Chapter 6

Southwest Florida

Contributors:

Kara R. Radabaugh and **Stephen P. Geiger,** Florida Fish and Wildlife Conservation Commission

Eric Milbrandt, Marine Laboratory, Sanibel-Captiva Conservation Foundation

Thomas F. Ries, ESA

Nicole Iadevaia, Coastal & Heartland National Estuary Partnership

Melanie Parker and **Phyllis Klarmann,** South Florida Water Management District

In

Oyster Integrated Mapping and Monitoring Program Report for the State of Florida No. 2

Edited by Kara R. Radabaugh, Stephen P. Geiger, and Ryan P. Moyer

Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
100 Eighth Avenue Southeast
St. Petersburg, Florida 33701
MyFWC.com

Technical Report No. 22, Version 2 • 2022

Chapter 6
Southwest Florida

Kara R. Radabaugh and **Stephen P. Geiger,** Florida Fish and Wildlife Conservation Commission

Eric Milbrandt, Marine Laboratory, Sanibel-Captiva Conservation Foundation

Thomas F. Ries, ESA

Nicole Iadevaia, Coastal & Heartland National Estuary Partnership

Melanie Parker and **Phyllis Klarmann,** South Florida Water Management District

Description of the region

The southwest Florida region includes Charlotte Harbor, Estero Bay, Rookery Bay, Ten Thousand Islands, and the Everglades. The surface water hydrology of southwest Florida has been severely affected by human modifications (e.g., impoundment and channelization), which have changed the quality, quantity, timing, and distribution of freshwater flow delivered to coastal wetlands and estuaries. Before development, the hydrology of the Everglades was tightly linked to a large watershed that encompassed much of central and southern Florida (Fig. 6.1; Chimney and Goforth 2001, Huber et al. 2006). Water meandered down the Kissimmee River to Lake Okeechobee, where it spilled over the southern edge of the lake into an expansive sawgrass marsh. The sheet of surface water then slowly made its way south, supporting a variety of freshwater marshes in the interior and mangroves, salt marshes, and oyster reefs along the coasts. Harvests of eastern oysters (*Crassostrea virginica*) were documented in the late 1800s from Charlotte Harbor, Gordon's Pass in Naples Bay, Cape Romano, and Whitewater Bay in the Everglades (Ingersoll 1881).

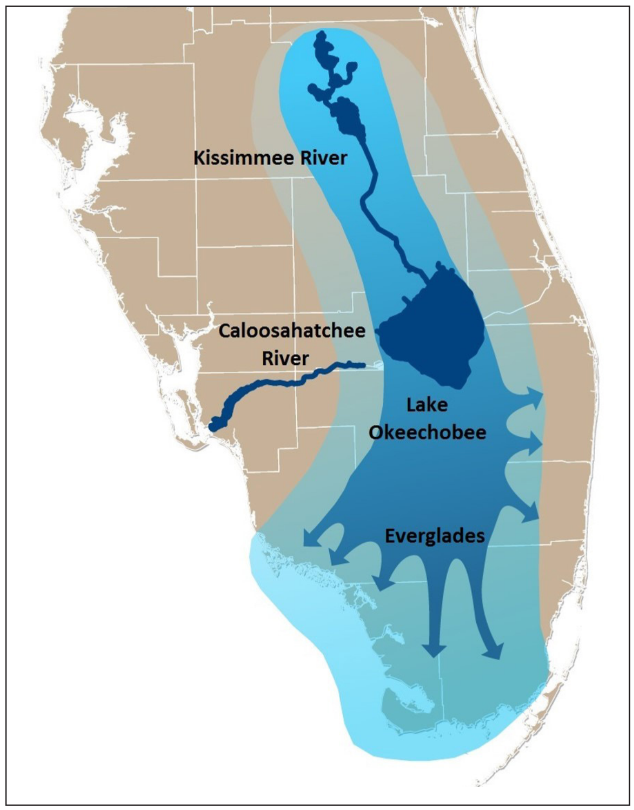

Figure 6.1. Historical surface water flow in South Florida. Figure credit: Chris Anderson, based on Chimney and Goforth (2001).

Significant hydrological changes began in 1881, when the Caloosahatchee River was connected to Lake Okeechobee by Hamilton Disston for steamboat transportation. In the 1950s and 1960s, the U.S. Army Corps of Engineers' Central and Southern Florida Project made major changes to the watershed in an effort to avert floods and drain wetlands for agriculture (Chimney and Goforth 2001). The Herbert Hoover Dike prevented water from seeping over the southern edge of Lake Okeechobee, stopping the sheet flow of surface water through the Everglades and instead diverting large amounts of freshwater flow into constructed channels with outlets in the Caloosahatchee and St. Lucie rivers (Fig. 6.2). These hydrological alterations resulted in markedly lower salinity and increased nutrient and sediment supply in the Caloosahatchee and St. Lucie estuaries. Meanwhile, draining

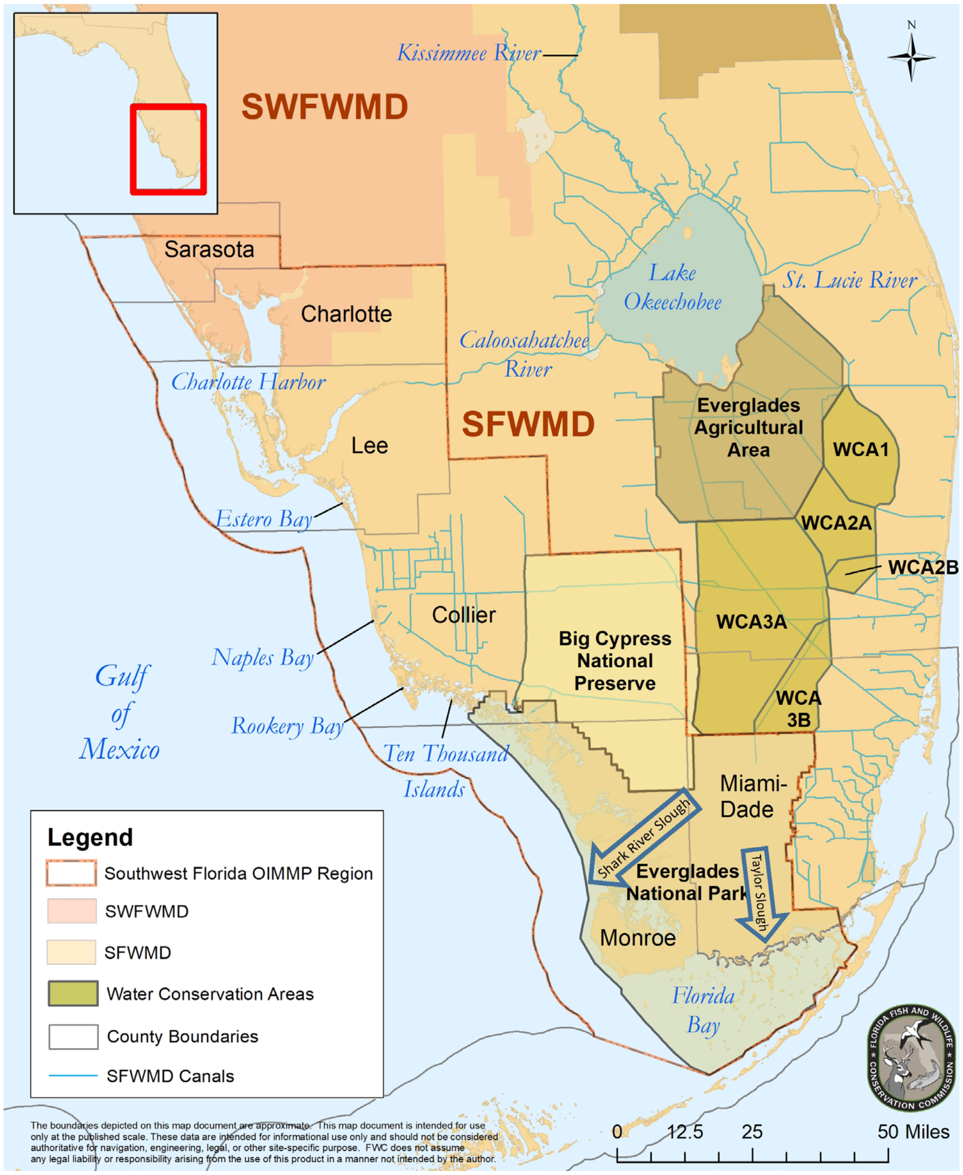

Figure 6.2. Major features impacting the hydrology of the southwest Florida region.

and channelization of wetlands increased the severity and frequency of droughts in other estuaries of the Everglades and Ten Thousand Islands, causing high salinity and shifting the center of abundance of oysters in rivers and creeks upstream (Chimney and Goforth 2001, Huber et al. 2006, Volety et al. 2009a).

Awareness of the extensive environmental damage caused by this alteration of surface water flow prompted the Comprehensive Everglades Restoration Plan (CERP), which the U.S. Congress authorized in 2000. Major components of CERP include ecological management of Lake Okeechobee, decreasing channelized freshwater releases from the lake, increasing freshwater sheet flow to rehydrate the Everglades, and retaining water in reservoirs for slow release during the dry season (Huber et al. 2006, Volety et al. 2008). CERP also includes projects that focus on improving habitat for oysters, such as removing muck accumulations and providing substrate for oyster establishment (Volety et al. 2008).

Charlotte Harbor and the Caloosahatchee River

Charlotte Harbor is a large, complex estuary bordered by barrier islands and includes the cities of Fort Myers, Cape Coral, Punta Gorda, and North Port. The estuary falls on the boundary between the jurisdictions of the Southwest and South Florida water management districts (SWFWMD and SFWMD, respectively) (Fig. 6.2). It receives freshwater input from the Myakka, Peace, and Caloosahatchee rivers along with many other minor trib-

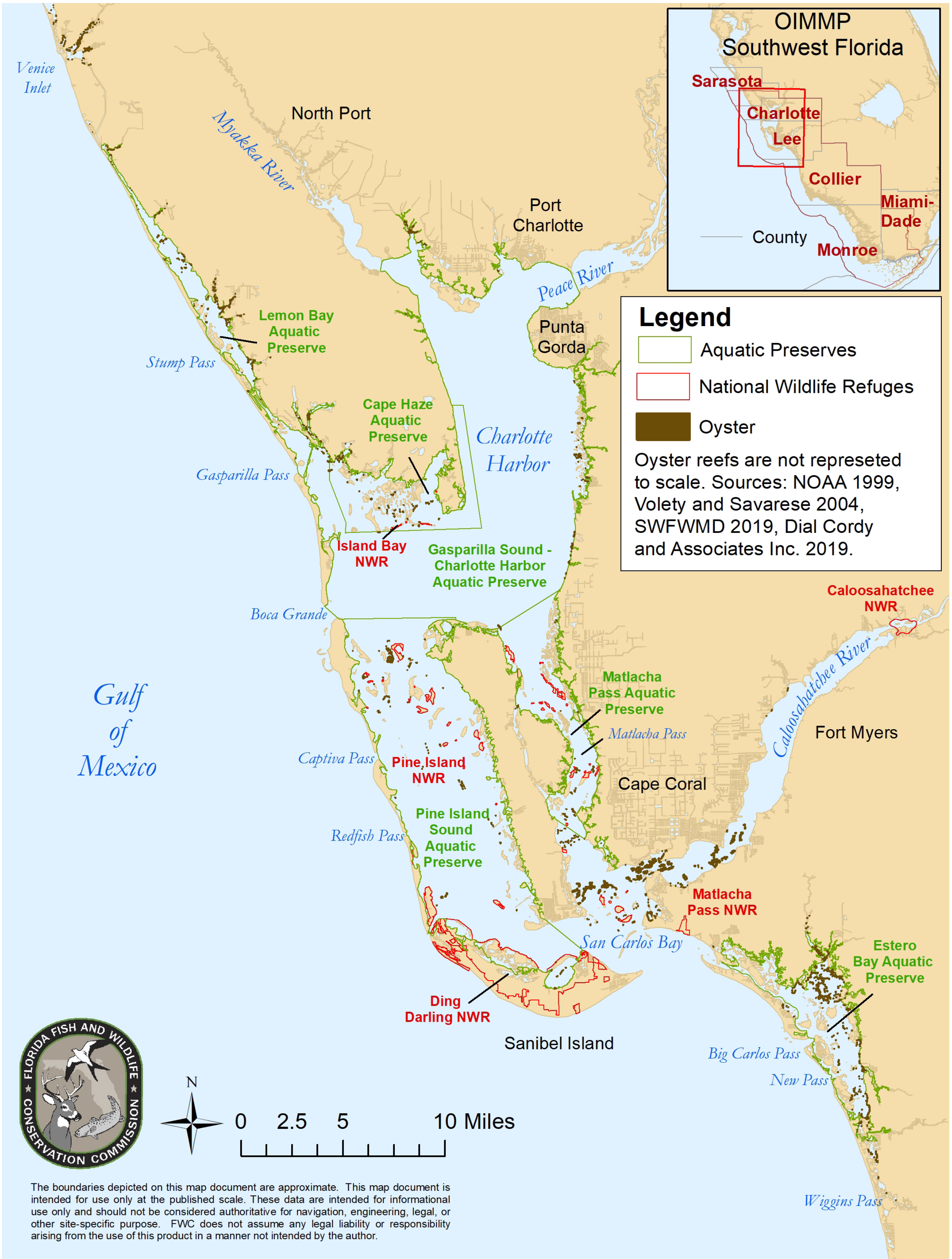

Figure 6.3. Greater Charlotte Harbor mapped oyster extent, aquatic preserves, and national wildlife refuges. Oyster mapping sources: NOAA (1999), made from 1999 aerial photographs; Volety and Savarese (2004); SWFWMD (2019), from 2018 photographs; and Dial Cordy and Associates Inc. (2019), from side-scan sonar.

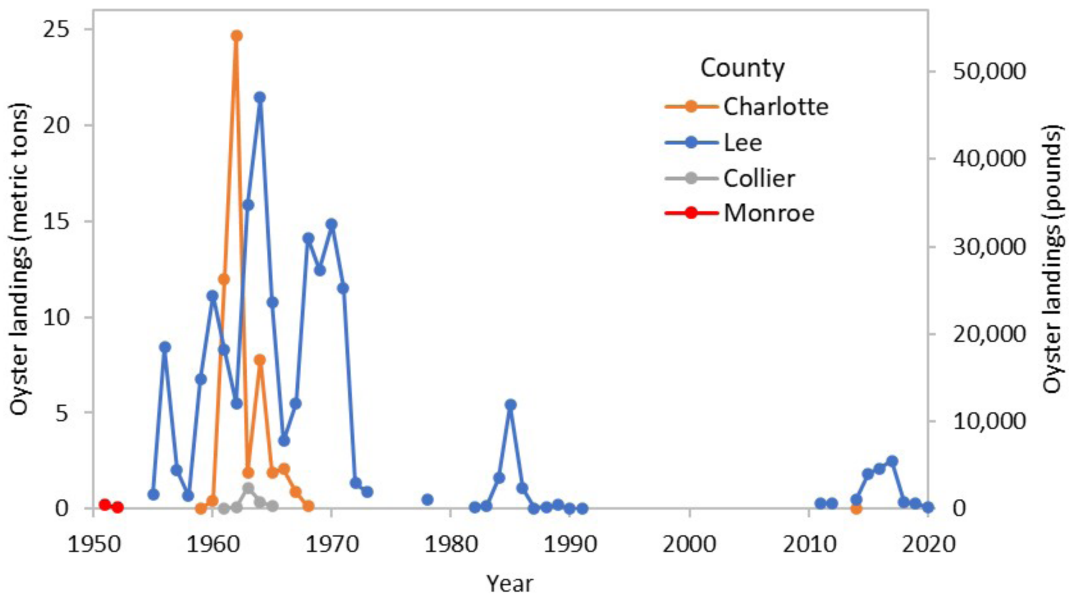

Figure 6.4. Commercial oyster landings in southwest Florida. Oyster landing data before 1986 were collected under a voluntary reporting system. Data sources: FWC (2021) and summary of Florida commercial marine fish landings (see Appendix A).

utaries. Management of the region is facilitated by the Coastal and Heartland National Estuary Partnership (CHNEP), renamed from the Charlotte Harbor National Estuary Program in 2019, and large areas are protected from development under the Florida Department of Environmental Protection (FDEP) Aquatic Preserve program (Fig. 6.3). The J.N. "Ding" Darling Wildlife Refuge complex, owned and managed by the U.S. Fish and Wildlife Service (USFWS), includes Island Bay, Pine Island Sound, Matlacha Pass, and Caloosahatchee National Wildlife Refuges (NWRs) and encompasses a significant area of mangrove islands.

Most oyster reefs in Charlotte Harbor are intertidal, although subtidal reefs are present at depths of at least 1.8 m (6 ft) in the Caloosahatchee River (Boswell et al. 2012). Reefs in open water are common in San Carlos Bay at the mouth of the Caloosahatchee River, Matlacha Pass, and Pine Island Sound (Fig. 6.3). Reefs in San Carlos Bay are located north of the Sanibel Island Causeway and are typically elongate and perpendicular to the predominant direction of tidal or river flow. They also occur as fringing reefs around low-relief spoil islands. Typical healthy oyster density on these reefs is 300–1,500 oysters/m^2 (28–139 oysters/ft^2) with shell heights of 21–35 mm (0.8–1.4 in). Many of the remaining reefs in Charlotte Harbor, however, have large areas with loose, scattered shell or appear to have lost substrate since the widespread development and land-use conversion that began in the late 1960s (Milbrandt, pers. obs.). Many of the reefs are surrounded by shallow sand bottom with submerged aquatic vegetation (SAV) growing up to the reef edge; the most common species of SAV are turtlegrass (*Thalassia testudinum)*, manateegrass (*Syringodium filiforme*), and shoalgrass (*Halodule wrightii*). Larval supply to these oyster reefs depends partly on proximity to a healthy reef. Recent advances in larval transport modeling (Dye et al. 2021) combined with monitoring aim to improve oyster reef restoration and research efforts.

In addition to open-water reefs, oysters grow on seawalls, attach to mangrove prop roots, and create fringing reefs along mangrove shorelines. FDEP's Aquatic Preserve and Buffer Preserve programs have protected much of the mangrove habitat in Charlotte Harbor from development. The shade provided by the canopy and the relatively stable root system creates an excellent place for oysters to thrive. However, settlement of oysters on prop roots may be limited because flow restrictions and shallow water may either prevent larvae from reaching the mangrove shorelines or limited water flow may restrict food supply.

While data are limited on the extent of oyster reefs before development, it has been estimated that Charlotte Harbor lost 990 ha (2,450 ac), or 90%, of its oyster reefs from the 1950s through the 1990s (Boswell et al. 2012, CHNEP 2019). These reefs were lost due to the mining of oyster shell for road construction, unsustainable harvesting rates, changes in surface-water hydrology, excess sedimentation, and direct habitat destruction due to coastal development (Boswell et al. 2012). Commercial oyster harvests in Charlotte Harbor and the Caloosahatchee River peaked in the 1960s (Fig. 6.4), and by the early 1970s much of Charlotte Harbor was closed to commer-

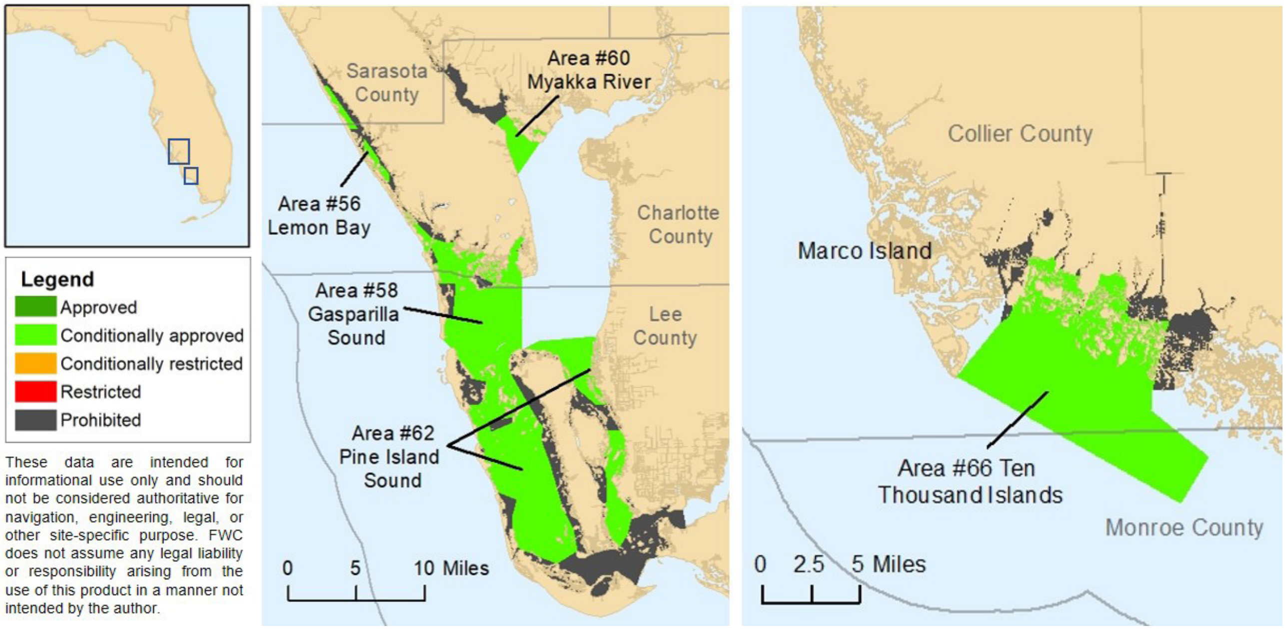

Figure 6.5. Shellfish harvesting areas in southwest Florida. Source: FDACS (2021).

cial oyster harvest due to pollution and declining oyster populations (Taylor 1974). Following a resurgence in the 1980s, oysters were not harvested commercially in Charlotte Harbor from 1992 through 2010. Commercial harvest resumed in 2011, and landings increased to 2.5 metric tons (5,494 pounds) in 2017. Though landings declined again during 2018–2020, the impact of this commercial fishery relative to the scale of the resource in this region is a concern. Most oysters in this area do not reach the legal harvest size of 76 mm (3 in.) shell height. Harvest of the few large oysters that are present could lead to selection pressure toward smaller sizes, removal of the most productive individuals for spawning, and loss of the large shells that contribute to reef stability.

There are five shellfish harvesting areas in southwest Florida. Four are found in Charlotte Harbor and the other in the Ten Thousand Islands (Fig. 6.5; FDACS 2021). The Florida Department of Agriculture and Consumer Services (FDACS) classifies shellfish harvesting areas using the standards and requirements of the National Shellfish Sanitation Program to ensure that the shellfish are safe for human consumption. Harvesting areas are classified as approved, conditionally approved, restricted, conditionally restricted, or prohibited waters. Each classification type reflects the area's suitability for shellfish harvesting based on fecal-coliform data and in some cases toxins such as heavy metals. FDACS routinely monitors shellfish harvesting areas for fecal-coliform bacteria. The open or closed status of a specific shellfish harvesting area can be obtained from FDACS at https://shellfish.fdacs.gov/seas/seas_statusmap.htm. Maps of shellfish harvesting areas, aquaculture use zones, and lease areas are also available from FDACS, at https://fdacs.maps.arcgis.com/apps/webappviewer/index.html?id=57f7d4b7d900496d99891f22681c66d0. Shellfish are also harvested recreationally in the greater Charlotte Harbor region (Boswell et al. 2012). Removal of oysters for use as chum is technically prohibited but does occur and does not adhere to shellfish harvesting areas or regulations.

Eastern oysters prefer a salinity range of 14–28 on the practical salinity scale, although they can survive brief exposure to salinity ranging from 0 to 42 (Shumway 1996, Volety et al. 2008, VanderKooy 2012). Oysters in Charlotte Harbor are exposed to widely divergent conditions. Oysters in many portions of the estuary (near and in Matlacha Pass and the Peace, Myakka, and Caloosahatchee rivers) can experience low-salinity stress. Oysters in the Caloosahatchee River Estuary must cope with the stress of freshwater flow from the Caloosahatchee watershed and of regulatory releases from Lake Okeechobee that result in rapid and extended declines in salinity. Juvenile oysters are particularly susceptible to freshwater exposure, and salinity <5 can result in 95% juvenile mortality (Volety et al. 2003). The combination of low salinity and high flow in summer hinders larval recruitment in the Caloosahatchee (Volety et al. 2003, 2008). Conversely, oysters in other regions, such as Lemon Bay, Pine Island Gasparilla Sound, and San Carlos Bay, can be exposed to salinity higher than 28 during periods of low river flow.

Eastern oysters are a key ecological indicator species monitored in the Caloosahatchee River Estuary for the purposes of evaluating progress in hydrologic restoration under CERP (Volety and Haynes 2012). Oysters are a useful indicator of high flows because they are sensitive to prolonged periods of low (<10) salinity. Because they are sessile after settlement, they also integrate the impact of varying water quality over the course of weeks to months or even years, depending on the metric used (Volety et al. 2014, CHNEP 2019). The presence of oysters is often a gauge of the overall biodiversity of an ecosystem, because biomass, density, and species richness of fish and invertebrates are all greater on oyster reefs than on unvegetated sand or mud bottoms (Tolley and Volety 2005).

CERP's scientific and technical arm, the Restoration, Coordination, Verification (RECOVER) program, updated the flow target for the Caloosahatchee to 20–60 m^3/sec (750–2100 ft^3/sec), as measured at the S-79 water control structure located upstream on the Caloosahatchee River (RECOVER 2020a). This flow target was designed to balance the needs of both the oyster populations and the SAV community. Simulations using this flow range in a hydrodynamic salinity model (Sheng 1986) show that average salinity between Cape Coral and the mouth of the Caloosahatchee River estuary should remain within 10–25 at least 80% of the time. Meeting these restoration flow targets would reduce the frequency and magnitude of large salinity changes throughout this zone and could improve metrics in RECOVER's oyster monitoring program (Parker and Radigan 2020). Additionally, an oyster habitat suitability index adapted from Barnes et al. (2007) was used to simulate conditions for oysters in the lower Caloosahatchee River Estuary using the new flow targets and several other new CERP projects coming online (RECOVER 2020b). Conditions are projected to improve between the 2020 baseline and 2032 for at least 28 ha (70 ac) of oyster reefs as a result of reduced high-flow releases of freshwater to the Caloosahatchee River and increased water storage south of Lake Okeechobee.

The CHNEP Oyster Habitat Restoration Plan (Boswell et al. 2012) determined that the CHNEP study area should ideally support 400–2,400 ha (1,000–6,000 ac) of oyster reefs; the plan also included an oyster restoration suitability model to assist with site selection for artificial oyster reefs. The restoration suitability model indicates that there are more than 16,000 ha (40,000 ac) of highly suitable areas for oyster restoration in the study area. To advance oyster restoration in the Charlotte Harbor region and throughout the state, The Nature Conservancy (TNC) facilitated a statewide team of stakeholders in the development of a new FDEP general permit specifically for low-profile oyster restoration efforts. The permit was approved by the state in 2013 and is the only state permit designed specifically for oyster restoration. TNC also used Charlotte Harbor as a case study for creating a guide and online oyster calculator tool for managers setting oyster restoration objectives based on fishery enhancement and water filtration (zu Ermgassen et al. 2017, https://oceanwealth.org/tools/oyster-calculator/).

Estero Bay

South of Charlotte Harbor and the Caloosahatchee River, Estero Bay is enclosed by barrier islands and receives freshwater flow from many small rivers and creeks (Figs. 6.3 and 6.6). Much of the shoreline was protected from development and has been preserved as Estero Bay Preserve State Park, although there is extensive development on the barrier islands and uplands surrounding the bay. A large network of oyster reefs is present in northern Estero Bay, and smaller reefs are found in the southern part of this system (FDEP 2014; Fig. 6.6). The reefs in Estero Bay are subject to modified timing and delivery of freshwater flow, but to a lesser extent than the Caloosahatchee River.

The irregular shape of the coastline and mangrove islands in Estero Bay are a result of oyster reef formation and accretion of sediments in the early to middle Holocene (Savarese et al. 2004a). The sedimentation, along with shell growth and recruitment of young oysters, results in high rates of accretion and provides substrate for settlement of red mangroves (*Rhizophora mangle*). These mangroves eventually mature into mangrove islands, but evidence of past oyster reefs remains in the underlying stratigraphy (Savarese et al. 2004a).

Naples Bay

Historically, the majority of freshwater flowing into Naples Bay came from rainfall-derived sheet flow and small natural tidal tributaries: Gordon River, Rock Creek, and Haldeman Creek. The watershed's drainage area was approximately 25 km^2 (10 mi^2) before it was developed and comprised mostly mesic and hydric flatwoods (Woithe and Brandt-Williams 2006). Mangroves dominated the shoreline of this shallow estuary, and the bay once thrived with oyster reefs, seagrass beds, and numerous fish species (Simpson et al. 1979).

Extensive development, watershed alterations, and dredge-and-fill activities since the 1950s transformed Naples Bay (Fig. 6.7) into a highly urbanized estuary (Laakkonen 2014). Residential development led to an increase in hardened shorelines in the 1950s and 1960s (Schmid et al. 2006). Navigation canals lined with sea-

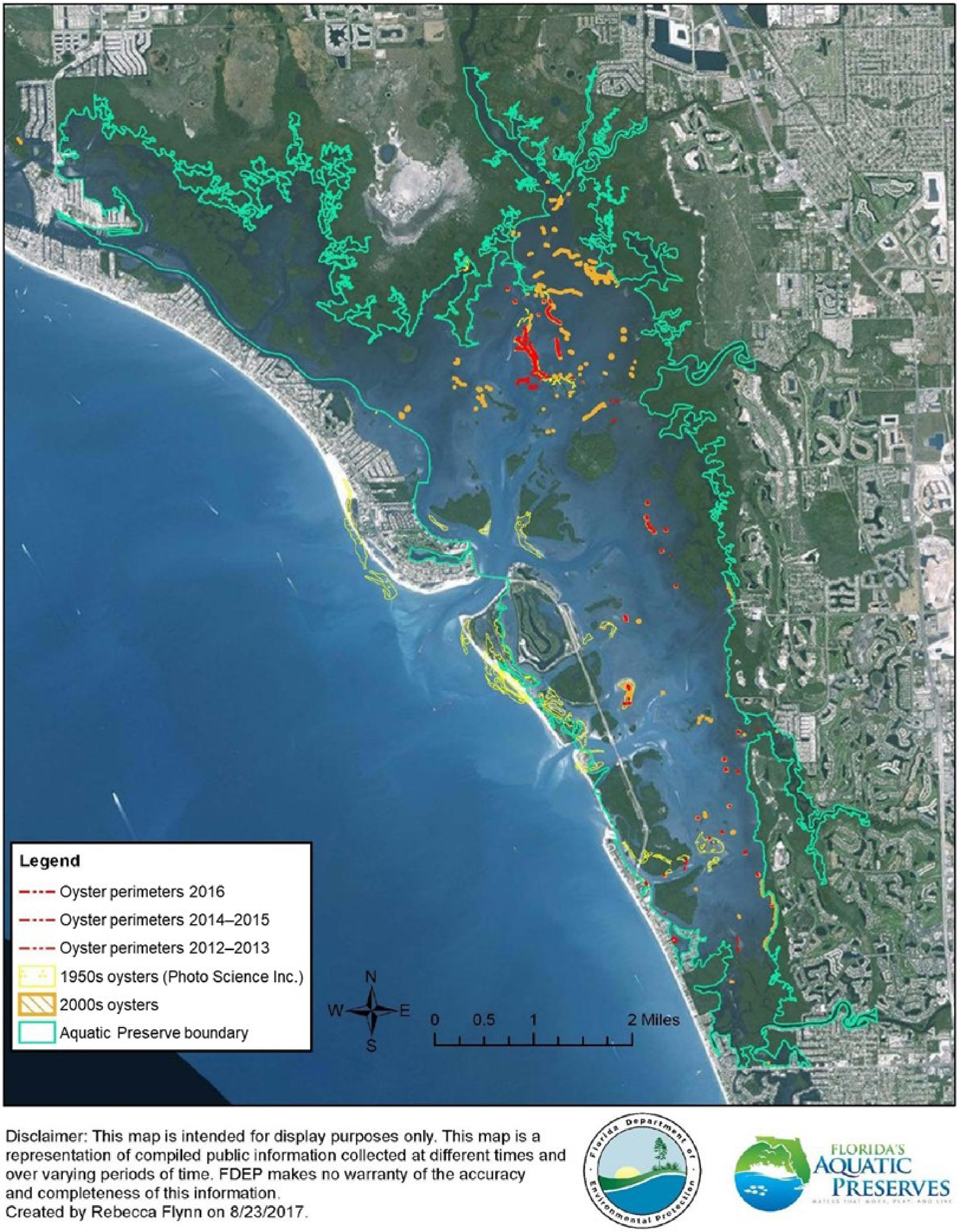

Figure 6.6. Map of oyster reefs from the 1950s and oyster reefs mapped during 2012–2016 in Estero Bay. Figure source: Rebecca Flynn, FDEP Estero Bay Aquatic Preserve.

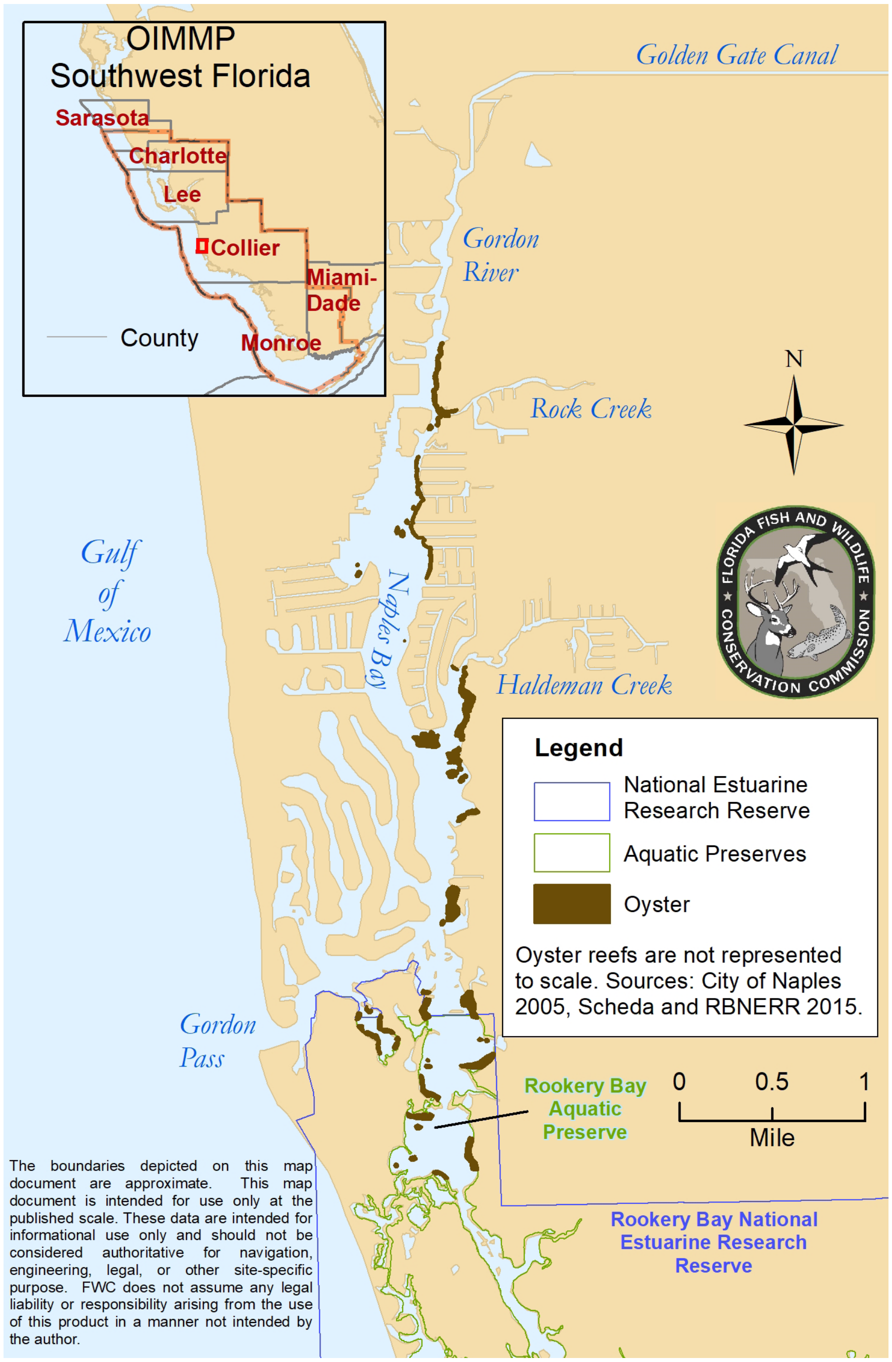

Figure 6.7. Mapped oyster extent in Naples Bay. Oyster mapping sources: City of Naples (2005), made from 2005 sonar data; Scheda and RBNERR (2015), from 2014 aerial photography.

walls and bulkheads replaced more than 70% of the mangrove shoreline. The bay has lost 90% of its seagrass beds and 80% of its oyster reefs (Fig. 6.8; Schmid et al. 2006). Today subtidal oyster reefs are present on sandy substrates in the northern part of the bay and fringing reefs are found in the southern part of the bay. Seismic profiling in Naples Bay revealed few buried oyster reefs, indicating that most of the historical reef extent was lost to dredging rather than sedimentation (Savarese et al. 2006). Today, Naples Bay remains a challenging environment for oysters due to water quality issues, muddy substrates, and suspended sediments, which can smother reefs (Savarese et al. 2006).

The natural tributaries of Naples Bay have been severely altered by urbanization and the addition of numerous canals, significantly changing the hydrology and dis-

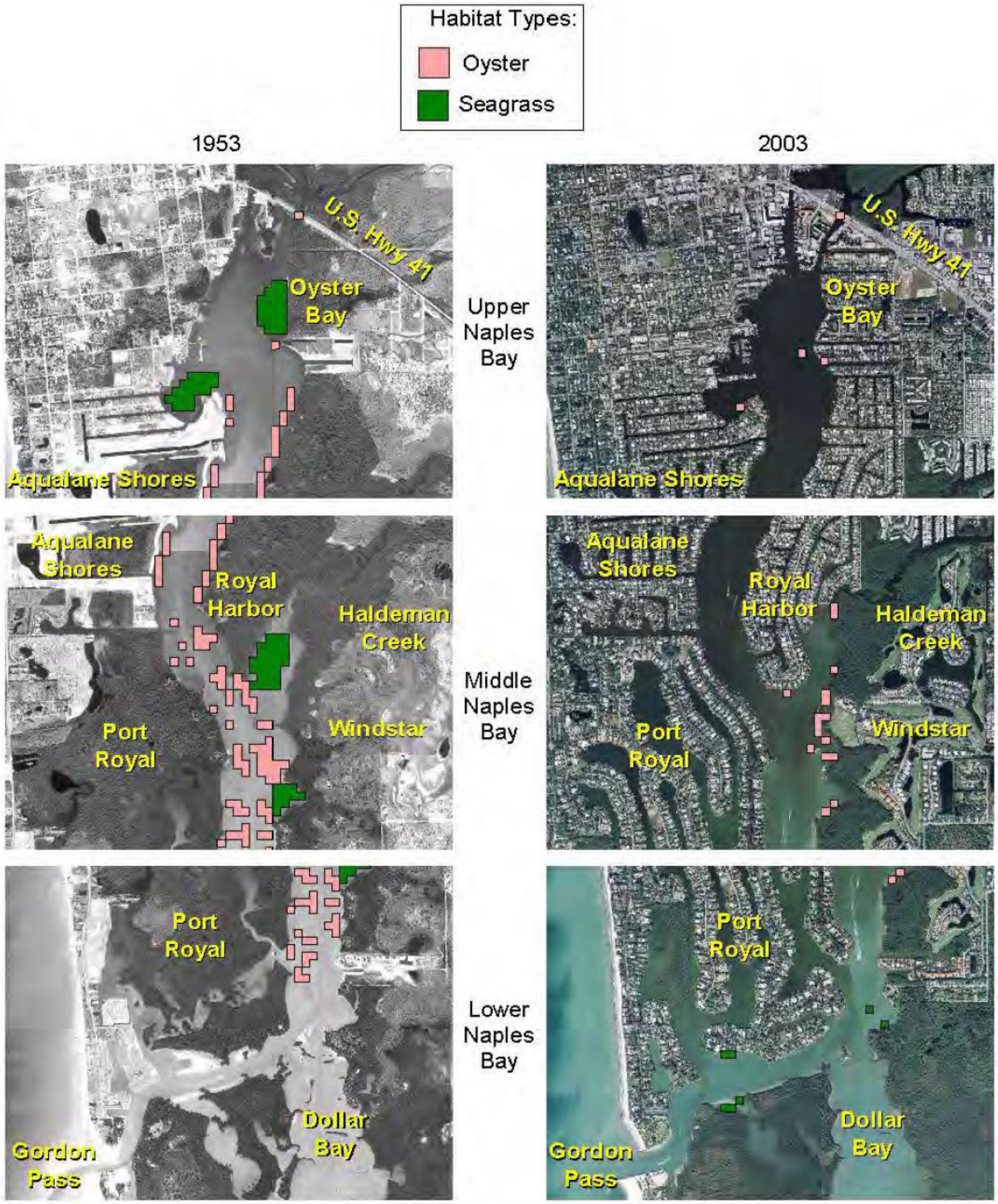

Figure 6.8. Coastline comparison between 1953 and 2003, with the approximate historical and present-day oyster and seagrass coverage. Figure source: Schmid et al. (2006).

rupting the timing and magnitude of freshwater flow to the estuary. The construction of canal systems in residential areas has increased the perimeter of the bay by 53% and the water surface area by 23% (Schmid et al. 2006). Land use in the watershed is a mosaic of residential developments, industrial areas, and agricultural lands, which have increased the pollutant load to the bay (Woithe and Brandt-Williams 2006). Surface water that once traveled as a sheet flow through wetlands is now rapidly conveyed to Naples Bay via stormwater pipes and surface canals, resulting in degraded water quality including increased nutrients, sediments, and metals (CSF 2011, 2017).

The construction of the Golden Gate Canal (Fig. 6.7) in the 1960s to drain the Northern Golden Gate Estates increased the size of the Naples Bay watershed from approximately 25 km^2 (10 mi^2) to more than 300 km^2

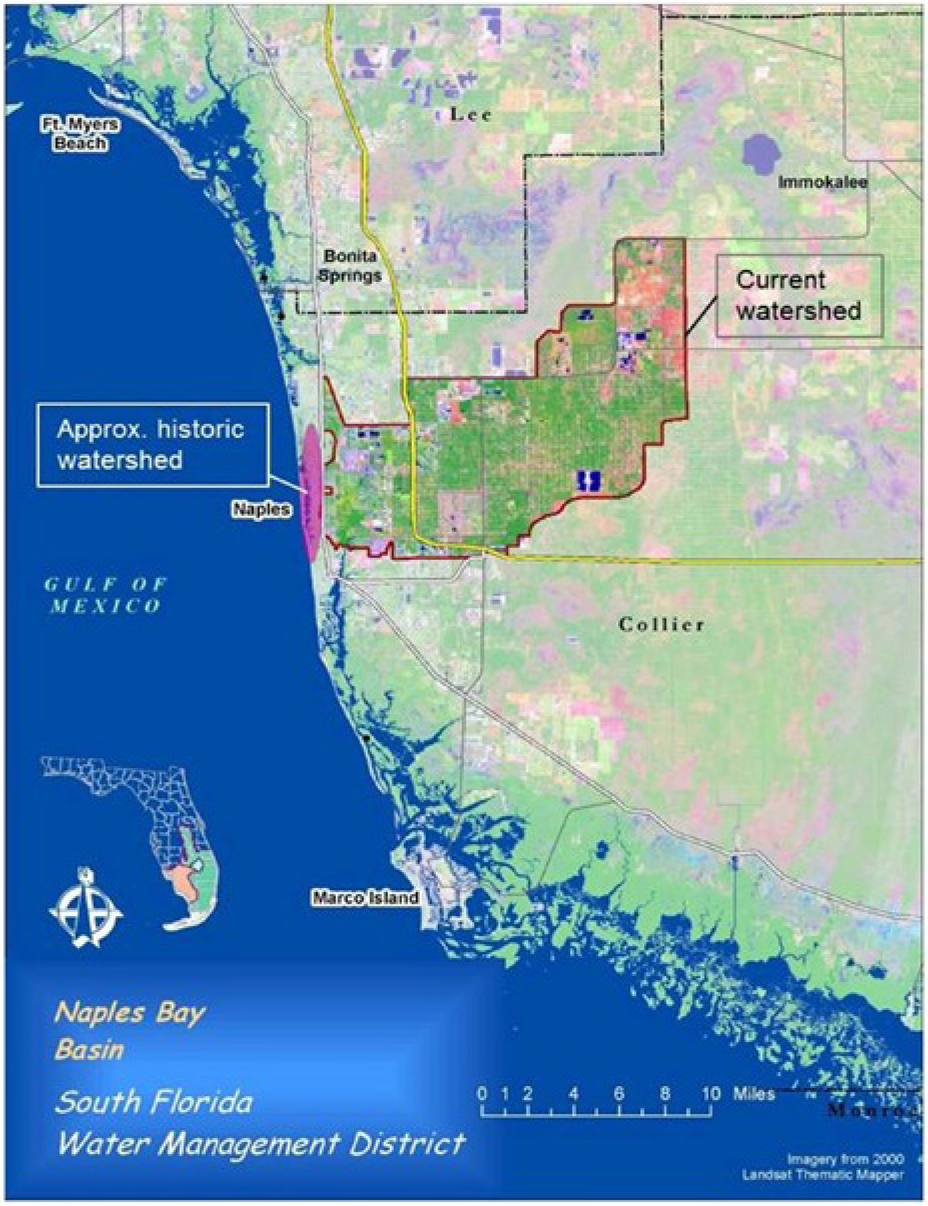

Figure 6.9. Historical (25 km^2 [10 mi^2]) watershed and expanded Naples watershed (300 km^2 [120 mi^2]) resulting from the dredging of the Golden Gate Canal. Figure credit: SFWMD.

(120 mi^2), drastically increasing rainy season freshwater flow into Naples Bay (Fig. 6.9; Woithe and Brandt-Williams 2006, CSF 2011, 2017). Average annual discharge from this weir-controlled canal is 7 m^3/sec (250 ft^3/sec), with flows exhibiting high seasonal variability ranging from 0 m^3/sec (0 ft^3/sec) in the dry season to 40 m^3/sec (1,400 ft^3/sec) in the wet season (CSF 2011). In the dry season (November–May), salinity is relatively uniform from Gordon Pass through the Gordon River. In the wet season (June–October), freshwater flow from the Golden Gate Canal causes severe stratification of the water column, which lowers benthic dissolved oxygen, inhibits vertical mixing, and decreases water clarity (Woithe and Brandt-Williams 2006). In addition, these large wet-season freshwater influxes greatly reduce salinity in the bay. When combined with the other stressors, this results in harmful impacts to the aquatic biota, including declines in oyster populations (Simpson et al. 1979).

Rookery Bay and the Ten Thousand Islands

Rookery Bay and the Ten Thousand Islands (Fig. 6.10) are considerably less developed than the Naples and Charlotte Harbor watersheds. Apart from Marco Island, much of the watershed and coastal waters are protected from development by Rookery Bay National

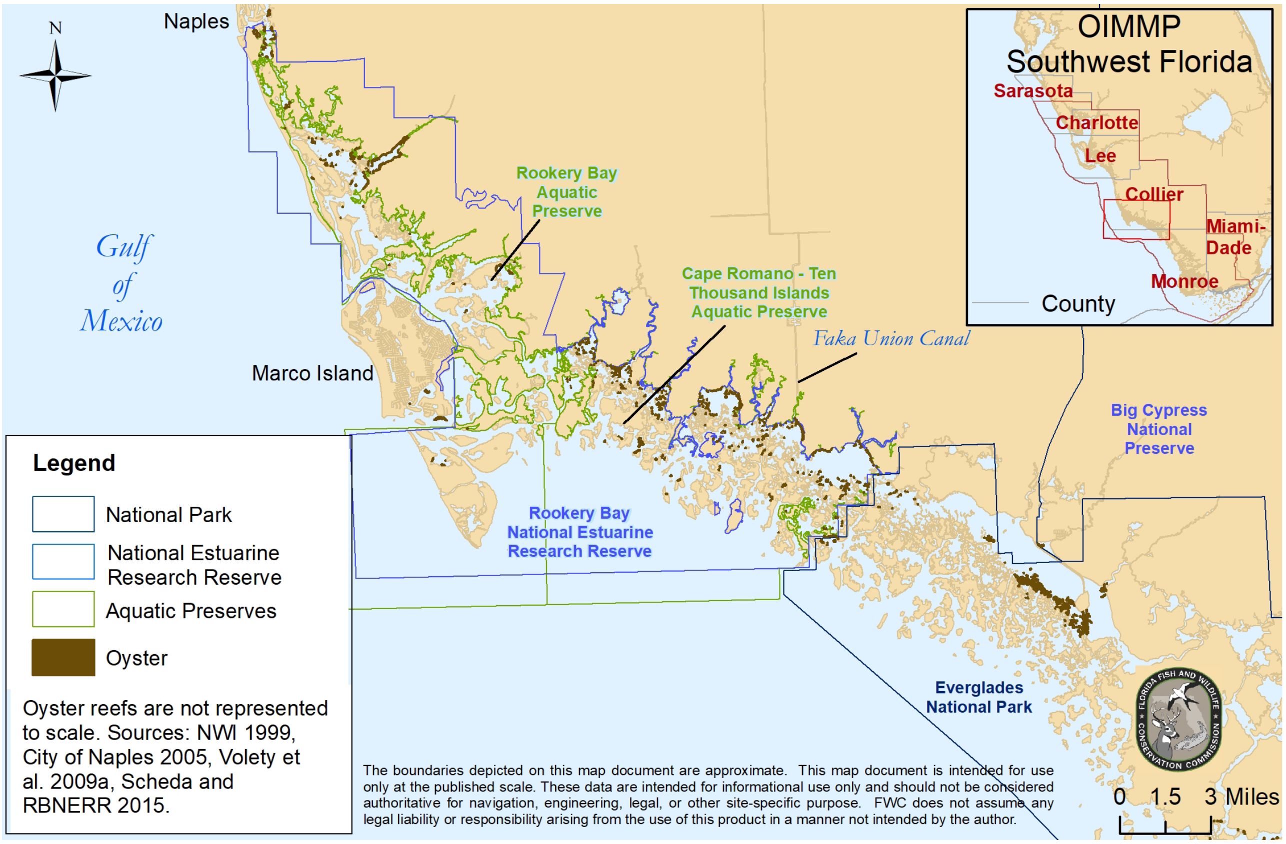

Figure 6.10. Oyster extent in Rookery Bay and Ten Thousand Islands. Oyster mapping sources: NWI (1999), made from 1999 aerial photography; City of Naples (2005) from 2005 sonar data; Volety et al. (2009a), from 2007 photography; and Scheda and RBNERR (2015), from 2014 photography.

Figure 6.11. Red mangrove (*Rhizophora mangle*) propagules take root after settling on an intertidal oyster reef in the Ten Thousand Islands. Photo credit: Ryan P. Moyer

Estuarine Research Reserve (RBNERR), Rookery Bay Aquatic Preserve, Cape Romano–Ten Thousand Islands Aquatic Preserve, Ten Thousand Islands National Wildlife Refuge, Collier Seminole State Park, Picayune Strand State Forest, and Fakahatchee Strand State Preserve. Although much of the natural mangrove coastline remains intact, the watershed has been historically affected by widespread dredge-and-fill operations that drained large tracts of land for development and an increasing demand for freshwater by the growing population of southwest Florida. As a result, the timing and volume of freshwater entering the estuary has been altered (Scheda and RBNERR 2015). North of the Ten Thousand Islands, canals were dug to drain the failed planned community of the Southern Golden Gate Estates. These canals connect to the Faka Union Canal (Fig. 6.10), delivering large amounts of freshwater and increasing turbidity in the Ten Thousand Islands (USFWS 2000). The State of Florida purchased the private lots in the undeveloped community, and the land is now the Picayune Strand State Forest. Restoration efforts to improve hydrology are under way and include refilling canals, pumping water, and removing roads (SFWMD and USDA 2003, FDACS 2020). Salinity in the Ten Thousand Islands in the winter dry season generally stays above 34 in the shallow coastal waters as a result of limited freshwater flow; in the summer wet season it fluctuates between 20 and 32 (Soderqvist and Patino 2010). The region is suscep-

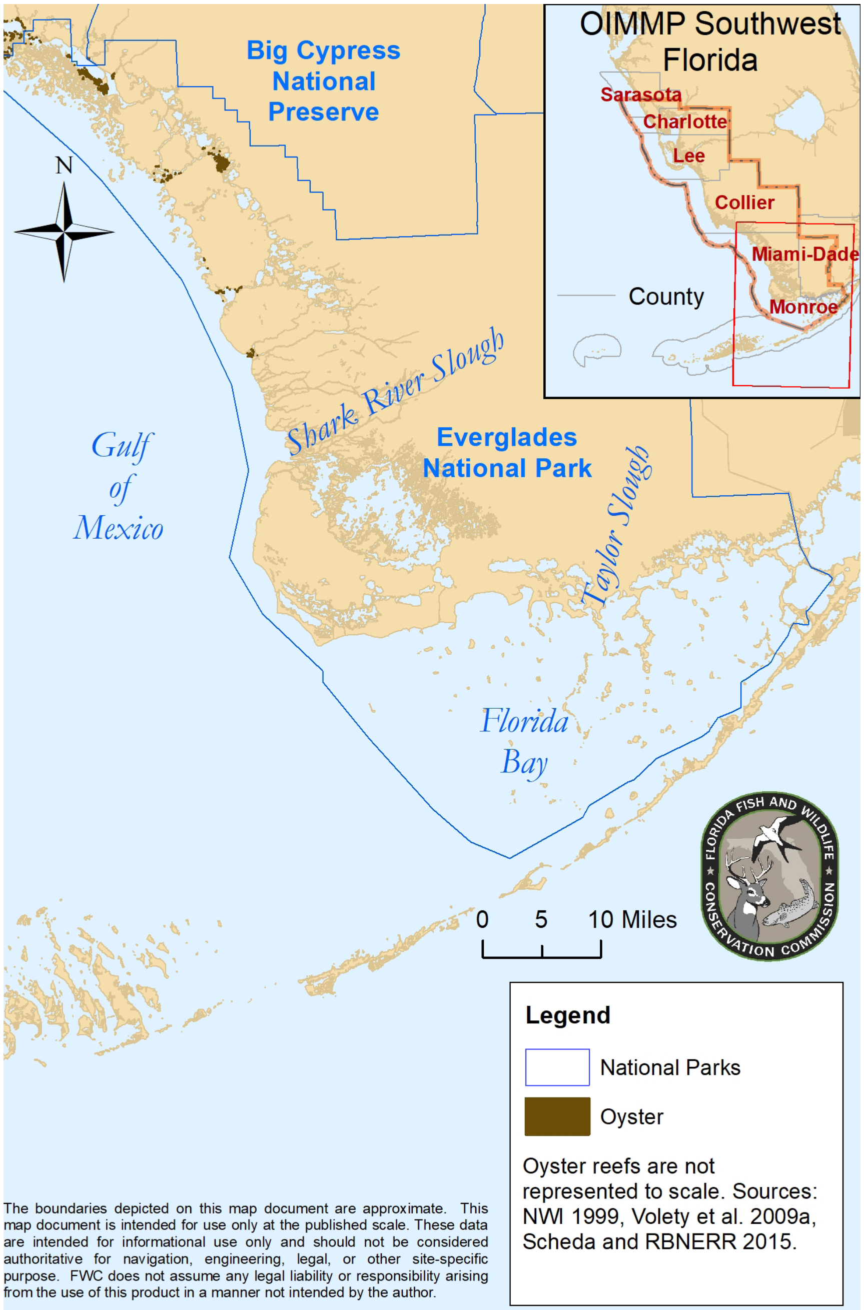

Figure 6.12. Oyster extent in the Everglades and Florida Bay. Oyster mapping sources: NWI (1999), made from 1999 aerial photography; Volety et al. (2009a), from 2007 photography; and Scheda and RBNERR (2015), from 2014 photography.

tible to impaired water quality, including low dissolved oxygen and pollution from nutrients and heavy metals (CSF 2011, 2017). Shellfish harvesting is conditionally approved for a large part of the Ten Thousand Islands in shellfish harvesting area #66 (Fig. 6.5), although Florida Fish and Wildlife Conservation Commission (FWC) records do not show any commercial harvest in Monroe County or Collier County since 1965 (FWC 2021).

Like Estero Bay, the geomorphology and formation of the Ten Thousand Islands can also be attributed to topography created by oyster and vermetid gastropod reefs formed during the early to middle Holocene (Volety et al. 2009a). Mud and shell accretion on these reefs provided a substrate for the settlement of mangrove propagules (Fig. 6.11), which matured into the mangrove islands that give the Ten Thousand Islands its name (Volety et al. 2009a). A layer of oyster shell hash, a remnant of past oyster reefs, is common in subtidal stratigraphy in the area (Volety et al. 2009a, FDEP 2012).

Everglades and Florida Bay

Historically, sheet flow and groundwater flow made salinity favorable for oyster growth along the coast of the Everglades (Volety et al. 2009a). With reduced sheet flow, however, oysters are now restricted to brackish river mouths, inland bays, and channels (Fig. 6.12; Volety et al. 2009a). Mapping data are limited for much of Everglades National Park and may underestimate oyster extent. A limited extent of oyster reefs has been observed in the Taylor Creek and Shark River Slough systems, but since salinity is so dependent upon the timing and volume of upstream freshwater flows, their presence is highly variable (Penny Hall, pers. comm.).

Florida Bay is a broad, shallow bay south of the Everglades (Fig. 6.12). Some oysters are found in brackish waters on prop roots of mangroves bordering Florida Bay (Goodman et al. 1999), including the tree oysters (*Isognomon* spp.; Mikkelsen and Bieler 2007). These mangrove-root oysters are difficult to detect via remote imagery and so have not been mapped. Florida Bay itself does not support extensive oyster reefs and experiences widely variable water quality, including warm temperatures and hypersaline conditions as a result of reduced freshwater flow and evaporation (Fourqurean and Robblee 1999).

Threats to oysters in southwest Florida

- **Altered hydrology:** The portion of the available estuary that provides suitable habitat for oyster reefs is affected by quantity, quality, timing, and duration of the freshwater supply. Oysters located in concentrated freshwater outflows such as the Caloosahatchee River Estuary or the Faka Union Canal must cope with very low salinity (<10) during the rainy season, which results in increased mortality and decreased reproduction (La Peyre et al. 2003, Volety et al. 2008). Changes in the rate of freshwater delivery may also limit the upstream extent to which oyster populations remain viable. High nutrients in urban runoff and freshwater releases from Lake Okeechobee support algal blooms that smother oyster reefs, cause hypoxia, and may release biotoxins (Volety et al. 2014). Most oysters in southwest Florida, including those near freshwater outflows, must also cope with low freshwater flow and high salinity, which increases rates of disease and predation (Volety et al. 2003, Volety et al. 2008). The consequences of reduced freshwater flow can be seen in the Everglades, where the range of oysters has shifted inland to areas with lower salinity (Volety et al. 2009a).

  Land use such as agriculture, mining, and increased coastal development have also altered the quality and quantity of the freshwater delivered to southwest Florida estuaries, often increasing nutrient concentrations and decreasing or channelizing freshwater supply (FDEP 2005, Schmid et al. 2006). Additionally, numerous communities were built in wetlands across southwest Florida using dredge-and-fill construction. In these developments, the paved surfaces and finger canals with limited circulation alter surface water delivery to the estuary. The net impact of these land-use changes and altered hydrology on oyster reefs still needs study.

- **Sedimentation:** Several regions in Charlotte Harbor and Naples Bay must cope with excessive sedimentation as a result of runoff and altered hydrology. Fine sediment can interfere with filter feeding, cause decomposition-induced hypoxia, and accumulate as muck substrates that are unsuitable for oyster settlement (Volety et al. 2008). Frequent resuspension of sediments can occur due to boat wakes and wave reflection off seawalls along the Caloosahatchee.

- **Habitat loss:** Large areas of oyster reef in Charlotte Harbor, Naples, and Marco Island were destroyed as a result of shell mining, commercial fishing, and dredge-and-fill construction (Boswell et al. 2012, Volety et al. 2014). Mangroves, and thus mangrove-root-oyster habitat, were also lost to coastal development.

- **Climate change and sea-level rise:** Altered precipitation patterns, increasing temperatures, rising sea level, and ocean acidification all pose threats to oysters (Miller et al. 2009, Hoegh-Gulberg and Bruno 2010, Rodriguez et al. 2014), but the degree of the detrimental effect on oyster populations in southwest Florida is uncertain, particularly when the many other anthropogenic impacts in the region are considered. This is a complex topic that requires further investigation and substantive review.

- **Harvesting:** Commercial harvesting in southwest Florida is not as extensive as in the other coastal areas of the state, but Lee and Charlotte counties have experienced extensive shell mining and widely variable harvest intensities. The impact of the recent resurgence in commercial harvesting on severely reduced oyster populations needs to be assessed and managed.

- **Disease:** *Perkinsus marinus* (dermo) infections have been found in 65–95% of oysters in southwest Florida (Volety et al. 2009a, Volety et al. 2014). Although infection is common, infection intensity (as gauged on the scale developed by Mackin 1962) is often relatively low as warm summer temperatures are counteracted by the low salinity of the rainy season (La Peyre et al. 2003, Volety et al. 2008). Areas that do not receive high freshwater flow in the summer rainy season are more vulnerable to infection (Volety et al. 2009a).

- **Invasive species:** The Asian green mussel, *Perna viridis,* was first found in Charlotte Harbor in 2000 and in Estero Bay in 2002 (FDEP 2014). These mussels have no natural predators in Florida and reach sexual maturity quickly, at the age of 2–3 months. But McFarland et al. (2013) found that *P. viridis* were physiologically limited in lower salinities and closed their valves when salinity was <15. *Perna viridis* is therefore not expected to be a significant threat to eastern oysters in most parts of southwest Florida due to periodic exposure to low salinity in the region (McFarland et al. 2013). The Charlotte Harbor Aquatic Preserves have been monitoring green mussels since 2009 (FDEP 2017). Efforts to combat these invasive mussels include targeted removal and educating the public on invasive species (FDEP 2014). Other present and possible invasive species include tunicates, sponges, crustaceans, mollusks, worms, and many microorganisms.

Oyster reef mapping and monitoring efforts

The compilation of data used to create the oyster maps in this report is available for download at http://geodata.myfwc.com/datasets/oyster-beds-in-florida. This compilation of oyster maps is updated by the FWC as new mapping sources become available.

Southwest Florida Water Management District mapping

The SWFWMD has conducted seagrass mapping every two years since 1988 using a modified version of the Florida Land Use and Cover Classification System (FLUCCS; FDOT 1999) for coastal areas in the district, including northern Charlotte Harbor. Subtidal habitats are mapped using natural-color aerial photography collected in winter at a scale of 1:24,000. Mapped habitats include tidal flats, beaches, patchy and continuous seagrass, and attached algae. In 2014, the oyster bar (FLUCCS 6540) classification was added. The most recent effort was released in 2019 (SWFWMD 2019).

Charlotte Harbor mapping efforts

Several oyster mapping studies have been conducted in this region (Harris et al. 1983, Avineon 2004, Photo Science 2007), but they are limited in scope, have used different methods, and the accuracy of results is not consistent. The Charlotte Harbor Oyster Restoration Plan provides a good summary of the past mapping efforts in the Charlotte Harbor estuary (Boswell et al. 2012). Comprehensive mapping of subtidal and intertidal oyster habitat throughout the estuary is needed, as is condition analysis of reefs to inform restoration and management decisions. Upcoming FWC oyster mapping and monitoring (described below) will help address this need.

FWC oyster mapping and monitoring

In early 2022, the FWC began a project to expand oyster mapping and monitoring in several estuaries along the Florida Gulf coast, including Charlotte Harbor, as part of a project to be carried out with funding from the Florida Trustee Implementation Group. The first objective of the project is to assess gaps in mapping and monitoring data. The second step will include an extensive bay-wide survey of the Charlotte Harbor system. This study will include an analysis of remote imagery for evidence of previously unmapped intertidal and subtidal oyster reefs. Maps will be ground truthed, and short-term (3–4 years) monitoring stations will be established throughout the bay. Monitoring at these stations will document baseline conditions for oysters in areas not already being monitored by CERP. In addition to providing a benchmark for future comparisons, the baseline will assist in development of oyster habitat suitability indices for the selected estuaries, which will support oyster restoration and conservation efforts there.

Caloosahatchee River benthic habitat mapping

Dial Cordy and Associates Inc. was contracted by the U.S. Army Corps of Engineers to map benthic substrate in the Caloosahatchee River Estuary, St. Lucie Estuary, Loxahatchee Estuary, and Lake Worth Lagoon (Dial Cordy and Associates Inc. 2011). Resulting maps were created through the interpretation of high-resolution aerial photography as well as side-scan sonar to differentiate bottom types (e.g., seagrass, oyster bed, shell, muck). Substrates were verified via ground truthing, and the densities of living oysters were quantified on mapped oyster reefs. In the Caloosahatchee River, 9,244 ha (22,844 ac) were surveyed. The principal habitat was sand (and silty or shelly sand), but the report also documented seagrass (1,262 ha [3,119 ac]) and oyster

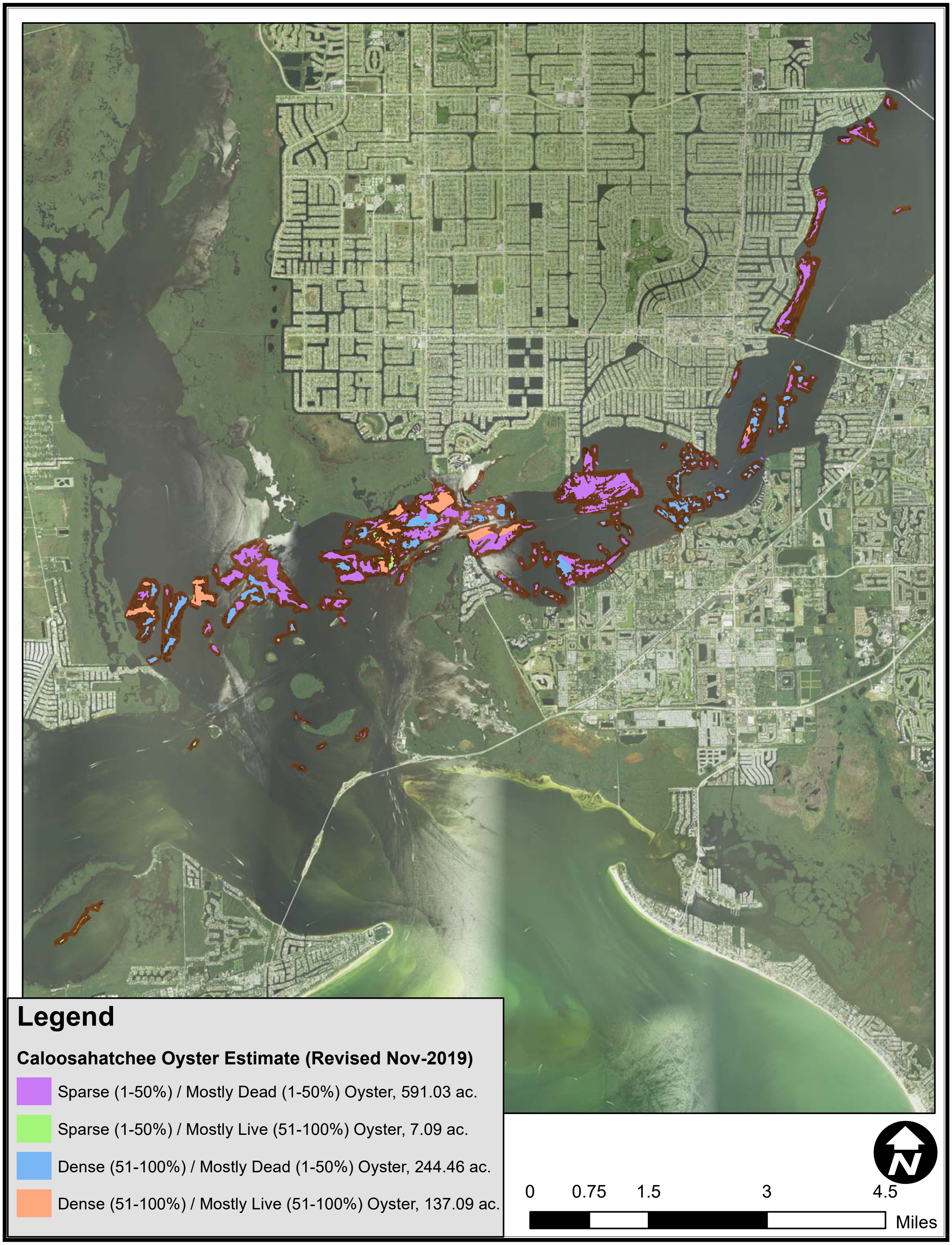

Figure 6.13. Oyster reefs in the Caloosahatchee River. Figure from Dial Cordy and Associates Inc. (2019); ground truthing completed by Ecological Associates Inc. (2019).

substrate (342 ha [847 ac]). Small, scattered clumps of oysters were observed as far upstream as midway between the U.S. 41 bridge and the Midpoint Bridge; the main concentration of oysters was observed downstream of the Cape Coral bridge and Bird Island. Additional oysters were scattered among the island and bars of San Carlos Bay.

Caloosahatchee River oyster habitat mapping

Dial Cordy and Associates Inc. again completed mapping of oyster reefs in the Caloosahatchee River in 2019 (Fig. 6.13; Dial Cordy and Associates Inc. 2019). This effort sought to improve and update the 2011 oyster maps mentioned above (Dial Cordy and Associates Inc. 2011) and to use ground-truthing data to classify the density of live oysters on each mapped reef. Side-scan sonar was used to resurvey the areas mapped in 2011. Ground truthing of the surveyed area was completed by Ecological Associates Inc. (2019). The resulting map classified the reef density as sparse (1–50% coverage) or dense (50–100% coverage) and also identified whether a reef contained mostly dead oysters (1–50% live) or mostly live oysters (50–100%). A total of 397 ha (980 ac) was mapped from Cape Coral to San Carlos Bay (Fig. 6.13). The reefs classified as sparse, mostly dead oysters were omitted from the mapping compilation of the region (Fig. 6.3).

CHNEP Volunteer Tidal Shoreline Survey/Mapping

The CHNEP completed volunteer tidal shoreline surveys in 2007, 2010, and 2013 (CHNEP 2013). These surveys documented the condition of the estuary by assessing various characteristics of mangroves as well as gathering data on oyster presence or absence, invasive vegetation, and shoreline hardening. In 2013, 318 km (198 mi) of shoreline accessible by vessel were surveyed (80% of the shoreline length that had been identified for the survey); oysters were present along 18% of the surveyed shoreline. Oysters in the accessible areas tended to be located on the shorelines having the highest estuarine salinity and not along the banks of the rivers with lower salinity. Survey results are available at http://www.chnep.wateratlas.usf.edu/shoreline-survey/.

CHNEP and TNC volunteer oyster habitat monitoring

The CHNEP volunteer oyster habitat monitoring program is intended to enable the collection of meaningful long-term monitoring data from oyster habitat restoration sites by citizen scientists. The CHNEP Oyster Habitat Restoration Plan (Boswell et al. 2012) and volunteer monitoring program manual (CHNEP 2017) provide monitoring protocols that can be used by all partner organizations in the Charlotte Harbor region and elsewhere.

The program was developed through experience gained working with volunteers to assist in monitoring TNC's Trabue Harborwalk Oyster Habitat Restoration Pilot Project in Punta Gorda. The protocols (CHNEP 2017) were vetted through both a scientific steering committee and a volunteer steering committee to ensure that the protocols were appropriate for volunteers and are also in line with those in Baggett et al. (2014). Results are therefore comparable to oyster habitat restoration projects in other regions. By recruiting and training volunteers to conduct the majority of the monitoring using scientifically vetted protocols, this program will enable long-term collection of monitoring data at a lower cost and with less agency staff time and will increase community support for and understanding of habitat restoration projects.

The Trabue Harborwalk Oyster Habitat Restoration Pilot Project includes nine pilot reefs—three each of bagged fossilized shell, loose fossilized shell surrounded by oyster bags, and oyster mats made with recycled shells. TNC is collaborating with Charlotte Harbor Aquatic Preserves, the CHNEP Volunteer Oyster Habitat Monitoring Program, Friends of the FDEP, and the FWC to monitor these pilot reefs (Geselbracht 2016). Monitoring includes a focus on oyster recruitment, macroinvertebrate populations, bird presence, and use of the reefs by smalltooth sawfish (*Pristis pectinata*). The first of three years of postconstruction monitoring (2016) demonstrated that the reefs created a thriving community of oysters and other invertebrates. As of April 2017, 1,300 volunteers and citizen scientists had provided a total of 2,950 hours toward this restoration project, including material assembly, deployment, and monitoring (Geselbracht et al. 2017). Postconstruction monitoring of the project was also completed in 2017 and 2018. Monitoring reports and data from this project may be downloaded from http://chnep.wateratlas.usf.edu/oyster-habitat-restoration/.

Caloosahatchee River estuary habitat suitability model

Barnes et al. (2007) developed a habitat suitability model for oysters in the Caloosahatchee River estuary based on salinity, temperature, depth, substrate, and frequency of high-flow events. The habitat suitability model indicated that CERP efforts would improve habitat conditions for oysters over baseline conditions. The Barnes et al. (2007) model was used recently to simulate conditions for oysters in the lower Caloosahatchee River Estuary using the new flow targets (RECOVER 2020b).

CHNEP oyster habitat restoration suitability model

The CHNEP Oyster Habitat Restoration Plan and oyster restoration suitability model (Boswell et al. 2012) were funded by TNC and developed by the CHNEP Technical Advisory Committee as well as the oyster experts and stakeholders who made up the Southwest Florida Oyster Working Group. The purpose of the plan was to establish oyster restoration goals, methods, and partnerships in the region. The plan also included an oyster restoration suitability model, which identified locations in the estuary that ranged from least to most optimal for oysters based on five key restoration factors: local seagrass persistence, aquaculture lease areas, boat channels, bathymetry, and salinity (Boswell et al. 2012).

Sanibel–Captiva Conservation Foundation (SCCF) oyster restoration and monitoring

The SCCF Marine Laboratory has constructed or restored numerous oyster reefs from the mouth of the Caloosahatchee River to bayous west of Sanibel Island. All of its projects have included long-term monitoring of the restoration sites and adjacent reference sites. Monitoring metrics include density, size frequency, reef area, and reef height, plus ancillary measures including monthly spat settlement in Tarpon Bay, San Carlos Bay, and Matlacha Pass.

Oil spill impact study

Loren Coen, of Florida Atlantic University, and Ed Proffitt, of Texas A&M University Corpus Christi, led a study on the impacts of the 2010 Deepwater Horizon oil spill on oyster reefs in Florida Gulf estuaries. Goals for this study include assessing oyster conditions; its components focus on survival, growth, genetic diversity, and the concentration of polycyclic aromatic hydrocarbons in oyster tissues. A project overview may be found at http://research.gulfresearchinitiative.org/research-awards/projects/?pid=51.

CERP oyster monitoring

CERP conducts monitoring of oyster health and water quality on Florida's southeast and southwest coasts. Locations monitored on the Gulf coast include four stations in the Caloosahatchee River Estuary; San Carlos Bay and the Ten Thousand Islands were also monitored in the past (Volety et al. 2008, 2009b, 2014, Volety and Haynes 2012, Parker and Radigan 2020). Florida Gulf Coast University led the first monitoring efforts on the Gulf coast, while the FWC did so on the Atlantic coast, using a similar methodology (Boswell et al. 2012). In 2017, the FWC assumed monitoring responsibilities in the Caloosahatchee River. Monitored parameters include water quality, spat recruitment, reproductive histology, dermo prevalence and intensity, recruitment, density, and juvenile oyster growth (Volety and Haynes 2012, Volety et al. 2014).

Charlotte Harbor benthic habitat mapping and biodiversity efforts

Mote Marine Laboratory and CHNEP completed a mapping and biodiversity survey of benthic habitats in 10 basins of greater Charlotte Harbor (CHNEP and MML 2007). Surveyed habitats included mangroves, sandbars, mud flats, salt marsh, oyster reefs, and seagrass beds. More than 370 invertebrate taxa were identified from more than 44,000 organisms collected (CHNEP and MML 2007). The study also examined the impact of habitat and salinity on biodiversity.

Molluscan bioindicators of the tidal Myakka River and inshore waters of Venice

Mote Marine Laboratory conducted a survey of important mollusk species in the lower Myakka River and Dona and Roberts bays and their tributaries (Estevez 2005). Data were collected on density, shell size, and degree of shell weathering for living and dead oysters. Oysters were much more abundant in Dona and Roberts bays than in the Myakka River. Oyster shells were found in the Myakka River, but all shells were dead and highly weathered, indicating that the shells were old (Estevez 2005).

Estero Bay Aquatic Preserve oyster mapping and monitoring

The Estero Bay Aquatic Preserve (EBAP) oyster mapping and monitoring program began in the winter of 2012. The original goal of the project was to map every oyster reef in Estero Bay Aquatic Preserve and compare reef extent to aerial photographs from the 1950s and 2000s. The focus has shifted toward assessing the health of a subset of oyster reefs in the bay (Stephanie Erickson, pers. comm.). Mapping and monitoring have typically been completed from October through March to take advantage of the low winter tides, but on a few occasions have been done in summer. In winter 2012–2013, 67 reefs were mapped and data were collected on reef status (natural live reef, natural live shell, natural nonliving, restored live reef, restored live shell, restored nonliving), presence of oysters, the perimeter of the intertidal oyster reef, presence of surrounding seagrass species, presence of green mussels, substrate, and water depth.

Since 2013, more parameters have been added to the protocol, including presence of mangroves and tide stage. In addition, each reef is surveyed using a transect and randomly placed quadrats. Data include the transect heading, type of oyster reef (patch, fringing, or string), reef length, shell height, reef height, percent cover (live oyster, oyster shell, sediment, or other), and presence of any other organisms. Several 0.25-m^2 quadrats are used to measure oyster density (including spat), size frequency distribution, and recruitment. Finally, water quality readings including temperature, salinity, dissolved oxygen, pH, and turbidity are collected near each reef. EBAP staff are developing a new long-term monitoring strategy for oyster health in Estero Bay that will comprise aerial mapping and annual monitoring of a handful of representative oyster reefs throughout the bay.

Naples Bay mapping

Savarese et al. (2004b and 2006) conducted substrate and subsurface mapping in Naples Bay and the Ten Thousand Islands. Substrate maps delineated oyster reefs using side-scan sonar (City of Naples 2005). Subsurface acoustic profiles were produced using shallow seismic chirp profiling, which could identify the presence of buried oyster reefs (Saverese et al. 2006). The effort also identified suitable locations for oyster reef restoration. GIS data are available as bathymetry maps at http://g.naplesgov.com/cityofnaplesgis2.

Schmid et al. (2006) detailed the historical development and loss of estuarine habitat in Naples Bay. Historical and current maps of seagrass, oyster, and mangrove habitats were created in this effort. Benthic habitat maps were created using 1999 digital orthoquads, and sediment and biotic characteristics were verified with field sampling (Schmid et al. 2006).

Additionally, a master's thesis titled *Effects of salinity and other stressors on eastern oyster (*Crassostrea virginica*) health and a determination of restoration potential in Naples Bay, Florida* includes maps of historical oyster reef coverage, 2014 coverage, and restoration strategies for Naples Bay (Laakkonen 2014).

Naples Bay monitoring

Oyster restoration in Naples Bay included the creation and monitoring of 2 ha (5 ac) of reef habitat using concrete oyster reef balls, limestone rock, and shell. Monitoring includes documentation of oyster density, reef elevation, spat settlement, mangrove recruitment, and bird use on the created reefs (Douglass et al. 2020). Further information on reef construction and monitoring is available at https://www.naplesgov.com/naturalresources/page/restoring-oyster-reefs-naples-bay.

Rookery Bay National Estuarine Research Reserve (RBNERR) mapping

In 2014, the RBNERR assessed estuarine conditions in Henderson Creek and the surrounding drainage basin. Scientists from Scheda Ecological Associates were hired to perform a literature review and analysis of available historical aerial imagery to assess the feasibility of documenting anthropogenic changes in estuarine habitats over time. This process included review of habitats (SAV, oyster reefs, and hard bottom) based on visual signatures in aerial photographs. Aerial photography had never been taken specifically to identify submerged aquatic resources (seagrass or oysters) in the Rookery Bay Estuary. The project team acquired high-definition, geo-referenced aerial photography to provide baseline data that could be used in evaluating changes in the natural communities of Rookery Bay and the Ten Thousand Islands area in response to freshwater inflow alterations. Maps were created for SAV, seagrass, hard bottom, and oyster habitat (Scheda and RBNERR 2015).

Ten Thousand Islands and Everglades mapping and monitoring

An extensive geomorphologic study of the Ten Thousand Islands and the coastal Everglades was conducted to determine past and present oyster distribution (Volety et al. 2009a). Data products include maps of oyster extent, including those on reefs and mangrove roots, and information on oyster presence in the geologic record through stratigraphy. Mapping was based on digital orthophoto quarter quads (DOQQs); geographic information system (GIS) data layers of the mapping product include a confidence category that compares features visible on DOQQs to mapped and ground-truthed habitats. Monitoring parameters included oyster condition index, dermo prevalence and intensity, spat recruitment, size, survival and density (Volety et al. 2009a).

National Wetlands Inventory (NWI) mapping

For more than 30 years, NWI generated and updated highly detailed wetland and intertidal habitat maps following the Cowardin et al. (1979) classification scheme. Estuarine intertidal mollusk reefs (coded as E2RF2) were mapped in Chokoloskee Bay using imagery from 1999 (NWI 1999). NWI maps are available at https://www.fws.gov/wetlands/index.html.

NOAA Mussel Watch

The National Oceanic and Atmospheric Administration (NOAA) National Status and Trends Program has monitored pollutants in bivalves through the Mussel Watch program across the coastal United States from 1986 to present. Monitoring locations in this region include Bird Island in Charlotte Harbor, Naples Bay, Henderson Creek in Rookery Bay, Faka Union Bay in the Everglades, and Flamingo and Joe Bay in Florida Bay (Kimbrough et al. 2008). High levels of mercury were found in oysters at these locations, and high levels of copper were found in Naples Bay. Many oysters in Florida have high copper concentrations as a result of the use of copper in fungicides, algaecides, and antifouling paints (Kimbrough et al. 2008).

Recommendations for management, mapping, and monitoring

- CERP efforts to moderate freshwater flow are key to maintaining brackish salinity and are crucial for oyster survival. More frequent water sampling, such as sampling with autonomous instruments, is needed to capture data on freshwater pulses and their impact on oysters (CHNEP 2019).
- Compared with more urbanized areas of Florida, oyster mapping and monitoring are notably lacking for many regions of Everglades National Park. Oyster distribution in the region should be documented before completion of major improvements to U.S. 41 that will improve surface water flow. The Shark River Slough and Taylor Creek areas should be monitored after construction to assess whether the changes have improved conditions for oyster development.
- Complete new maps of the Ten Thousand Islands for oysters and seagrass. Updates to the 2014 maps (Scheda and RBNERR 2015) will enable assessment of whether oyster reef area is stable, declining, or even increasing.
- To gauge progress toward the goal of 400–2,400 ha (1,000–6,000 ac) of oyster habitat in Charlotte Harbor, the CHNEP Oyster Habitat Restoration Plan recommends mapping oyster habitats by type and implementing and monitoring oyster restoration efforts throughout the estuary (Boswell et al. 2012). Expansion of shellfish monitoring throughout greater Charlotte Harbor is also recommended (CHNEP 2019).
- Continue efforts to determine patterns of oyster distribution before European settlement using historical records and sedimentary coring techniques (Boswell et al. 2012).
- Improve mechanistic understanding of reef-forming and reef-eroding processes (i.e., improve shell budget calculations).
- Improve understanding of how larval supply and transport among oyster reefs is impacted by river flow.
- Improve ecosystem service estimates (e.g., habitat provision, wave attenuation, water filtration, food-web contributions) for reef-forming and mangrove-root oysters.
- Improve estimates of predation and disease, especially as they relate to droughts.
- Assess whether recent regional oyster-harvest yields are sustainable.

Acknowledgments

The first version of this chapter was written by Anne Birch, Eric Milbrandt, Mark Thompson, Thomas Ries, Allison Conner, and Kara Radabaugh for the Oyster Integrated Mapping and Monitoring Report for the State of Florida, version 1, published in 2019. Version 1 geographic information system (GIS) support was provided by Christi Santi. Technical review was completed by Caroline Gorga (version 2) and Amber Whittle and William Arnold (version 1). Scientific and copy review of versions 1 and 2 was completed by Bland Crowder; additional copy review of version 2 was provided by Adrienne Ruga and Emily Ritz. OIMMP is funded by the FWC, Florida's Wildlife Legacy Initiative, and the U.S. Fish and Wildlife Service's funding support of Florida's State Wildlife Grants Program (award number F20AF00245).

Works cited

Avineon. 2004. Analysis of submerged aquatic vegetation, intertidal unvegetated, saltwater marsh, mangrove, oyster, freshwater wetland and native upland habitats within the greater Charlotte Harbor watershed. CHNEP FY03 technical project final map and database.

Baggett LP, Powers SP, Brumbaugh R, Coen LD, et al. 2014. Oyster habitat restoration monitoring and assessment handbook. Arlington, VA: The Nature Conservancy. Available from http://www.oyster-restoration.org/wp-content/uploads/2014/01/Oyster-Habitat-Restoration-Monitoring-and-Assessment-Handbook.pdf.

Barnes TK, Volety AK, Chartier K, Mazzotti FJ, Pearlstine L. 2007. A habitat suitability index model for the Eastern oyster (*Crassostrea virginica*). A tool for restoration of the Caloosahatchee Estuary, Florida. J Shellfish Res. 26: 949–959.

Boswell JG, Ott JA, Birch A, Cobb D. 2012. Charlotte Harbor National Estuary Program oyster habitat restoration plan. Fort Myers, FL: Charlotte Harbor National Estuary Program. Available from http://www.polk.wateratlas.usf.edu/upload/documents/CHNEP-Oyster-Rest-Plan-No-Appends-Final-2012-12-17.pdf.

Chimney MJ, Goforth G. 2001. Environmental impacts to the Everglades ecosystem: a historical perspective and restoration strategies. Water Sci Technol. 44:93–100.

CHNEP (Charlotte Harbor National Estuary Program). 2013. 2013 Volunteer tidal shoreline survey. Technical report 13-2. Fort Myers, FL: CHNEP. Available from http://www.chnep.wateratlas.usf.edu/upload/documents/CHNEP-2013-Volunteer-Shoreline-Survey-FINAL.pdf.

CHNEP (Charlotte Harbor National Estuary Program). 2017. CHNEP volunteer oyster habitat monitoring program. Punta Gorda, FL: CHNEP. Available from http://www.chnep.wateratlas.usf.edu/upload/documents/Final_Volunteer-Coordinator-Manual-1517-with-Appendices.pdf.

CHNEP (Coastal and Heartland National Estuary Partnership). 2019. 2019 comprehensive conservation and management plan for the CHNEP area in central and southwest Florida. https://www.chnep.org/our-plan, accessed July 2021.

CHNEP and MML (Charlotte Harbor National Estuary Program and Mote Marine Laboratory). 2007. Benthic invertebrate species richness & diversity at different habitats in the greater Charlotte Harbor system. Fort Myers, FL: CHNEP. Mote Marine Laboratory Technical Report No. 1169. Available from http://www.chnep.wateratlas.usf.edu/upload/documents/BenthicBiodiversityReport.pdf.

City of Naples. 2005. Naples Bay substrates. Naples, FL. https://naples.maps.arcgis.com/apps/webappviewer/index.html?id=1302c4d677c744fc89aee566a49c69fc/, accessed June 2017.

Cowardin LM, Carter V, Golet FC, Laroe ET. 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31. Washington, DC: U.S. Department of the Interior. Available from https://www.fws.gov/wetlands/Documents/Classification-of-Wetlands-and-Deepwater-Habitats-of-the-United-States.pdf.

CSF (Conservancy of Southwest Florida). 2011. Estuaries report card. Naples, FL: Conservancy of Southwest Florida.

CSF (Conservancy of Southwest Florida). 2017. Estuaries report card: a guide to understanding the health of Southwest Florida's rivers, estuaries, and bays. Naples, FL: Conservancy of Southwest Florida. Available from https://chnep.wateratlas.usf.edu/upload/documents/2017-ConservancySWFla-EstuariesReportCard.pdf.

Dial Cordy and Associates Inc. 2011. Benthic habitat mapping and substrate characterization in the northern estuaries, Florida. Washington, DC: U.S. Army Corps of Engineers.

Dial Cordy and Associates Inc. 2019. Oyster habitat mapping and substrate characterization in the Caloosahatchee River, Florida. Washington, DC: U.S. Army Corps of Engineers.

Douglass JG, Thomas S, Pinel R. 2020. Naples Bay oyster restoration project, 2018–2021 report: site 1 oyster reef restoration monitoring event #2. Fort Myers, FL: Florida Gulf Coast University.

Dye B, Jose F, Richard J, Mortensen JB, Milbrandt EC. 2021. An agent-based model accurately predicts larval dispersal and identifies restoration and monitoring priorities for eastern oyster (*Crassostrea virginica*) in a Southwest Florida estuary. Restor Ecol. e13487. https://doi.org/10.1111/rec.13487

Ecological Associates Inc. 2019. Caloosahatchee Estuary oyster map ground-truthing summary report (final). West Palm Beach, FL: South Florida Water Management District.

Estevez ED. 2005. Molluscan bio-indicators of the tidal Myakka River and inshore waters of Venice Florida. Final Report. Sarasota, FL: Sarasota County. Sarasota County Contract 2004-134. Mote Marine Laboratory Technical Report No. 990. Available from http://www.sarasota.wateratlas.usf.edu/upload/documents/Mote_Myakka_DARB_molluskreportfinal.pdf.

FDACS (Florida Department of Agriculture and Consumer Services). 2020. Ten-year land management plan for the Picayune Strand State Forest.

Tallahassee, FL: Florida Department of Agriculture and Consumer Services. Available from https://www.fdacs.gov/content/download/76952/file/Picayune_10_Year_Plan.pdf.

FDACS (Florida Department of Agriculture and Consumer Services). 2021. Division of Aquaculture GIS. https://fdacs.maps.arcgis.com/apps/webappviewer/index.html?id=57f7d4b7d900496d99891f22681c66d0, accessed June 2021.

FDEP (Florida Department of Environmental Protection). 2005. Water quality assessment report: Charlotte Harbor. Tallahassee, FL: FDEP. Available from http://manatee.wateratlas.usf.edu/upload/documents/Water%20Quality%20Assessment%20Report%20for%20the%20Charlotte%20Harbor%20Basin.pdf.

FDEP (Florida Department of Environmental Protection). 2012. Rookery Bay National Estuarine Research Reserve management plan, January 2012–December 2017. Tallahassee, FL: FDEP. Available from https://coast.noaa.gov/data/docs/nerrs/Reserves_RKB_MgmtPlan.pdf.

FDEP (Florida Department of Environmental Protection). 2014. Estero Bay Aquatic Preserve management plan. Tallahassee, FL: FDEP. Available from http://publicfiles.dep.state.fl.us/cama/plans/aquatic/Estero-Bay-AP-Management-Plan.pdf.

FDEP (Florida Department of Environmental Protection). 2017. Charlotte Harbor Aquatic Preserves management plan. Tallahassee, FL: FDEP. Available from http://publicfiles.dep.state.fl.us/CAMA/plans/aquatic/Charlotte-Harbor-AP-Management-Plan.pdf.

FDOT (Florida Department of Transportation). 1999. Florida land use, cover and forms classification system, 3rd edition. Tallahassee, FL: FDOT. Available from https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/content/geospatial/documentsandpubs/fluccmanual1999.pdf.

Fourqurean JW, Robblee MB. 1999. Florida Bay: a history of recent ecological changes. Estuaries Coast. 22:345–357.

FWC (Florida Fish and Wildlife Conservation Commission). 2021. Commercial fisheries landings in Florida. http://myfwc.com/research/saltwater/fishstats/commercial-fisheries/landings-in-florida/, accessed July 2021.

Geselbracht L, Graves A, Birch A. 2017. Trabue Harborwalk Oyster Habitat Restoration Project: overview and one-year monitoring results. Arlington, VA: The Nature Conservancy. Available from http://chnep.wateratlas.usf.edu/upload/documents/Trabue%20Oyster%20Project_Report__FINAL_9-20-17.pdf.

Geselbracht LL. 2016. Monitoring plan for created oyster reef at Trabue Harborwalk, city of Punta Gorda, Florida. October 2016 revision. Arlington, VA: The Nature Conservancy.

Goodman LR, Lewis MA, Macauley JM, Smith R Jr, Moore JC. 1999. Preliminary survey of chemical contaminants in water, sediment, and aquatic biota at selected sites in northeastern Florida Bay and canal C-111. Gulf Mex Sci. 17:1–6.

Harris BA, Haddad KD, Steidinger KA, Huff JA. 1983. Assessment of fisheries habitat: Charlotte Harbor and Lake Worth, Florida. St. Petersburg, FL: Florida Department of Natural Resources. Final Report. https://fgcu.digital.flvc.org/islandora/object/fgcu%3A27188, accessed July 2021.

Hoegh-Guldberg O, Bruno JF. 2010. The impact of climate change on the world's marine ecosystems. Science. 328:1523–1528.

Huber WC, Bedford BL, Blum LK, Boesch DF, et al. 2006. Progress toward restoring the Everglades: the first biennial review. Washington, D.C: National Research Council. The National Academies Press. https://www.nap.edu/read/11754/chapter/1, accessed July 2021.

Ingersoll, E. 1881. The oyster-industry. The history and present condition of the fishery industries. Report to the Commissioner of Fish and Fisheries. U.S. Dept. of the Interior. Washington, DC: Government Printing Office. Available from https://www2.census.gov/prod2/decennial/documents/1880d-01.pdf

Kimbrough KL, Johnson WE, Lauenstein GG, Christensen JD, Apeti DA. 2008. An assessment of two decades of contaminant monitoring in the nation's coastal zone. Silver Spring, MD: National Oceanic and Atmospheric Administration. NOAA Technical Memorandum NOS NCCOS 74. https://coastalscience.noaa.gov/data_reports/an-assessment-of-two-decades-of-contaminant-monitoring-in-the-nations-coastal-zone/, accessed July 2021.

Laakkonen KS. 2014. Effects of salinity and other stressors on eastern oyster (*Crassostrea virginica*) health and a determination of restoration potential in Naples Bay, Florida [master's thesis]. Fort Myers, FL: Florida Gulf Coast University. Available from https://fgcu.digital.flvc.org/islandora/object/fgcu%3A27276/datastream/OBJ/view/EFFECTS_OF_SALINITY_AND_OTHER_STRESSORS_ON_EASTERN_OYSTER__CRASSOSTREA_VIRGINICA__

HEALTH_AND_A_DETERMINATION_OF_RESTORATION_POTENTIAL_IN_NAPLES_BAY__FLORIDA_.pdf.
La Peyre MK, Nickens AD, Volety AK, Tolley GS, La Peyre JF. 2003. Environmental significance of freshets in reducing *Perkinsus marinus* infection in eastern oysters *Crassostrea virginica*: potential management applications. Mar Ecol Prog Ser. 248:165–176.
Mackin JG. 1962. Oyster diseases caused by *Dermocystidium marinum* and other microorganisms in Louisiana. Contrib Mar Sci. 7:132–229.
McFarland K, Donaghy L, Volety A. 2013. Effect of acute salinity changes on hemolymph osmolality and clearance rate of the non-native mussel, *Perna viridis*, and the native oyster, *Crassostrea virginica*, in Southwest Florida. Aquat Invasions. 8:299–310.
Miller AW, Reynolds AC, Sobrino C, Riedel GF. 2009. Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. Plos One. 4(5):e5661.
NOAA 1999. Benthic habitats of Estero Bay area, Florida 1999 Geoform. NOAA Office for Coastal Management. Submitted to the Florida Fish and Wildlife Conservation Commission and South Florida Water Management District https://catalog.data.gov/dataset/benthic-habitats-of-estero-bay-area-florida-1999-geoform, accessed June 2017.
NWI (National Wetlands Inventory). 1999. NWI surface waters and wetlands mapper. Available from https://www.fws.gov/wetlands/data/Mapper.html, accessed July 2021.
Parker ML, Radigan R. 2020. Oyster monitoring in the northern estuaries on the southeast and southwest coasts of Florida 2005-2018, Final Report. Submitted to the South Florida Water Management District. St. Petersburg, FL: Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute.
Photo Science. 2007. Historic coastal Charlotte Harbor benthic habitat map. Charlotte Harbor National Estuary Program FY06 Technical Project final map and database.
RECOVER (Restoration Coordination and Verification). 2020a. Northern estuaries performance measure, salinity envelope. Jacksonville, FL: U.S. Army Corps of Engineers, Jacksonville District. West Palm Beach, FL: South Florida Water Management District. Available from https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/14793.
RECOVER (Restoration Coordination and Verification). 2020b. The RECOVER Team's recommendations for revisions to the interim goals and interim targets for the Comprehensive Everglades Restoration Plan: 2020. Jacksonville, FL: U.S. Army Corps of Engineers, Jacksonville District. West Palm Beach, FL: South Florida Water Management District. Available from https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/14710.
Rodriguez AB, Fodrie FJ, Ridge JT, Lindquist NL, et al. 2014. Oyster reefs can outpace sea-level rise. Nat Clim Chang. 4:493–497.
Savarese M, Dellapenna T, Volety A. 2004b. Preliminary study of the sedimentary surface and subsurface of Naples Bay and the Ten Thousand Islands using acoustic geophysical techniques. West Palm Beach, FL: South Florida Water Management District. Available from https://www.sfwmd.gov/sites/default/files/documents/chirp%20study%20substratemapfinalreport_1.pdf.
Savarese M, Fielder B, Dellapenna T. 2006. Substrate and subsurface mapping of Naples Bay using geophysical techniques: implications for oyster reef restoration. West Palm Beach, FL: South Florida Water Management District. Available from https://www.sfwmd.gov/sites/default/files/documents/naplessubstratefinalreport0706.pdf and https://www.sfwmd.gov/sites/default/files/documents/naplesbaysubstratereportfigs.pdf.
Savarese M, Loh AN, Trefry JH. 2004a. Environmental and hydrologic history of Estero Bay: implications for watershed management and restoration. Appendix 12-5 in: 2006 South Florida Environmental Report. Palm Beach, FL: South Florida Water Management District. https://www.researchgate.net/publication/267950955_Appendix_12-5_Environmental_and_Hydrologic_History_of_Estero_Bay_Implications_for_Watershed_Management_and_Restoration, accessed July 2021.
Scheda and RBNERR (Scheda Ecological Associates Inc. and Rookery Bay National Estuarine Research Reserve). 2015. Rookery Bay watershed engineering research project. Rookery Bay, FL: Rookery Bay National Estuarine Research Reserve. Task 3.6.3 – final report and map. Available from https://rookerybay.org/wp-content/uploads/7-Benthic.habitat.map_.Task3_.6.3FinalReport.pdf.
Schmid JR, Worley K, Addison DS, Zimmerman AR, Van Eaton A. 2006. Naples Bay past and present: a chronology of disturbance to an estuary. Fort Myers, FL: South Florida Water Management District. Final Report to the city of Naples. Available from https://www.sfwmd.gov/sites/default/files/documents/coswf_uf%20naplesbayfinalreport_feb2006.pdf.

Sheng YP. 1987. On modeling three-dimensional estuarine and marine hydrodynamics. Nihoul JCJ, Jamart BM, editors. In: Three-dimensional models of marine and estuarine dynamics. Elsevier Oceanography Series, Elsevier. p. 35–54.

Shumway SE. 1996. Natural environmental factors. Kennedy VS, Newell RIE, Eble AF, editors. In: The eastern oyster: *Crassostrea virginica*. College Park, MD: Maryland Sea Grant College. p. 467–513.

Simpson B, Aaron R, Betz J, Hicks D, et al. 1979. The Naples Bay study. Naples, FL: The Collier County Conservancy.

Soderqvist LE, Patino E. 2010. Seasonal and spatial distribution of freshwater flow and salinity in the Ten Thousand Islands Estuary, Florida, 2007–2009. Reston, VA: U.S. Geological Survey. Data Series 501. Available from https://pubs.usgs.gov/ds/501/pdf/ds501_report.pdf.

SFWMD and USDA (South Florida Water Management District and U.S. Department of Agriculture). 2003. Southern Golden Gate Estates watershed planning assistance cooperative study. Naples, FL: South Florida Water Management District. Final Report. Available from https://www.sfwmd.gov/sites/default/files/documents/sgg_wpa_coop_stdy_oct_2003.pdf.

SWFWMD (Southwest Florida Water Management District). 2019. Seagrass in 2018. GIS, maps and survey: shapefile library. West Palm Beach, FL: Southwest Florida Water Management District. Available from https://data-swfwmd.opendata.arcgis.com/datasets/seagrass-in-2018/explore, accessed July 2021.

Taylor JL. 1974. The Charlotte Harbor estuarine system. Florida Scientist. 37:205–216.

Tolley SG, Volety AK. 2005. The role of oysters in habitat use of oyster reefs by resident fishes and decapod crustaceans. J Shell Res. 24:1007–1012.

USFWS (U.S. Fish and Wildlife Service). 2000. Ten Thousand Islands National Wildlife Refuge comprehensive conservation plan. Washington, DC: U.S. Fish and Wildlife Service. Available from https://www.fws.gov/southeast/planning/PDFdocuments/Ten%20Thousand%20Island/Ten%20Thousand%20Isl.%20CCP.PDF.

VanderKooy S, editor. 2012. The oyster fishery of the Gulf of Mexico, United States: a regional management plan – 2012 revision. Ocean Springs, MS: Gulf States Marine Fisheries Commission. Publication No. 202. Available from https://www.gsmfc.org/publications/GSMFC%20Number%20202.pdf.

Volety A, Arnold W, Barnes T, Sime P. 2008. American oysters. Doren R, editor. In: Indicators for restoration: South Florida ecosystem restoration report to the South Florida ecosystem restoration task force from the science coordination group 2006. Report to the South Florida Ecosystem Restoration Task Force from the Science Coordination Group p. 99–112.

Volety AK, Haynes L. 2012. Oyster monitoring in the Caloosahatchee River and Estuary. Florida Gulf Coast University. West Palm Beach, FL: South Florida Water Management District. Annual report 2012.

Volety AK, Haynes L, Goodman P, Gorman P. 2014. Ecological condition and value of oyster reefs of the southwest Florida shelf ecosystem. Ecol Indic. 44:108–119.

Volety A, Savarese M. 2004. GIS oyster reef mapping in the Caloosahatchee River and Estero Bay. West Palm Beach, FL: South Florida Water Management District. Technical report.

Volety AK, Savarese M, Hoye B, Loh AN. 2009a. Landscape pattern: present and past distribution of oysters in South Florida coastal complex (Whitewater Bay/Oyster Bay/Shark to Robert's Rivers). Florida Gulf Coast University. West Palm Beach, FL: South Florida Water Management District. Available from https://www.researchgate.net/publication/234025368_Landscape_Pattern_Present_and_Past_Distribution_of_Oysters_in_South_Florida_Coastal_Complex_Whitewater_BayOyster_BayShark_to_Robert's_Rivers, accessed April 2017.

Volety AK, Savarese M, Tolley SG, Arnold WS, et al. 2009b. Eastern oysters (*Crassostrea virginica*) as an indicator for restoration of Everglades ecosystems. Ecol Indic. 9:S120–S136.

Volety AK, Tolley SG, Winstead J. 2003. Investigations into effects of seasonal and water quality parameters on oysters (*Crassostrea virginica*) and associated fish populations in the Caloosahatchee Estuary. West Palm Beach, FL: South Florida Water Management District. Interpretive report (Award #C 12412-A 1).

Woithe DC Inc., Brandt-Williams S. 2006. Naples Bay surface water improvement & management plan reconnaissance report. West Palm Beach, FL: South Florida Water Management District. Available from https://www.sfwmd.gov/sites/default/files/documents/naplesbayreconfinal_2006.pdf.

zu Ermgassen P, Hancock B, DeAngelis B, Greene J, et al. 2017. Setting objectives for oyster habitat restoration using ecosystem services: a manager's guide. Updated version May 2017. Arlington VA: The Nature Conservancy. Available from https://www.conservationgateway.org/ConservationPractices/Marine/Area-basedManagement/mow/mow-library/Documents/OysterHabitatRestoration_ManagersGuide.pdf.

General references and additional regional information

Charlotte Harbor Water Atlas
http://www.chnep.wateratlas.usf.edu/
Coastal & Heartland National Estuary Program
http://www.chnep.org/
Conservancy of Southwest Florida
http://www.conservancy.org/
Comprehensive Everglades Restoration Program
http://evergladesrestoration.gov/
Everglades National Park
http://www.nps.gov/ever/index.htm
Florida Coastal Everglades Long Term Ecological Research, http://fcelter.fiu.edu/
Southwest Florida Regional Planning Council
http://www.swfrpc.org/
South Florida coastal salinity status
http://publicfiles.dep.state.fl.us/owp/SalinityReports/SalinityUpdate.html
South Florida Water Management District
http://www.sfwmd.gov/
Southwest Florida Water Management District
http://www.swfwmd.state.fl.us/

Regional contacts

Eric Milbrandt, Marine Laboratory, Sanibel-Captiva Conservation Foundation, emilbran@sccf.org

Thomas Ries, ESA, tries@esassoc.com

Phyllis Klarmann, South Florida Water Management District, Restoration Coordination Verification (RECOVER), pklarman@sfwmd.gov

Nicole Iadevaia, Coastal & Heartland National Estuary Partnership (CHNEP), niadevaia@chnep.org