013.org/report/. ● USACE Sea Level Calculator: http://www.corpsclimate.us/ccaceslcurves.cfm. ● NOAA Tides and Currents: http://tidesandcurrents.noaa.gov. ● NPS Storm Surge Mapping (e.g., Caffrey 2015): http://mariacaffrey.com/storms. ● NOAA Historical Storm Data: http://www.ncdc.noaa.gov/ibtracs/. ● NPS Climate Change Response Program storm surge maps: https://www.flickr.com/photos/125040673@N03/sets/.

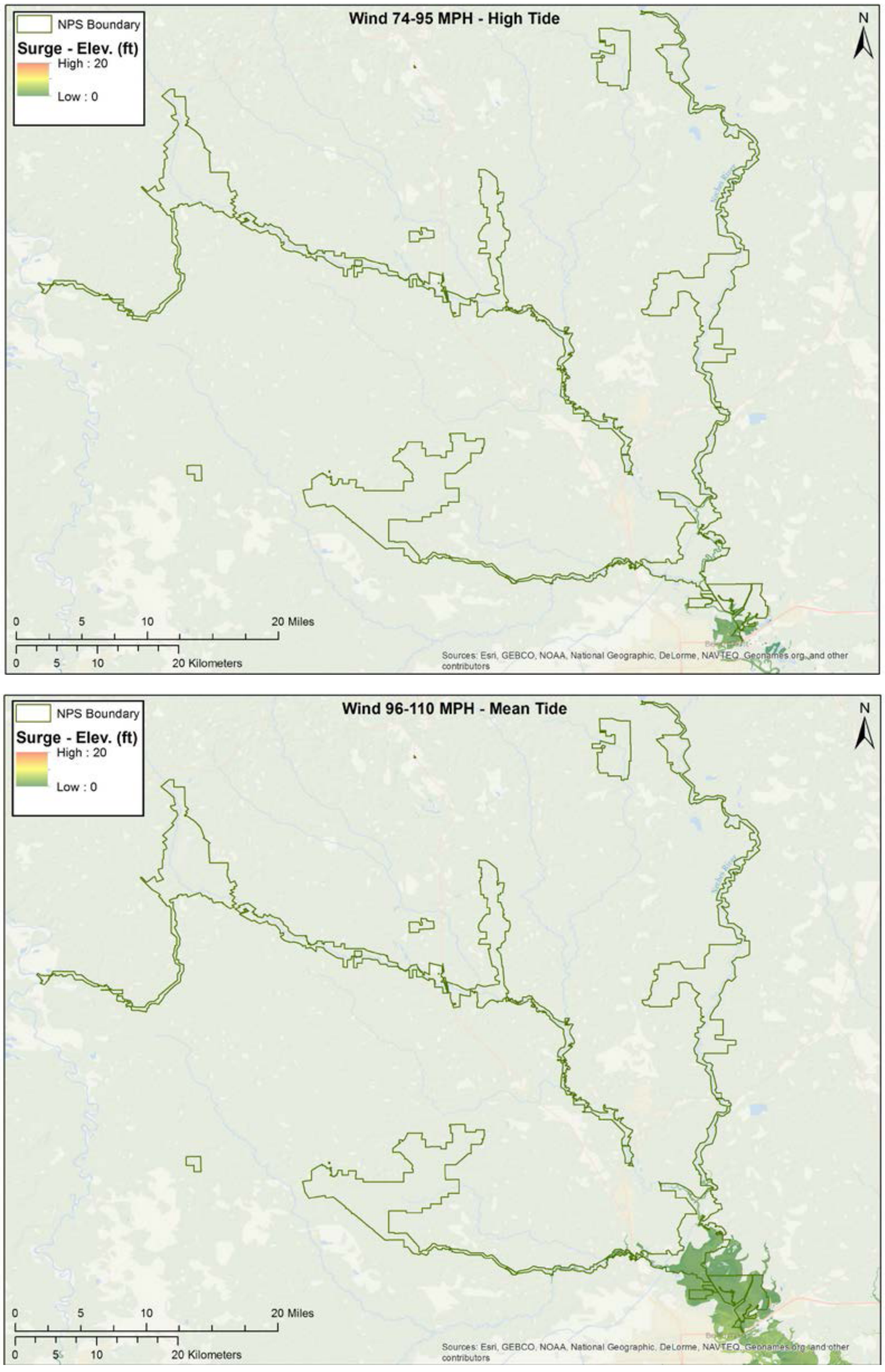


Figure 17. Maps of potential storm surge height and areal extent.
Top image shows conditions of a Saffir-Simpson category 1 hurricane at high tide. The bottom image of a Saffir-Simpson category 2 hurricane during mean tide. Graphics are from figure 2 in Caffrey (2015).

Figure 18. Photograph of the LVNA saltwater barrier of the Neches River.
Image shows above-normal flow conditions with open gates to accommodate high discharge of the river. Note elevated water turbidity associated with high flows. Photograph by Joe Meiman (National Park Service) in spring, 2009, presented as figure 1 in Meiman (2012).

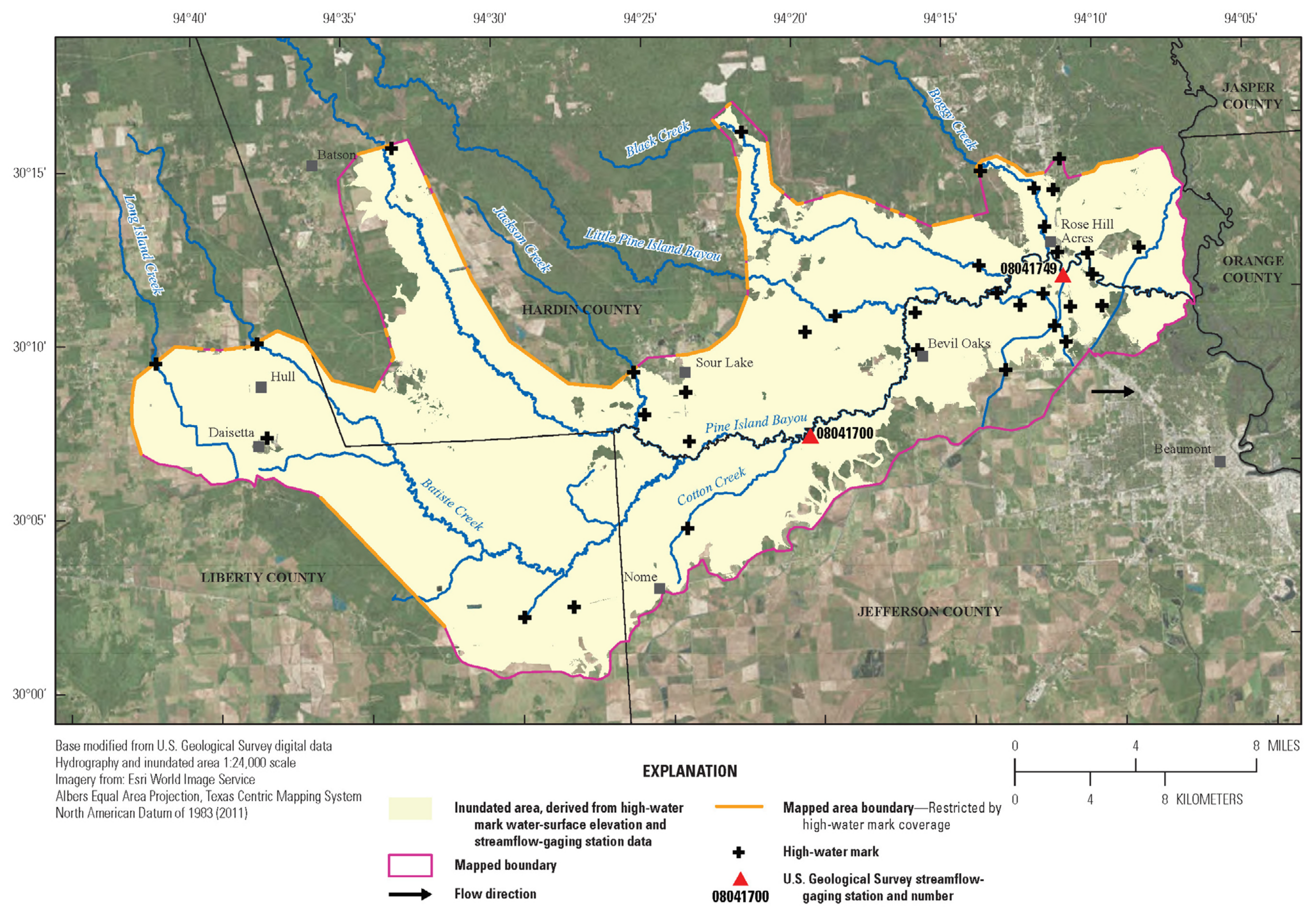


Figure 19. Flood-inundation map of Pine Island Bayou for the August and September 2017 Hurricane Harvey-related flood event in southeastern Texas and southwestern Louisiana.
Pine Island Bayou is a tributary to the Neches River. The Little Pine Island-Pine Island Bayou Corridor Unit of Big Thicket National Preserve is primarily along the Little Pine Island Bayou between Black Creek and Jackson Creek. Much of the preserve area is west of the mapped area boundary. US Geological Survey streamflow gage 08041749 is located along Pine Island Bayou above BI Pump Plant in Beaumont. It was inundated during the storm event, and a high water mark peak of 8.83 m (28.97 ft) above stream gage datum (water-surface elevation of 8.574 [28.13 ft] above NAVD 88) was documented on October 18, 2017. The date of the peak was not recorded because the station was damaged during the storm event, but the estimated date of the peak is August 30, 2017. Information from Watson et al. (2018). See current conditions and access historical data for the gage here: https://waterdata.usgs.gov/tx/nwis/uv?site_no=08041749. Map is figure 8 from Watson et al. (2018).

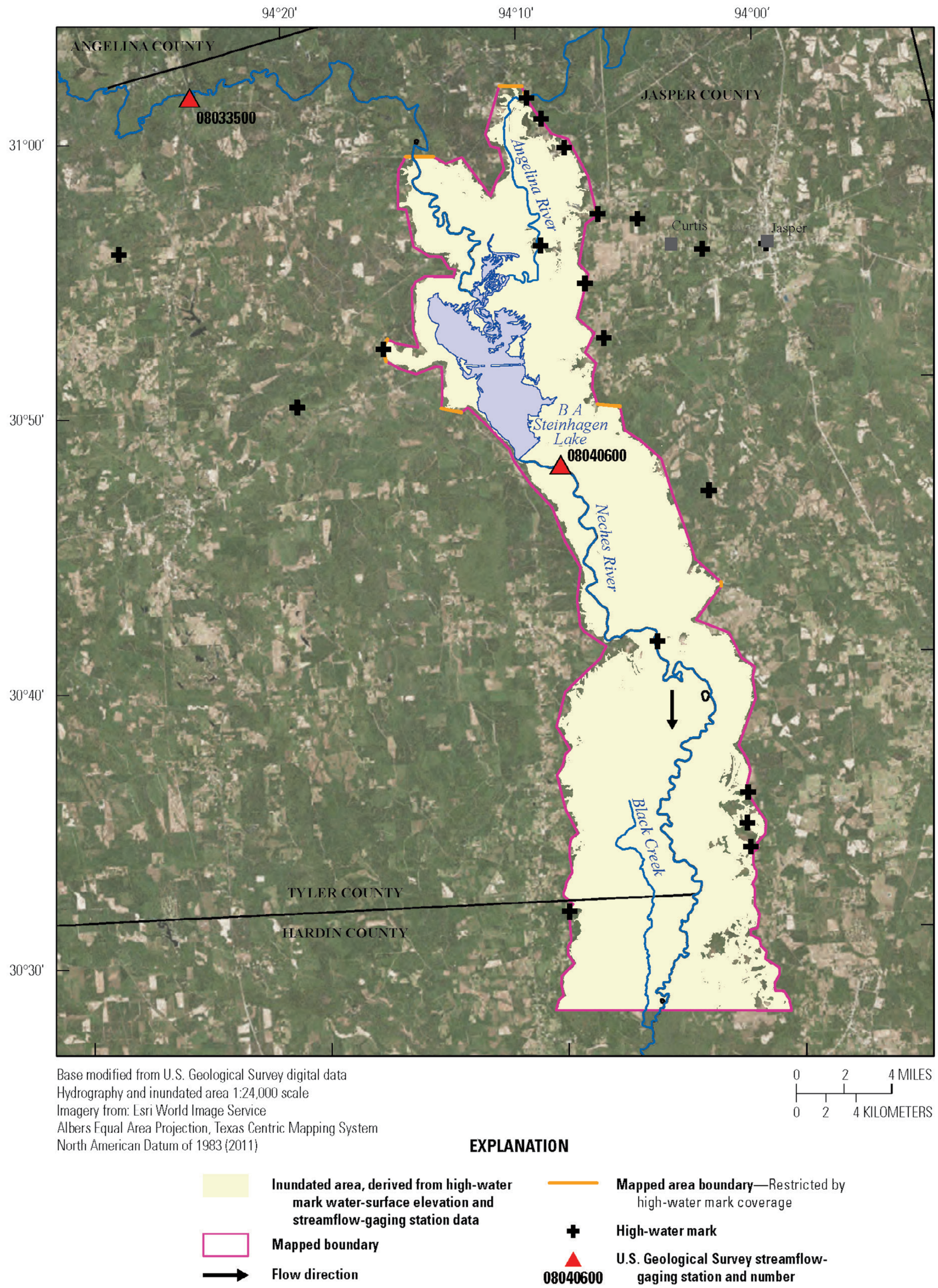


Figure 20. Flood-inundation map of the upper reach of the Neches River for the August and September 2017 Hurricane Harvey-related flood event in southeastern Texas and southwestern Louisiana.
The Upper Neches River Corridor Unit follows the Neches River from B.A. Steinhagen Lake south to the extent of this figure (continued on figure 21). US Geological Survey streamflow gage 08040600 is located near Town Bluff and recorded peak discharge during the Harvey-related event of 2,600 cubic meters per second (91,000 cubic feet per second [cfs]) and a gage height of 24.60 m (80.70 ft) (Watson et al. 2018). See current conditions and access historical data for the gage here: https://waterdata.usgs.gov/tx/nwis/uv?site_no=08040600. Map is figure 6 from Watson et al. (2018).

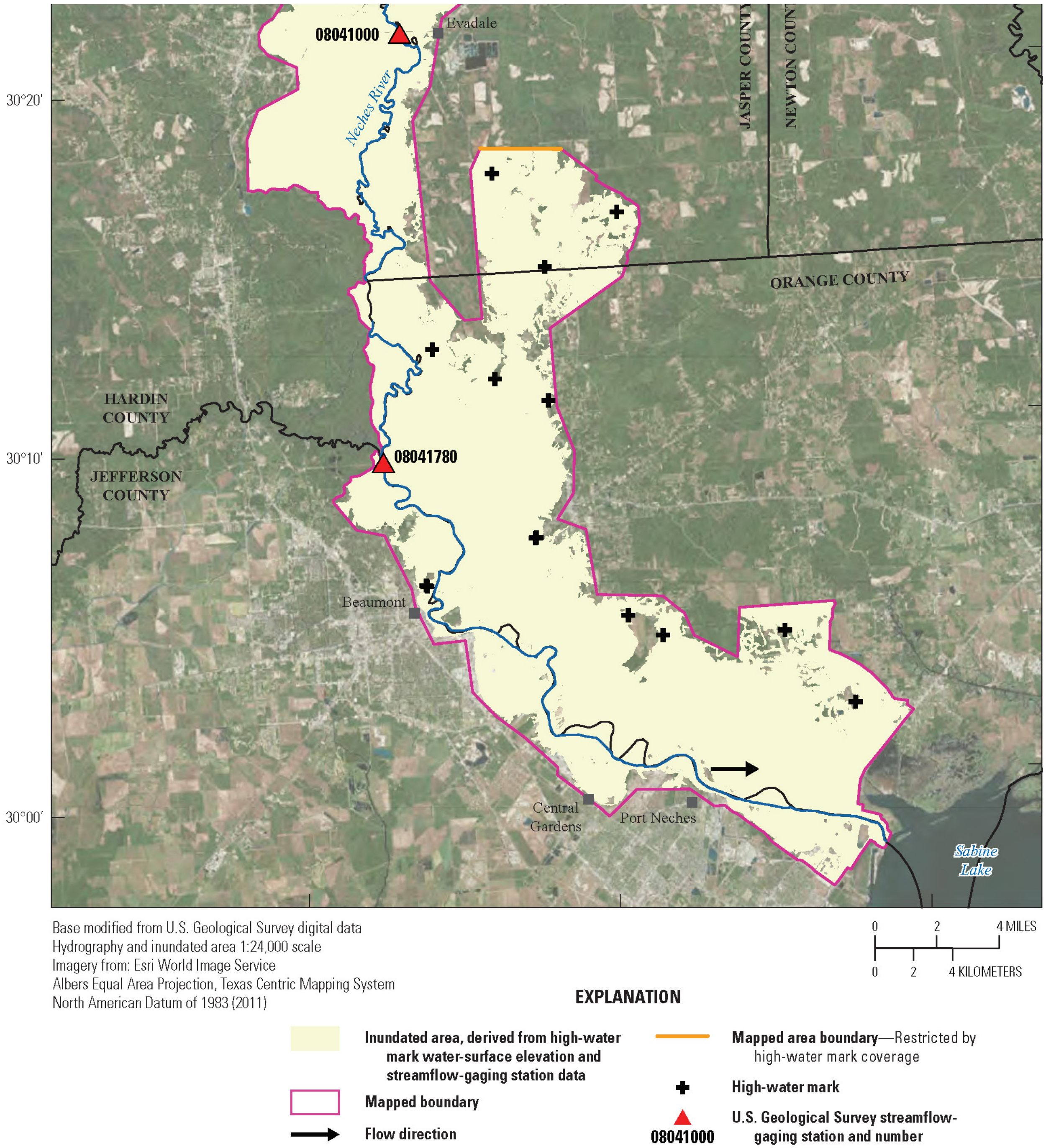


Figure 21. Flood-inundation map of the lower reach of the Neches River for the August and September 2017 Hurricane Harvey-related flood event in southeastern Texas and southwestern Louisiana. The Lower Neches River Corridor Unit follows the Neches River from the northernmost extent of this map (continued from fig. 20) south to near the Interstate 10 crossing of the Neches River (next to the "Beaumont" square on the map above). US Geological Survey streamflow gage 08041000 is located near Evadale and recorded peak discharge during the Harvey-related event of 2,033 cubic meters per second (71,800 cubic feet per second [cfs]) and a gage height of 8.37 m (25.11 ft) (Watson et al. 2018). See current conditions and access historic data for the gage here: https://waterdata.usgs.gov/tx/nwis/uv?site_no=08041000. US Geological Survey streamflow gage 08041780 is located at the Saltwater Barrier along the Neches River and recorded peak discharge during the Harvey-related event of 6,570 cubic meters per second (232,000 cubic feet per second [cfs]) and a gage height of 6.57 m (21.56 ft) (Watson et al. 2018). See current conditions and access historical data for the gage here: https://waterdata.usgs.gov/tx/nwis/uv?site_no=08041780. Map is figure 7 from Watson et al. (2018).

Table 12. Summary of resource management issues associated with slope movement hazards and risks.

Resource management issue	Slope Movement Hazards and Risks
Description	• Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity and include soil creep, slumps, rockfalls, debris flows, and landslides which occur on time scales ranging from seconds to years (fig. 22). • The Big Thicket landscape is primarily low relief. Higher relief areas are typically found along cut banks or terrace scarps. • Ares where vegetation has been disturbed are more susceptible to erosion and slope movements. • Erosion and slope movements could expose cultural artifacts, particularly at sand ridges or mounds, or abandoned oil and gas wells or pipelines.
Related map units and/ or preserve examples	• Colluvium in geologic map unit **Qca** was deposited at least in part by slope movement processes. • Scarps are mapped within **Qt3** of the Big Sandy Creek unit. • Low cuestas or scarps mark sharp boundaries between **Oby**, **Qm**, or **Ql**, and **Qbc/Qbs**; one such scarp is the Hockley Scarp within **Ql** (between **Qby** and **Qm**) just north of Turkey Creek unit. • Land resources map units include a relative, qualitative, assessment of slope stability. • Slope failures occur most commonly along riverbanks in units with the most topographic relief. The total area in the preserve with slopes greater than 5% is more than 6,005 ha (14,840 ac), most of which is within the Canyonlands, Menard Creek Corridor, Upper Neches River Corridor, Neches Bottom and Jack Gore Baygall, and Big Sandy Creek units. • Slumps are most probable in the Canyonlands unit. • A rock slide in the Upper Neches River Corridor unit is filled with riprap. • Slope movements are documented along Village Creek and Neches River. • Erosion is an issue along bluffs overlooking the Trinity River at Menard Creek Corridor unit (fig. 23). • If the preserve acquires the Rush Creek area, the varied terrain there is also likely to pose slope issues.
Related fundamental resources	• Structural diversity.
Potential action items	• Identify areas where slope processes or erosion may coincide with sand ridges or mounds to potentially protect or preserve cultural artifacts. • Identify areas where slope processes or erosion may coincide with oil and gas wells or other infrastructure (both current and abandoned); slope failure in those areas could create contamination issues. • A trail management plan could identify areas where trail use is contributing to erosion or slope movements and suggest site specific actions. Development of such a plan was identified as a high priority planning need in the foundation document.
Primary references	• GRI scoping meeting summary: Fay (2009). • NPS Geologic Resources Division Geohazards website http://go.nps.gov/geohazards. • NPS Geologic Resources Division Slope Movement Monitoring website (based on Wieczorek and Snyder 2009): http://go.nps.gov/monitor_slopes. • US Geological Survey landslides website http://landslides.usgs.gov/. • US Geological Survey landslide handbook: Highland and Bobrowsky (2008). • Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

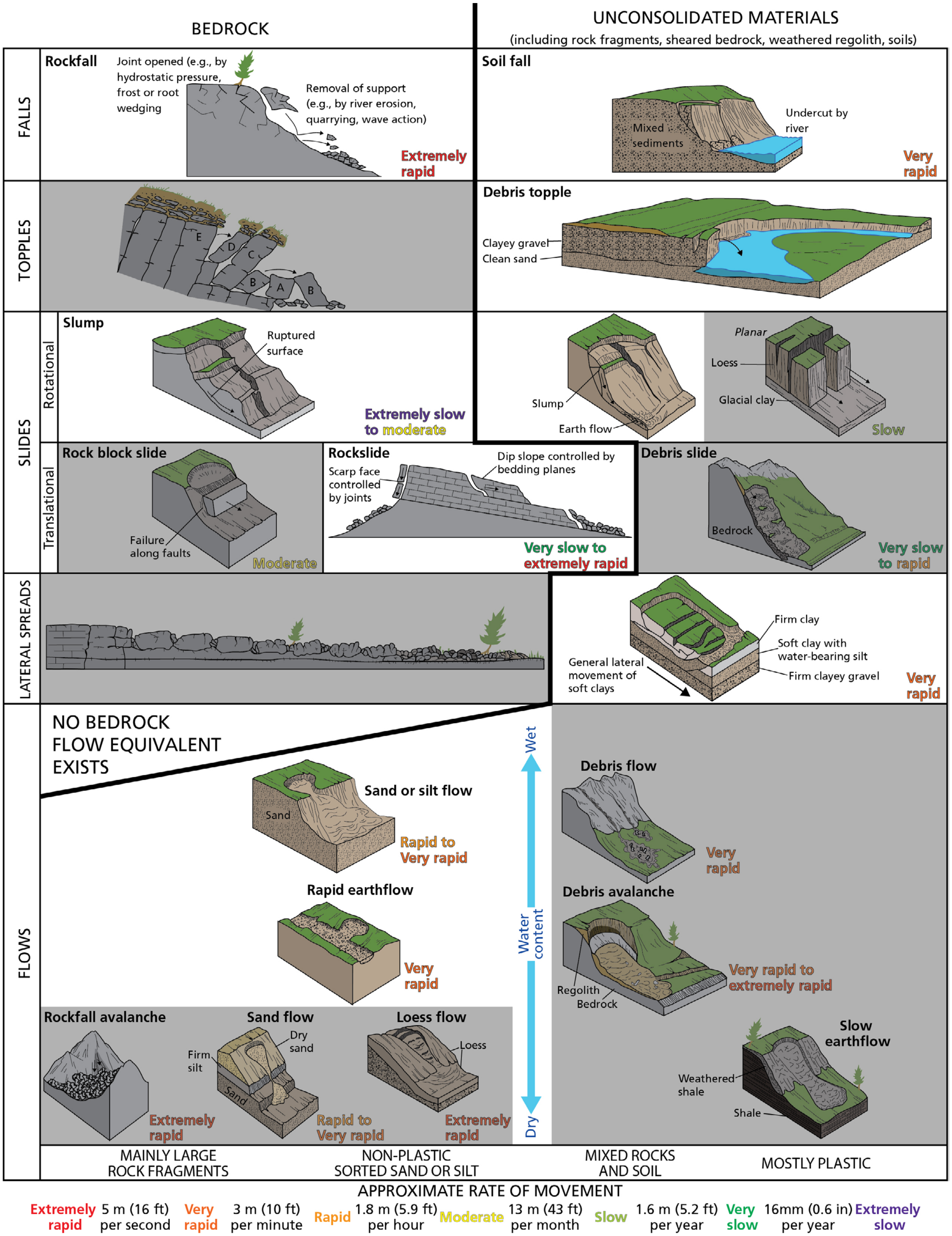


Figure 22. Schematic illustrations of slope movements.
Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed areas represent conditions that are unlikely to exist at Big Thicket National Preserve. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978) and Cruden and Varnes (1996).

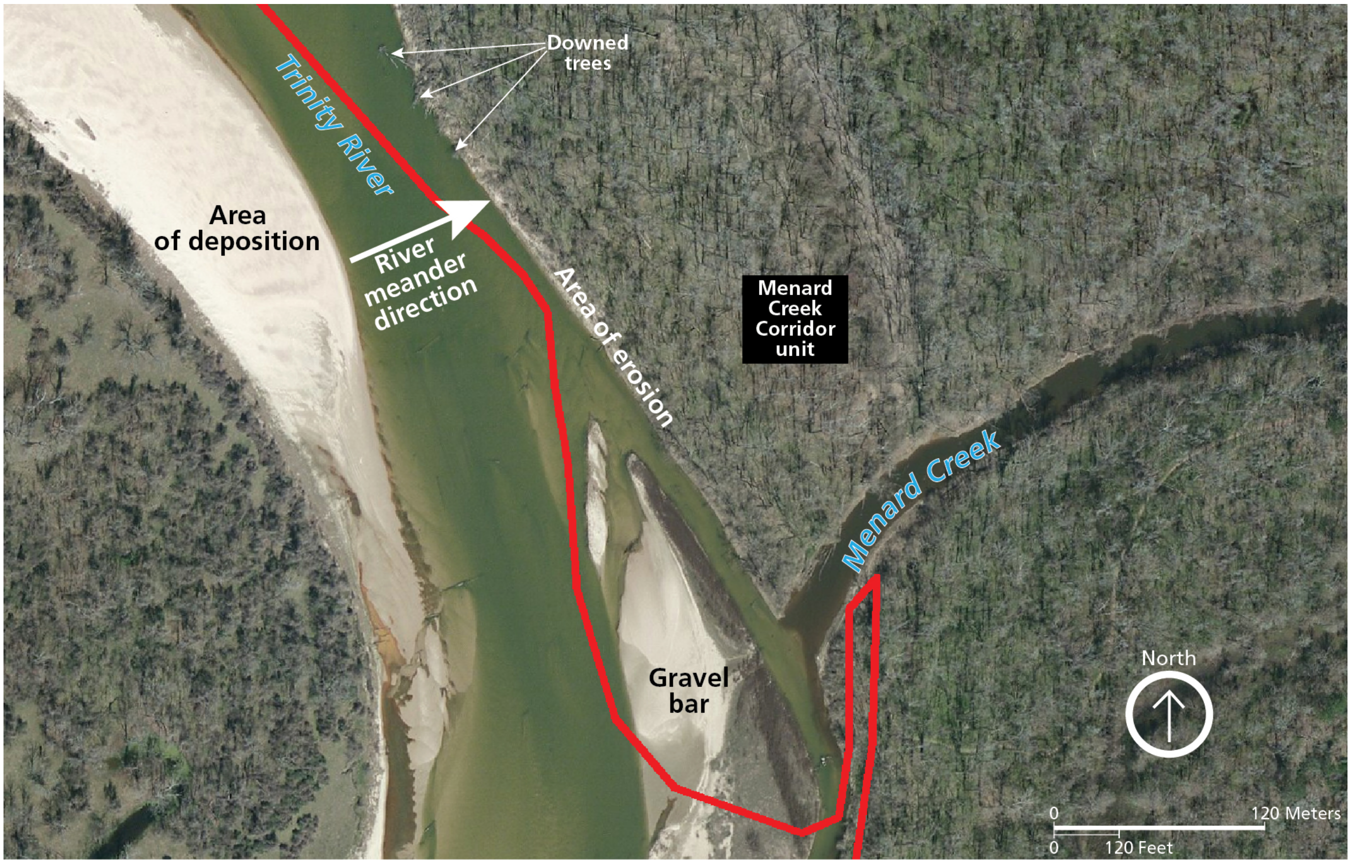


Figure 23. Image of eroding shoreline at Menard Creek and Trinity River.
Erosion along the Trinity River is causing trees to fall into the river and the river to meander across the preserve boundary. The inside of the river meander is a site of deposition, creating gravel bars. Red line is the preserve boundary. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap (accessed 16 May 2016).

Table 13. Summary of resource management issues associated with paleontological resource inventory, monitoring, and protection.

Resource management issue	Paleontological Resource Inventory, Monitoring, and Protection
Description	• Fossils have been found in the preserve. Some are in the preserve's museum collections. • All of the sedimentary map units in the preserve are potentially fossiliferous. • All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act.
Related map units and/ or preserve examples	• **Mlf** contains vertebrate fossils; Miocene rhinoceros fossils were likely collected within the preserve near Town Bluff. • **Qal** may contain Holocene or recent organic materials, as well as fossils "reworked" from older layers. • **Qwl, Qwc, Qw**, and **Qd** may contain petrified wood. • Pleistocene mammoth tooth and partial jaw were collected from the Menard Creek Corridor unit (Trinity River) and are now within the preserve museum collection. May have been discovered in **Qt1, Qt2,** or **Qt3**. • **Ql** regionally contains Pleistocene megafauna such as ancestral horse, mastodon, giant ground sloth, turtle, and saber-tooth cat remains (the holotype for ***Smilodon fatalis*** was discovered near Sour Lake in **Ql** deposits). • Illegal collecting may occur where bluffs, gullies, and cutbanks expose Pleistocene and Miocene map units. • Fossils have been discovered in the Rush Creek area, which may be acquired by the National Park Service.
Related fundamental resources	• Scientific value.
Potential action items	• A field-based survey of fossil resources would provide site-specific information if the preserve is interested in more detailed paleontological resource inventory and monitoring. Increase public education and interpretation regarding (1) fossils, (2) the stewardship mission of the preserve, and (3) the boundaries of the preserve to minimize unauthorized collecting and increase the collective knowledge and awareness of local paleontological resources. • Establish a study collection of local fossils for preserve staff to use during interpretive programs or display at visitor centers.
Primary references	• Gulf Coast Network paleontology summary: Kenworthy et al. (2007). • Paleontological monitoring: Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. • GRI scoping meeting summary: Fay (2009). • Natural resources foundation report: Big Thicket National Preserve by Sobczak et al. (2010). • GRI GIS source maps (see Geologic Map Data chapter). • Contact Texas Memorial Museum for local paleontology expertise: http://tmm.utexas.edu/. • Servicewide information available at NPS Fossils and Paleontology website: http://go.nps.gov/fossils_and_paleo.

Table 14. Summary of resource management issues associated with seismic activity hazards and risks.

Resource management issue	Seismic Activity Hazards and Risks
Description	• Earthquakes are ground vibrations that occur when rocks suddenly move along a fault, releasing accumulated energy. • Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. • The preserve has a low risk for seismic hazards (fig. 24). • Minor faulting occurs at depth in southeast Texas associated with massive piles of sediment being deposited into the Gulf Basin and movement of salt deposits. • Earthquakes can directly damage park infrastructure, or trigger other hazards such as liquefaction (the transformation of a solid soil to a liquid) or slope movements that may impact park resources, infrastructure, or visitor safety. • Earthquakes in nearby Louisiana may have been induced by wastewater injection.
Related map units and/ or preserve examples	• The last earthquake perceptible by humans at the preserve occurred in the mid-1960s.
Related fundamental resources	• Structural diversity.
Primary references	• NPS Geologic Resources Division Seismic Monitoring website http://nature.nps.gov/geology/monitoring/seismic.cfm. • US Geological Survey Earthquakes Hazards website http://earthquake.usgs.gov/. • Seismic hazard maps: Petersen et al. (2008). • Report on seismic monitoring and research in Texas: Hennings et al. (2016). • Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. • GRI scoping meeting summary: Fay (2009).
Potential action items	• Determine if earthquake hazards and risk are increasing due to wastewater injection.

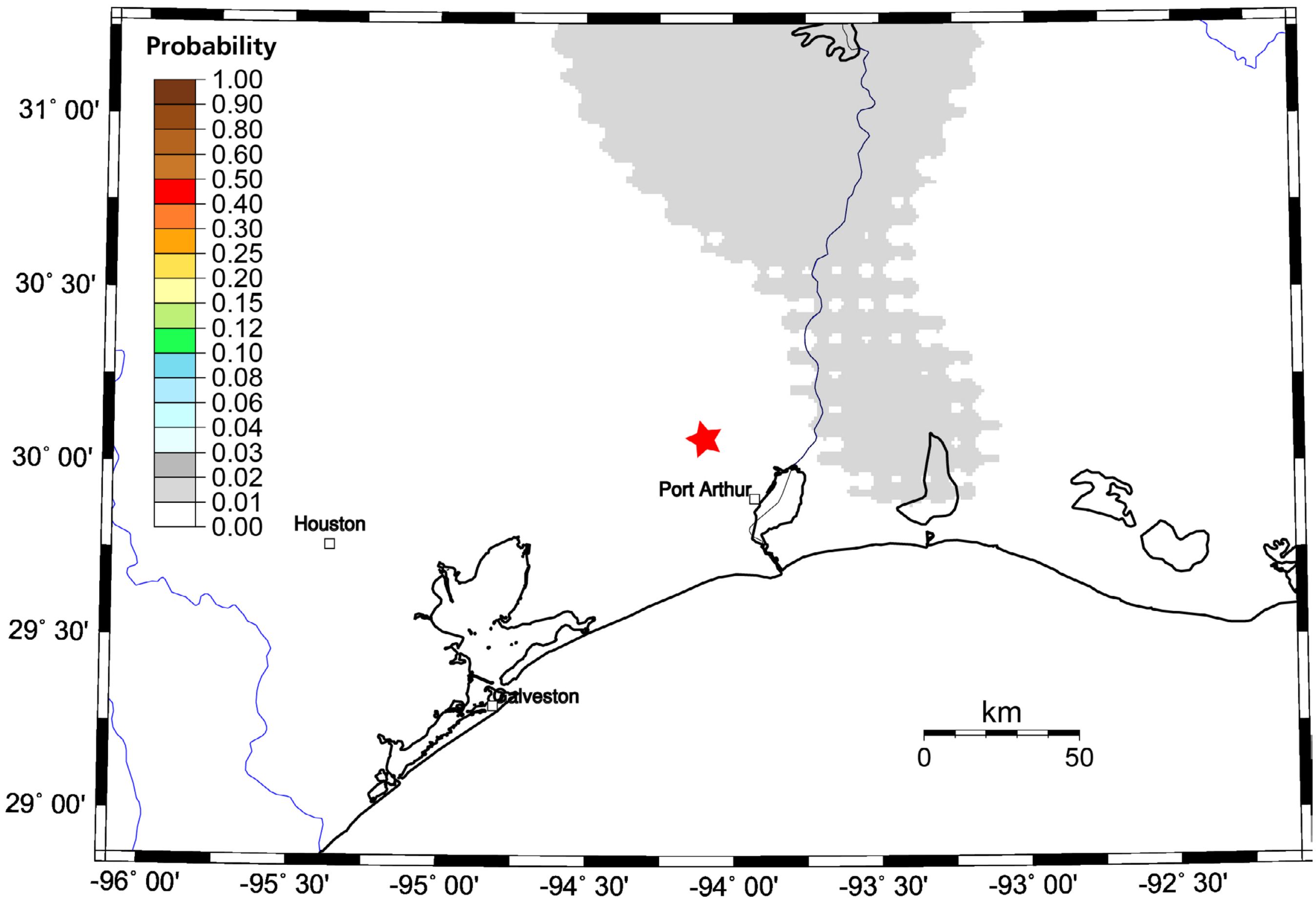


Figure 24. Map of probability of earthquakes with magnitude greater than 5.0 (moderate earthquake). This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Beaumont, Texas (red star). Graphic was generated by the US Geological Survey earthquake probability mapping program (no longer available online, accessed 21 March 2016; see https://earthquake.usgs.gov/ and http://www.beg.utexas.edu/texnet-cisr/texnet for more information about earthquakes in Texas).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the preserve follows the source maps listed here and includes components described in this chapter. Posters (in pocket) display the data over imagery of the preserve and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs. Contact GRI

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (see fig. 4) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. GRI produced a bedrock map for Big Thicket National Preserve (and broken out park unit maps), which includes many surficial units and land resources units.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in the bith_geology.pdf.

There are three primary sets of GRI-compiled map data of the geology of Big Thicket National Preserve:

1. Small-scale (1:250,000) geologic mapping of the entire preserve by the Texas Water Development Board (2007). These date are visible in the bith_geology.mxd (table 15; poster 2)
    - Oil and gas well locations (as of 2009) by the Railroad Commission of Texas are also visible in the bith_geology.mxd (table 15; poster 2)
2. Larger scale (1:24,000) geologic mapping of 10 of the 15 individual units of the preserve by Saul Aronow (geologist from Lamar University)
    - Beaumont unit: Aronow (1982a). These data are visible in the bmnt_geology.mxd (table 15; poster 3)
    - Beech Creek unit: Aronow (1982b). These data are visible in the becr_geology.mxd (table 15; poster 4).
    - Big Sandy Creek unit: Aronow (1982c). These data are visible in the bisa_geology.mxd (table 15; poster 5)
    - Lance Rosier unit: Aronow (1982d). These data are visible in the lanr_geology.mxd (table 15; poster 6)
    - Little Pine Island Bayou corridor unit: Aronow (1982e). These data are visible in the lpis_geology.mxd (table 15; poster 7)
    - Lower Neches River corridor unit: Aronow (1982f). These data are visible in the lone_geology.mxd (table 15; poster 8)
    - Menard Creek corridor unit: Aronow (1982g). These data are visible in the menc_geology.mxd (table 15; poster 9)
    - Neches Bottom and Jack Gore Baygall unit: Aronow (1982h). These data are visible in the necb_geology.mxd (table 15; poster 10)
    - Turkey Creek unit: Aronow (1982i). These data are visible in the turc_geology.mxd (table 15; poster 11)
    - Upper Neches River corridor unit: Aronow (1982j). These data are visible in the upne_geology.mxd (table 15; poster 12)
3. Small-scale (1:500,000) land resources map data of the entire preserve by the Texas Bureau of Economic

Geology (Kier et al. 1977). These data are visible in the bitl_geology.mxd (tables 16 and 17; poster 13)

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Salinas Pueblo Missions National Monument was compiled using data model version 2.1, which is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

GRI GIS data are available on the GRI Publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/Portal. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data set:

- A GIS readme file (bith_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 15);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (bith_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures; and
- An ESRI map document (xxxx_geology.mxd) that displays the GRI GIS data. (replace with "xxxx" with the unit code listed above, e.g., the Beaumont Unit data are visible in bmnt_geology.mxd).

GRI Map Posters

Posters of the GRI GIS data are included in the pocket as numbered in the Source Maps section. Not all GIS feature classes are included on the posters (table 15). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scales (1:24,000; 1:250,000; and 1:500,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 12 m (40 ft), 127 m (417 ft), and 254 m (834 ft), respectively of their true locations.

Table 15. GRI GIS data layers for Big Thicket National Preserve.

Note: "Yes" indicates that a layer is present in the data and is included on the associated poster. "No" indicates the data layer is present but is not included on the associated poster. "n/a" indicates that layer does not exist in the indicated data set.

Data Layer	On preserve-wide poster 2? (bith_geology.mxd)	On individual unit map posters 3–12? (xxxx_geology.mxd)
Oil and Gas Field Buffers	Yes	n/a
Geologic Contacts	No	Yes, all
Geologic Units	Yes	Yes, all
Mine Point Features (sand pits	n/a	No, bmnt; becr, bisa, lone, menc, necb
Geologic Exposures (observation locality)	n/a	No, bmnt; bisa, lone, menc, necb, turc
Depressions (undrained or intermittently drained)	n/a	Yes, becr, bisa, lanr, lpis, turc
Scarps	n/a	No, bisa
Fluvial Patterns	n/a	Yes, lone
Outcrops	n/a	Yes, menc, turc
Relict Streams	n/a	Yes, turc
Geologic Exposures and Small Outcrops	n/a	Yes, upne
Land Resources Unit Boundaries	n/a (see poster 13 and tables 16 and 17; in pocket)	n/a (see poster 13 and tables 16 and 17; in pocket)
Land Resources Units	n/a (see poster 13 and tables 16 and 17; in pocket)	n/a (see poster 13 and tables 16 and 17; in pocket)

Literature Cited

These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them.

Allen, J. R. L. 1964. Studies in fluviatile sedimentation: six cyclothems from the lower Old Red Sandstone, Angle-Welsh basin. Sedimentology III:163–198.

Aronow, S. 1981. Notes on the geologic units: Big Thicket National Preserve. Unpublished document. Lamar University, Beaumont, Texas.

Aronow, S. 1982a. Geologic map of Beaumont unit, Big Thicket National Preserve and vicinity (scale 1:24,000). Unpublished map.

Aronow, S. 1982b. Geologic Map of Beech Creek unit, Big Thicket National Preserve and vicinity (scale 1:24,000). Unpublished map.

Aronow, S. 1982c. Geologic Map of Big Sandy Creek unit, Big Thicket National Preserve and vicinity (scale 1:24,000). Unpublished map.

Aronow, S. 1982d. Geologic Map of Lance Rosier unit, Big Thicket National Preserve and vicinity (scale 1:24,000). Unpublished map.

Aronow, S. 1982e. Geologic map of Little Pine Island Bayou corridor unit, Big Thicket National Preserve and vicinity (scale 1:24,000). Unpublished map.

Aronow, S. 1982f. Geologic map of Lower Neches River corridor unit, Big Thicket National Preserve and vicinity (scale 1:24,000; two sheets). Unpublished map.

Aronow, S. 1982g. Geologic map of Menard Creek corridor unit, Big Thicket National Preserve and vicinity (scale 1:24,000; two sheets). Unpublished map.

Aronow, S. 1982h. Geologic map of Neches Bottom and Jack Gore Baygall unit, Big Thicket National Preserve and vicinity (scale 1:24,000; two sheets). Unpublished map.

Aronow, S. 1982i. Geologic map of Turkey Creek unit, Big Thicket National Preserve and vicinity (scale 1:24,000). Unpublished map.

Aronow, S. 1982j. Geologic map of Upper Neches River corridor unit, Big Thicket National Preserve and vicinity (scale 1:24,000; three sheets). Unpublished map.

Baker, E. T., Jr. 1995. Stratigraphic Nomenclature and Geologic Sections of the Gulf Coastal Plain of Texas. Open-File Report 94-461. U.S. Geological Survey, Austin, Texas, USA. http://pubs.usgs.gov/of/1994/0461/report.pdf (accessed 2 December 2015).

Beavers, R. L., A.L. Babson, and C.A. Schupp, editors. 2016. Coastal Adaptation Strategies Handbook. NPS 999/134090. National Park Service. Washington, DC. https://www.nps.gov/subjects/climatechange/coastalhandbook.htm (accessed 20 December 2016).

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 in R. Young, R. and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 17 November 2015).

Burghardt, J. E., E. S. Norby, and H. S. Pranger, II. 2014. Abandoned mineral lands in the National Park System: comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2014/906. National Park Service, Fort Collins, Colorado.

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 17 November 2015).

Byerly, G. R. 1991. Igneous activity. Pages 91–108 in Salvador, A., editor. The Gulf of Mexico Basin. The Geology of North America volume J. Geological Society of America, Boulder, Colorado.

Caffrey, M. 2015. Sea level and storm trends, Big Thicket National Preserve. Internal document. National Park Service, Denver, Colorado.

Callicott, J. B., M. Acevedo, P. Gunter, P. Harcombe, C. Linquist, and M. Monticino. 2006. Biocomplexity in the Big Thicket. Ethics, Place and Environment 9(1):21–45.

Cantu, L. 2012a. Geology - Turky (1943 to Village Creek). Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012b. Geology - PIB. Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012c. Geology - Neches - Dam to 96 Bridge. Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012d. Geology - Menard (Boundary to the Trinity). Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012e. Geology - Neches - 96 Bridge to SWB. Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012f. Geology - Neches - SWB to I-10. Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012g. Geology - Big Sandy (770 to Neches). Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Cantu, L. 2012h. Geology - Village Creek. Geoscientists-In-the-Parks document, 2011-BITH. National Park Service, Denver, Colorado.

Chowdhury, A. H., and M. J. Turco. 2006. Geology of the Gulf Coast aquifer, Texas. Report 365:25–30. Texas Water Development Board, Austin, Texas. http://www.i2massociates.com/downloads/chowdhury-turcoch02-ch02-gulfcoastgulfcoastgeology.pdf (accessed 15 March 2016).

Cozine, J. 2004. Saving the Big Ticket: from exploration to preservation, 1685–2003. University of North Texas Press, Denton, Texas.

Cruden, D. M., and Varnes, D. L. 1996. Landslide types and processes. Pages 36–75 (chapter 3) in A. K. Turner and R. L. Schuster, editors. Landslides: investigation and mitigation. Special Report 247. Transportation Research Board, National Research Council, Washington, DC.

Curdts, T. 2011. Shoreline length and water area in the ocean, coastal and Great Lakes parks: Updated statistics for shoreline miles and water acres (rev1b). Natural Resource Report NPS/WASO/NRR—2011/464. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/App/Reference/Profile/2180595/ (accessed 17 November 2015).

Diggs, G. M., B. L. Lipscomb, M. D. Reed, and R. J. O'Kennon.2006. Illustrated flora of east Texas. Sida Botanical Miscellany 26:1–1594.

Ewing, T. E. 2016. Texas through time. Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas.

Fay, L. 2009. Geologic Resources Inventory scoping summary: Big Thicket National Preserve, Texas. Geologic Resources Division, National Park Service, Lakewood, Colorado. http://go.nps.gov/gripubs (accessed 16 November 2015).

Hennings, P., A. Savvaidis, M. Young, and E. Rathje. 2016. Report on House Bill 2 (2016-17) seismic monitoring and research in Texas. Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas. http://www.beg.utexas.edu/files/content/texnet/docs/TexNet-Report-2016.pdf (accessed 10 April 2017).

Highland, L. M. and P. Bobrowsky. 2008. The landslide handbook—A guide to understanding landslides. US Geological Survey, Reston, Virginia. Circular 1325. http://pubs.usgs.gov/circ/1325/ (accessed 17 November 2015).

Just, B., R. Lloyd, and R. Anderson. 2013. Emerging oil and gas development in northwestern New Mexico: horizontal Gallup/Mancos play. Bureau of Indian Affairs, Division of Energy and Mineral Development, Lakewood, Colorado. http://www.indianaffairs.gov/cs/groups/xieed/documents/document/idc1-026005.pdf (accessed 19 April 2016).

KellerLynn, K. 2015. Aztec Ruins National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1245. National Park Service, Fort Collins, Colorado.

Kenworthy, J. P., V. L. Santucci, and C. C. Visaggi. 2007. Paleontological Resource Inventory and Monitoring, Gulf Coast Network. Natural Resource Technical Report TIC# D-750. National Park Service, Fort Collins, Colorado.

Kier, R. S., L. W. Garner, and L. F. Brown. 1977. Land Resources of Texas (scale 1:500,000; NE and SE sheets). University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 17 November 2015).

Marks, P. and P. Harcombe. 1981. Forest vegetation of the Big Thicket, Southeast Texas. Ecological Monographs 51:287–305.

McKendry, J. E., C. A. Brewer, S. D. Gardner, and J. M. Staub. 2004. A socioeconomic atlas for Big Thicket National Preserve and its region. National Park Service, Washington, DC. https://irma.nps.gov/DataStore/Reference/Profile/620069 (accessed 8 March 2016).

Meiman, J. 2012. Gulf Coast Network water quality report: status of water quality of Big Thicket National Preserve. Natural Resource Technical Report NPS/GULN/NRTR—2012/523. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2182111 (accessed 12 February 2016).

Melillo, J. M., T. C. Richmond, and G. W. Yohe, editors. 2014. Climate change impacts in the United States: the third national climate assessment. US Global Change Research Program. http://nca2014.globalchange.gov/downloads (accessed 18 March 2015).

Michael Baker Jr., Inc. 2006. Report for the focused site investigation, oil and gas sites, Big Thicket National Preserve, Beaumont Texas. Contract GSA-GS-00F-0032M. Michael Baker Jr., Inc., Moon Township, Pennsylvania.

Moring, J. B. 2003. Baseline assessments of fish communities, benthic macroinvertebrate communities, and stream habitat and land use, Big Thicket National Preserve, Texas 1999–2001. Water-Resources Investigations Report 03-4270. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/wri/wri034270/ (accessed 12 April 2016).

Nadeau, A., K. Allen, A. Davis, K. Benck, L. Meinke, S. Gardner, S. Amberg, and A. Robertson. 2016. Big Thicket National Preserve: Natural resource condition assessment. Natural Resource Report NPS/BITH/NRR—2016/1355. National Park Service, Fort Collins, CO. https://irma.nps.gov/DataStore/Reference/Profile/2237524 (accessed 10 April 2017).

National Parks Conservation Association. 2005. Big Thicket National Preserve state of the parks report. National Parks Conservation Association, Fort Collins, Colorado.

National Park Service. 1980. Resources management plan: Big Thicket National Preserve. Southwest Region, Santa Fe, New Mexico.

National Park Service. 2006. Oil and Gas Management Plan, Environmental Impact Statement, Big Thicket National Preserve, Texas.

National Park Service. 2014. Foundation Document: Big Thicket National Preserve. Document BITH 175/124076. National Park Service, Denver, Colorado.

NOAA [National Oceanographic and Atmospheric Administration]. 2014., Climate data online, retrieval menu. National Climatic Data Center [now the National Centers for Environmental Information], Asheville, North Carolina. http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp# (accessed [by Watson et al. 2018] 25 November 2014).

O'Dell, P. 2001. Trip report, Aztec Ruins National Monument, November 2001. National Park Service, Geologic Resources Division, Mineral Operations Branch, Lakewood, Colorado.

Railroad Commission of Texas. 2009. Wells of Hardin, Jasper, Jefferson, Liberty, Orange, Polk and Tyler Counties, Texas. Railroad Commission of Texas, Austin, Texas. http://www.rrc.state.tx.us/data/datasets/index.php (accessed 30 November 2015).

Rigsby, C. A. 1980. A brief overview of the Quaternary stratigraphy and geomorphology of the southeast Texas-southwest Louisiana coast. Pages 9–33 in Holocene depositional environments of the southeast Texas, southwest Louisiana Gulf Coast. Southwestern Association of Student Geological Societies Field Conference Guidebook April 24-27, 1980. Lamar University Geological Society, Beaumont, Texas.

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 17 November 2015).

Schenk, C., R. Charpentier, and J. W. Schmoker. 1999. Remaining oil and gas resources beneath Big Thicket National Preserve. Appendix E Final report to the Geologic Resources Division, National Park Service, U.S. Geological Survey, Denver, Colorado in National Park Service, 2005, Final oil and gas management plan and environmental impact statement, Big Thicket National Preserve. US Department of the Interior, Washington, DC.

Sobczak, R., G. Eckert, J. Woods, E. Porter, and D. Vana-Miller. 2010. Natural resources foundation report: Big Thicket National Preserve. Natural Resource Report NPS/NRPC/WRD/NRR—2010/180. National Park Service, Natural Resource Program Center, Fort Collins, Colorado.

Spearing, D. 1991. Roadside geology of Texas. Mountain Press Publishing Company, Missoula, Montana.

Texas Water Development Board. 2007. Geologic database of Texas (scale 1:250,000): geologic data for Beaumont sheet. Adapted from Barnes, V. E., Humble Oil and Refining Co., Shell Oil Co., S. Aronow, C. A. Shelby, D. H. Eargle, R. J. LeBlanc, F. G. Evans, G. W. Hinds, W. C. Holland, D. C. Van Siclen, M. K. Pieper, J. W. Macon, and B. Hartmann. 1968. Geologic atlas of Texas, Beaumont sheet (scale 1:250,000). Geologic Atlas of Texas 4. University of Texas at Austin, Bureau of Economic Geology, Austin, Texas.

Twilley, R., E. J. Barron, H. L. Gholz, M. A. Harwell, R. L. Miller, D. J. Reed, J. B. Rose, E. H. Seimann, R. G. Wetzel, and R. J. Zimmerman. 2001. Confronting climate change in the gulf coast region: prospects for sustaining our ecological heritage. Union of Concerned Scientists, Cambridge, MA and Ecological Society of America, Washington, DC. http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/gulfcoast.pdf (accessed 18 April 2016).

Varnes, D. J. 1978. Slope movement types and processes. Pages 11–33 in R. L. Schuster and R. J. Krizek, editors. Landslides: analysis and control. Special Report 176. Transportation and Road Research Board, National Academy of Science, Washin gton, DC.

Watson, K. M., G. R. Harwell, D. S. Wallace, T. L. Welborn, V. G. Stengel, and J. S. McDowell. 2018. Characterization of peak streamflows and flood inundation of selected areas in southeastern Texas and southwestern Louisiana from the August and September 2017 flood resulting from Hurricane Harvey. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Report 2018–5070. https://doi.org/10.3133/sir20185070 (accessed 20 August 2018).

Wells, F. C., and K. C. Bourdon. 1985. Summary of statistical and trend analyses of selected water-quality data collected near the Big Thicket National Preserve, southeast Texas. Open-File Report 85-183. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr85183 (accessed 21 February 2016).

Wermund, E. G. 1996. Physiographic map of Texas. State Map 5. Texas Bureau of Economic Geology, Austin, Texas, USA. http://www.beg.utexas.edu/UTopia/images/pagesizemaps/physiography.pdf (accessed 12 December 2015).

Wieczorek, G. F. and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 17 November 2015).

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 17 November 2015).

Zygo, L. 1999. Wetland distribution in the Big Thicket National Preserve. MS Thesis. Baylor University, Waco, Texas.

Additional References

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) Energy and Minerals; Active Processes and Hazards; Geologic Heritage: http://go.nps.gov/geology
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: https://www.nps.gov/applications/npspolicy/DOrders.cfm
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://www.globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- Bureau of Economic Geology, Austin, Texas: http://www.beg.utexas.edu/
- Stephen F. Austin State University, Geology: http://www.geology.sfasu.edu/TexasGeology.html
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): https://pubs.er.usgs.gov/
- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 3 October 2008, or the follow-up report writing conference call, held on 1 February 2016. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2008 Scoping Meeting Participants

Name	Affiliation	Position
Jeff Bracewell	NPS Gulf Coast Network	GIS specialist
Todd Brindle	NPS Big Thicket National Preserve	Superintendent
Eddie Collins	Texas Bureau of Economic Geology	Geologist
Lisa Fay	Geological Society of America	Geologist
Lisa Norby	NPS Geologic Resources Division	Geologist
Dusty Pate	NPS Big Thicket National Preserve	Biologist
Mark Peapenburg	NPS Big Thicket National Preserve	Chief ranger
Dave Roemer	NPS Big Thicket National Preserve	Chief, natural resources
Martha Segura	NPS Gulf Coast Network	Network coordinator
Heather Stanton	Colorado State University	Geologist

2016 Conference Call Participants

Name	Affiliation	Position
Jeff Bracewell	NPS Gulf Coast I&M Network	GIS specialist
Ryan Desliu	NPS Big Thicket National Preserve	Environmental protection specialist
Ken Hyde	NPS Big Thicket National Preserve	Chief of Resource Management
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Jeremiah Kimbell	NPS Geologic Resources Division	Petroleum Engineer
Wayne Prokopetz	NPS Big Thicket National Preserve	Superintendent
Martha Segura	NPS Gulf Coast I&M Network	Program manager
Trista L. Thornberry-Ehrlich	Colorado State University	Geologist-graphic designer
Don Weeks	NPS Intermountain Region	Program manager of physical resources

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2017. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/ releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/ adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/ submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • *16 USC § 698c (Big Thicket N Pres.),* • **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; • prepare/submit a reclamation plan; and • submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. American Indian Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108**, all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. Regulations re: Native American Lands within NPS Units: • **25 CFR Part 211** governs leasing of tribal lands for mineral development. • **25 CFR Part 212** governs leasing of allotted lands for mineral development. • **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. • **25 CFR Part 224** governs tribal energy resource agreements. • **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). • **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. • **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. • **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. • **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. • **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7 – Construction of buildings or other facilities**, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: ● only for park administrative uses; ● after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; ● after finding the use is park's most reasonable alternative based on environment and economics; ● parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; ● spoil areas must comply with Part 6 standards; and ● NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. *See also "Climate Change"*	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: ● Allow natural processes to continue without interference, ● Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, ● Study impacts of cultural resource protection proposals on natural resources, ● Use the most effective and natural-looking erosion control methods available, and avoid new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. *Continued in 2006 Management Policies column*	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (2016). *NPS guidance, continued:* **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable. *2006 Management Policies, continued:* **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. *continued in Regulations column*

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to ● prevent unnatural erosion, removal, and contamination; ● conduct soil surveys; ● minimize unavoidable excavation; and ● develop/follow written prescriptions (instructions).

NPS 175/148867, October 2018

National Park Service
U.S. Department of the Interior

Natural Resources Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

https://www.nps.gov/nature/index.htm

EXPERIENCE YOUR AMERICA™