Management Plan for the American Eel *Anguilla rostrata* on Bermuda

Government of Bermuda
Ministry of Home Affairs
Department of Environment and Natural Resources

Management Plan for the American Eel *Anguilla rostrata* on Bermuda

Prepared in Accordance with the Bermuda Protected Species Act 2003

Author

This plan was prepared by:
Mark Outerbridge Ph.D.
Senior Biodiversity Officer

Department of Environment and Natural Resources
Ecology Section
17 North Shore Road, Hamilton FL 04
Bermuda

Contact email: environment@gov.bm

Cover photo: Mature *Anguilla rostrata* in Bartram's Pond
Photo credit: Philippe Rouja

The aerial photographs in the appendix came from the Bermuda Planning Map Viewer
https://bdagov.maps.arcgis.com/apps/webappviewer/index.html?id=bc5f33868b724838a4e9c875c24d836f

Maps were created by Mark Outerbridge

Published by

Government of Bermuda
Ministry of Home Affairs
Department of Environment and Natural Resources

"To conserve and restore Bermuda's natural heritage"

CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

These plans delineate reasonable actions that are believed to be required to manage/recover and/or protect listed species. We, the Department of Environment and Natural Resources, publish plans, sometimes preparing them with the assistance of field scientists, other government departments, and other affected and interested parties, acting as independent advisors to us. Plans are submitted to additional peer review before they are adopted by us. Objectives of any plan will be attained and necessary funds made available subject to budgetary and other constraints affecting the parties involved. Plans may not represent the views nor the official positions or approval of any individuals or agencies involved in the plan formulation, other than our own. They represent our official position only after they have been signed by the Director of Environment and Natural Resources as approved. Approved plans are subject to modifications as dictated by new findings, changes in species status, and the completion of stated actions.

Literature citation of this document should read as follows: Outerbridge, M.E. 2022. Management Plan for the American Eel *Anguilla rostrata* on Bermuda. Department of Environment and Natural Resources, Government of Bermuda. 39 pages.

An electronic version of this recovery plan will also be made available at
www.environment.bm

Andrew Pettit

February 8, 2022

Andrew Pettit
Director
Department of Environment and Natural Resources
Bermuda Government

Date

EXECUTIVE SUMMARY

Current Species Status:

This management plan addresses the need for actions to conserve the American eel *Auguilla rostrata* on Bermuda.

Habitat Requirements and Threats:

American eels are highly adaptable and capable of living in waters that have wide ranges in temperature and salinity. In Bermuda, they have been recently recorded from brackish water ponds, marine cave systems, and the Pembroke Canal; however their historical distribution was much greater and included marshes in Pembroke and Devonshire as well as some mangrove swamps. It is thought that the principal factor which led to their current limited distribution is loss of habitat and fragmentation of wetlands. Pollution of these wetlands has also contributed to the decline in habitat quality. Change in local abundance over time is not known but there are many external factors which directly affect recruitment to local wetlands.

Management Objectives:

Given the vast geographic range of this species (millions of square kilometers) in comparison to the diminutive size of Bermuda (54 km^2), local actions are unlikely to make a significant contribution to the overall recovery of the species. Therefore, the main goal of this plan is to maximize survival while the species resides within Bermuda's wetlands. This can be accomplished by ensuring that there is a thorough understanding of which wetlands are capable of supporting American eels, the present distribution of the species , monitoring the resident sub-population for changes in distribution and abundance, restoring the wetland habitats they inhabit, and facilitating international research on the epi-pelagic stages of life. However, as there is evidence that both *A. rostrata* and the conspecific *A. anguilla* reproduce in the Sargasso Sea, the likely presence of breeding adults and leptocephali in the offshore waters of Bermuda's Exclusive Economic Zone (EEZ) should be taken into account when evaluating proposals for activities in EEZ waters.

Management Criteria:

More favourable conservation status for Bermuda's sub-population of American eels will be achieved when:

- There is evidence of an increasing or stable sub-population,
- Both the quality and quantity of Bermuda's wetland habitats are enhanced,
- Critical habitats are identified and protected,
- Threats have been identified and adequately addressed.
- The public is better informed about the local sub-population of American eels, where they live, and the threats they face.

Actions Needed:

1. Support scientific investigations of the biology and ecology of larval and benthic life stages.
2. Undertake population assessments in wetlands where eels are found in order to understand current distribution, abundance and demographic characteristics.
3. Survey the biotic and physical characteristics of Bermuda's wetlands to determine the quality and quantity of available habitat suitable for American eel survival.
4. Remediate wetland habitats where eels are found.
5. Designate suitable wetland(s) as 'Critical Habitat' for American eels as described under the Protected Species Act (2003).
6. Include conservation of eels during all life history stages when conducting the Marine Spatial Planning process and Environmental Impact Assessments.
7. Raise community awareness about American eels and their protected status.

Management Costs:

The total cost of management actions cannot be defined at this point. Funding needs to be secured through Non-Governmental Organizations (NGO's) overseas agencies and other interested parties for implementing the necessary research and monitoring studies. Developing budgets for each action are the responsibility of the leading party as outlined in the work plan.

Date of Management:

Meeting these management objectives is largely dependent on the availability of suitable habitat; however down listing can only be considered when the species has shown signs of recovery throughout its geographical range, which is likely to take many eel generations. Generation length ranges from four years (in the Caribbean) to more than 20 years (within the St. Lawrence River system), thus recovery of the American eel will be a long-term prospect.

PART I: INTRODUCTION

A. Brief Overview

There are at least 16 species of eels within the genus *Anguilla*, distributed throughout the tropical and temperate waters of the world, except for the eastern Pacific and the south Atlantic (Silfvergrip, 2009). Colloquially called 'freshwater eels', this group is in fact catadromous, meaning they typically spend the majority of their lives in fresh (and brackish) water but migrate to the ocean in order to spawn.

The American eel *Anguilla rostrata* is native to the western North Atlantic Ocean coastline, from Venezuela to Greenland, and throughout the Caribbean. It is the only species of eel to inhabit freshwater environments in North America. The species undergoes several morphological changes from egg to adult and faces a variety of threats, including habitat loss, environmental degradation, barriers to migration, fisheries exploitation, and changing oceanic conditions.

On Bermuda, American eels are found in their larval form (leptocephali) in the open ocean, while the juvenile and adult forms are found within various ponds, marine cave systems, marshes, and mangrove swamps. The reported sizes ranged from ca. 100-797 mm total length. This species appears to have had a wider historical distribution and greater abundance within Bermuda's wetlands, however there is a dearth of information about modern local abundance, population biology characteristics, and local threats.

Part I of this management plan summarizes current knowledge about the taxonomy, distribution, habitat requirements, biology and threats towards Bermuda's sub-population of American eels. Part II describes the proposed management objectives and provides a step-down narrative of the work plan actions. Part III presents a summary table which lists the priority tasks required to meet the management objectives.

B. Taxonomy and Description of Species

Two species of Anguillid eels inhabit the North Atlantic Ocean; the American eel *Anguilla rostrata* is found within the continental waters on the western side of the Atlantic Ocean, while the European eel *Anguilla anguilla* is found in continental waters on the eastern side of the Atlantic. Both species spawn within the Sargasso Sea**.**

Class: Actinopterygii
Order: Anguilliformes
Family: Anguillidae
Genus: *Anguilla*
Species: *rostrata*
Common name: American eel, freshwater eel, marsh eel (BDA)

American eels have an elongated, snake-like body with a broad, depressed snout (Fig. 1). The lower jaw extends beyond the upper jaw, and their eyes are placed well forward on the head (Fig. 2). The teeth are small and arranged in several rows on the jaws and palate. A tongue is present, and the lips are thick. One long dorsal fin originates far behind the pectoral fins and is continuous with the rounded caudal and anal fins. The pelvic fins are completely absent. One small gill slit is present in front of each pectoral fin. Scales are cycloid and embedded, and difficult to see with the naked eye. The lateral line is well developed and prominent. Body colouration varies depending on maturity level; the larval stage is transparent and leaf shaped with a prominent black eye; glass eels are also largely transparent, but have the typical serpentine shape; elvers typically exhibit dark coloration from grayish green to brown; yellow eels vary in colour from yellow to olive-brown; silver eels have prominent black eyes and are dark brown to gray with a metallic sheen on their dorsal side and silver to white on their ventral side. During the spawning migration, coloration may transition from bronze to silver. As individuals mature, the eye develops a gold tinge known as 'retinal gold'.

Figure 1. Mature *Anguilla rostrata* from Bartram's Pond.
Photo credit: Philippe Rouja

Figure 2. Mature *Anguilla rostrata* showing signs of advanced maturation.
Photo credit: Philippe Rouja

C. Current Status

Global Distribution

Eels in the continental phase of the life cycle (i.e. elvers, yellow eels and silver eels) inhabit rivers, lakes, coastal lagoons and tidal marshes along the Atlantic coast from Greenland and Iceland to Venezuela, including the Caribbean (Gollock et al., 2018). Spawning adults, leptocephali and glass eels are found in the open ocean of the western North Atlantic.

Local Distribution

American eels have been recorded from various in-land ponds, marshes, drainage ditches, canals, mangrove swamps, and marine cave systems in the central and eastern parishes of Bermuda (Fig. 3). Table 1 provides a summary of all reported captures of American eels from Bermuda between 1903 and 2013. The appendix contains more detailed descriptions of these wetlands. It is curious to note that there are no records of American eels being encountered within the wetlands of the western parishes (i.e. between Sandy's and Warwick); however this may be an artifact of sampling effort or because of differences in the limestone substrata restricting eel access.

Historical records described this species as commonly found in the ditches and dykes of Pembroke Marsh (Jones, 1859) and various un-named salt marshes (Goode, 1876). Barbour (1905) collected small specimens from mud-holes in the mangrove swamp at Hungry Bay and reported American eels as being common in the ditches of Devonshire Marsh. Beebe and Tee-Van (1933) listed them as inhabitants of Bermuda's brackish ponds. Boëtius and Boëtius (1967) captured 83 specimens from within the Pembroke Canal over a 25 day period. Catch per unit effort was reported to be 0.11 eels trap-day^{-1} and of the 80 eels which were examined, all proved to be *Anguilla rostrata*. Sizes ranged from 178 mm to 576 mm total length (TL) and the authors reported that the majority of eels they encountered (96%) were female. The discovery of a relatively large eel (568 mm TL) on a flooded parking lot situated adjacent to the Pembroke Canal during the summer of 2013 (M. Thompson, pers. comm.) serves to demonstrate that specimens can still be encountered within the canal.

Staff from the Department of Conservation Services observed 'two large eels and one smaller eel' in Bartram's Pond on 29 August 2011 (P. Rouja, pers. comm.) Photographs of one of the large eels were taken (see Figs. 1 and 2). Additionally, in November 2012 a dead eel was encountered on a grass field within Clearwater Middle School in St. David's. It is unclear where that specimen originated because there are no ponds, marshes, mangrove swamps, or known cave systems in the immediate area.

Table 1. Summary of reported *Anguilla rostrata* captures from Bermuda.

Collection date	No. collected	Size (mm TL)	Location	Source
April-July 1903	7	<100	Hungry Bay mangrove swamp (in mud-holes)	Barbour, 1905
10 Oct 1905	1	660	'The Lane' Hamilton	Smith-Vaniz et al., 1999
16 Oct 1905	1	497	East Paget Pond	Smith-Vaniz et al., 1999
19 Oct 1905	1	797	'The Lane' Hamilton	Smith-Vaniz et al., 1999
19 Oct 1905	1	540	'The Lane' Hamilton	Smith-Vaniz et al., 1999
20 Oct 1905	1	598	East Paget Pond	Smith-Vaniz et al., 1999
1933	6	305-356	Mangrove swamp at Spanish Point	Beebe, 1934
March 1966	2	213 & 430	Canal between Pitt's Bay Road and Mill's Creek	Boëtius and Boëtius, 1967
March 1966	16	178-480	Canal near (Belco) power station	Boëtius and Boëtius, 1967
March 1966	7	212-528	Canal near City Hall	Boëtius and Boëtius, 1967
March 1966	14	241-539	Ditch along Woodlands Road	Boëtius and Boëtius, 1967
March 1966	39	188-576	Canal in Pembroke Marsh near the garbage dump	Boëtius and Boëtius, 1967
17 Feb 1970	1	456	Westmeath brackish well (Pembroke)	BAMZ Collection (1990-083-033)
28 Dec 1973	1	153	Ditch in Pembroke Marsh	BAMZ Collection (1990-083-032)
15 Oct 1982	1	264	Sibley's Cave	Smith-Vaniz et al., 1999
12 June 1982	2	203 & 212	Fern Sink cave pool	Smith-Vaniz et al., 1999
9 June 2004	1	265	Bernard's Park canal	BAMZ Collection (2004-219-019)
11 Nov 2012	1	535	Clearwater school playground	BAMZ Collection (2015-291-010)
9 Aug 2013	1	568	Flooded parking lot on Belco property	BAMZ Collection (2015-291-011)

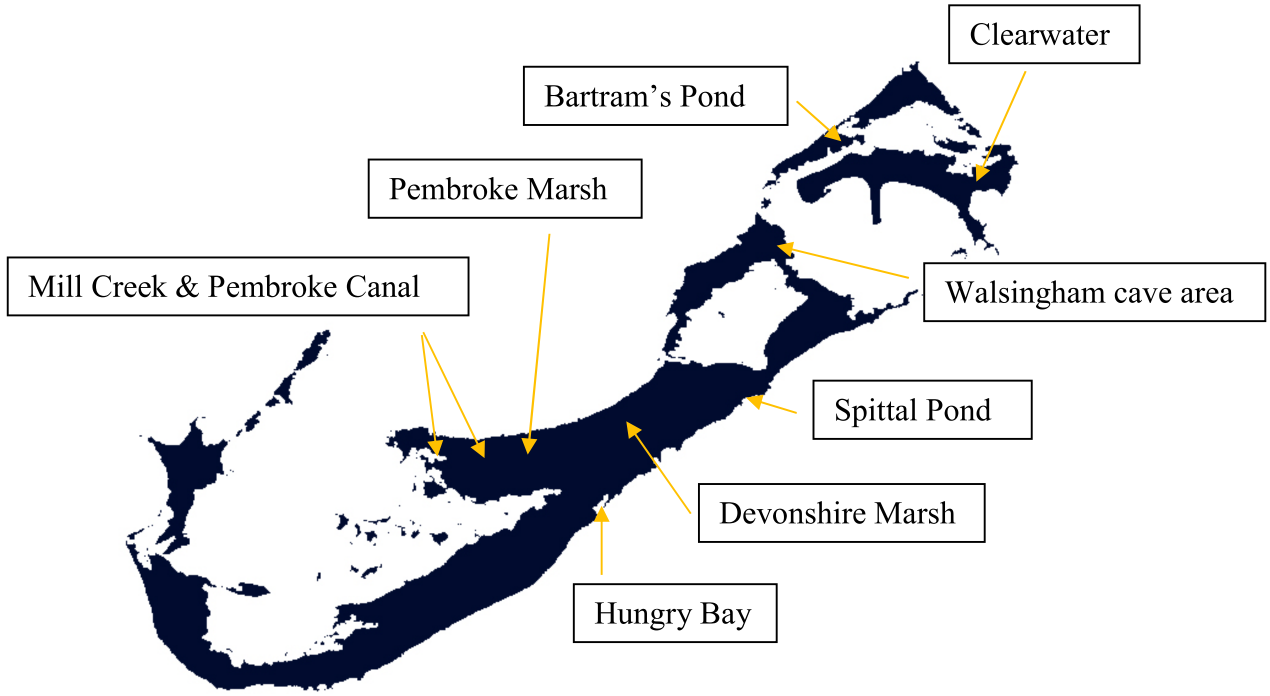

Figure 3. Map showing the locations of confirmed American eel encounters on Bermuda between 1903 and 2013.

Species Protection

No comprehensive population estimates exist for this species within the native range but in 2015 the U.S. Fish and Wildlife Service performed a species status review and concluded that *A. rostrata* was not in danger of extinction or likely to become endangered within the near future and was therefore not a candidate for listing under the U.S.A. Endangered Species Act (see www.regulations.gov Docket Number FWS-HQ-ES-2015-0143). *Anguilla rostrata* is, however, listed as 'Endangered' on the Red List published by the International Union for the Conservation of Nature (with a decreasing population trend), but the international trade of the species is not currently regulated by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). On Bermuda the American eel is classified as 'Vulnerable', following IUCN criteria, under the Protected Species Act (2003). This Act considers it an offence to willfully destroy, damage, remove or obstruct eel habitat, as well as the taking, importing, exporting, selling, purchasing, or transporting of American eels (or any other listed protected species). Offenders are liable to a fine of up to $15,000 or one year imprisonment.

Habitat Protection

Some of the areas inhabited by American eels occur in nature reserves (e.g. Spittal Pond, Bartram's Pond, Hungry Bay, Walsingham). Ponds (and the fish within them) located on lands owned by the Bermuda National Trust are provided protection through the Bermuda National Trust (Open Spaces and Property) Regulations (1975). Pembroke Marsh East is a mixture of Nature Reserve (pond and surrounding grass-dominated marsh), Open Space Reserve (Horticultural Waste Facility) and Recreation. The pond and its associated marsh have been designated as a Ramsar site which means that it is recognized as a wetland of international importance. Spittal Pond and Hungry Bay are also Ramsar sites. The Ramsar Convention is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

D. Ecology

Habitat Requirements

The American eel has a complex life cycle, spanning oceanic, nearshore coastal, estuarine and freshwater environments. During the continental phase, eels occupy all salinity zones, including shallow and sheltered marine waters, estuaries, and freshwater rivers and lakes. Some eels remain in a particular salinity zone during this phase, while others transition back and forth between fresh and marine waters. They are also capable of leaving the water for short periods and crawling across moss, damp grass, wet rocks and cement (MacGregor et al. 2010). Pratt el al. (2014) provides an excellent summary of American eel habitat requirements at each life stage.

Yellow eels (the life stage most represented on Bermuda) are primarily benthic, and use substrate (rock, sand, mud), and bottom debris such as woody debris and submerged vegetation for protection and cover. They appear to be habitat generalists, with little consistent preference for habitat type, cover, substrate, or water temperature (Wiley et al. 2004). Eels can readily burrow in mud (Tomie, 2012) and it has been suggested that eels <350 mm TL may live furtively in vegetated areas to reduce the risk of cannibalism from larger conspecifics.

The distribution of American eels within wetlands may be limited by the levels of dissolved oxygen (Rulifson et al. 2004; Greene et al. 2009). In the U.S.A, abundant catches of eels occurred in waters with dissolved oxygen levels above 4 mg/L (Rulifson et al., 2004) while Geer (2003) reported < 2% of eel captures at sites with dissolved oxygen levels < 4 mg/L.

Natural ponds on Bermuda vary both in size and in structure. Nearly all of the saline ponds date back in formation to the Holocene era (approximately 10,000 years ago.) The primary factor influencing salinity is the size and location of the underground connections each pond has with the ocean. Pond size and the nature of these connections influence the hydrographic characteristics of each pond. The sporadic addition of freshwater into these ponds from rainfall also influences salinity. Bermuda's marine ponds generally have a rich biota. Species richness increases with increasing physical stability and diversity of habitat, thus ponds having submerged rock substrata and an abundant submerged mangrove root community along the periphery of the pond show greater diversity than ponds that feature sedimentary substrata only (Thomas et al., 1992). The most important factor influencing physical stability is the amount of tidal exchange (Thomas et al., 1992). Temperature and salinity are dependent upon the amount of seawater that enters from the ocean, thus ponds close to the sea with relatively large connections have a higher flushing rate, narrower ranges of salinity and temperature and therefore provide a more stable environment than do ponds located further from the sea. The mean ocean tidal range in Bermuda is only 75 cm, but is greatly reduced in the salt water ponds where there are more restrictions to tidal flow. Salinity stratification can occur in poorly mixed ponds or where the connection to the sea is in the deepest part, although this phenomenon is unlikely to occur in very shallow ponds. Due to their small physical size and accumulated sediments, Bermuda's landlocked saline ponds are usually quite shallow, averaging depths of only 1.8 m. Thomas et al., (1991) and Thomas and Wassmann (1992) describe the physical characteristics of the six largest saline ponds on Bermuda (Mangrove Lake, Spittal Pond, Trott's Pond, Walsingham Pond, Evan's Pond, and Lover's Lake). Most possess a single connection to the ocean. Surface salinities ranged from 6.5 to 42.5 practical salinity units (psu) and temperatures varied from 15 to 37.5 ^{0}C.

All relatively large freshwater, brackish water, and marine ponds have been listed in Table 2 of the appendix. Where known, the characteristics thought to influence eel survival were collated. The data came from a variety of sources; temperature, salinity, and dissolved oxygen were reported by Thomas et al. (1991) and from unpublished data. The pollution data was collected by the Bermuda Amphibian Project between 1997 and 2019. Pond areas were calculated in ArcGIS 9.0 using a 2012 digitized aerial orthophotograph of Bermuda.

General Biology

American eels are catadromous; adults spawn and the eggs hatch in salt water, but individuals spend the majority of their lives inhabiting fresh and brackish water environments. They transition through five different life stages (see Fig. 4) before participating in a single spawning event and then dying. American eels from across their geographic range comprise one breeding population (Gagnaire et al. 2012). The species is sexually dimorphic in growth, maturation, and distribution, with females growing larger than males, maturing later than males, and residing in more northerly latitudes. Maturity is size-dependent rather than age-dependent and the generation time (i.e. average age of parents within a population) for eels residing in fresh water can be as long as 22 years, but is considerably shorter in eels that permanently reside in salt water (approx. 9 years).

Reproduction

Adult eels begin maturation of their reproductive organs during migration to their spawning grounds in the Atlantic Ocean. The precise spawning location is unknown but has been inferred from the smallest leptocephali captured at sea; somewhere in the southern region of the Sargasso Sea within the frontal area of the Subtropical Convergence Zone (see Miller and Hanel, 2011). Spawning is thought to take place from December to April (Pratt et al., 2014; Westerberg et al., 2018) during which individuals mate randomly in a single breeding population. Eggs are released into the ocean and fertilized externally by males in the pelagic environment. Embryonic development occurs rapidly and the eggs can hatch within as short a period as 48 hours when the ambient water temperature is 18-19°C (Oliveira and Hable, 2010). Oceanic currents disperse the young eels widely.

Diet

Food items vary with body size and environment but elvers and yellow eels typically consume insects and insect larvae, worms, molluscs, bivalves, crustaceans, small fishes and small frogs. On Bermuda, Boëtius and Boëtius (1967) reported that eels captured from the Pembroke Marsh canal preyed upon killifish *Fundulus bermudae*, insects (pupae of midges), aquatic snails from the genus *Physa*, and amphipods. American eels have also been reported to consume the young of waterfowl because Jones (1859) mentioned that they were 'very destructive to young ducklings'.

Life Cycle

The life cycle of the American eel (Fig. 4) can be divided into five main stages:

1. Eggs hatch into transparent, leaf-shaped larvae called leptocephali which are carried by ocean currents over a 7-12 month period.
2. Metamorphosis to glass eels (clear juveniles) is thought to occur at sea, usually when individuals attain a total length of 55-65 mm. After reaching the North American continental shelf, the glass eels move into coastal environments.
3. Growth continues and the glass eels turn into pigmented juveniles known as elvers, transitioning from brackish to freshwater habitats.
4. Within 12 to 14 months the elvers acquire a dark color with an underlying yellow hue. These yellow eels continue inhabiting freshwater habitats. Many migrate upriver into freshwater rivers, streams, lakes, and ponds, while others remain in estuarine environments. Eels can spend between three to 30 years in this stage of life.
5. Yellow eels transform into silver eels before migrating from continental freshwater environments to the open ocean in order to reproduce. Transformation includes a darkening of color, fattening of the body, skin thickening, enlarged eyes, and degeneration of the digestive tract.

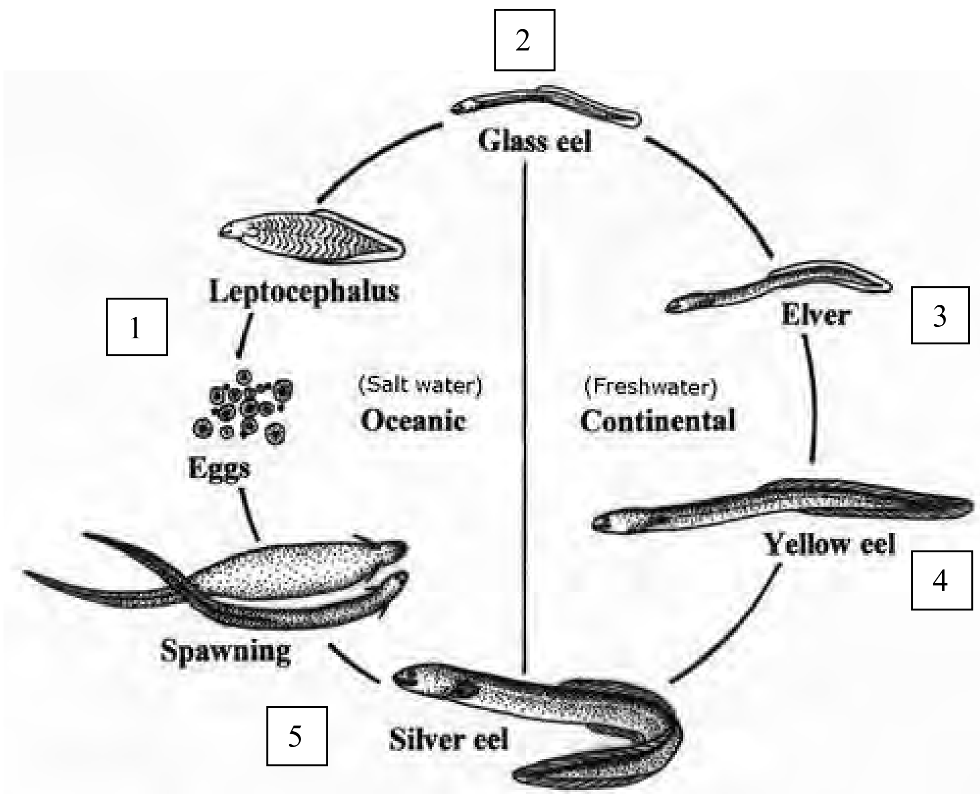

Figure 4. Life cycle of the American eel
Illustration from ICES, 2010

E. Current Threats

Global

American eels face a wide variety of threats during all phases of their life cycle:

1. Global climate change is likely to alter some of the physical and biological characteristics in the Sargasso Sea and also change oceanic current patterns which could interfere with the transport and survival of eel leptocephali. Starvation and unfavourable transport patterns that extend the duration of the pelagic phase are both highly likely to result in reduced recruitment to the North American continent.
2. Juvenile eels are commercially harvested after reaching the North American continental shelf and exported to eel farming countries in East Asia where they are grown under controlled conditions to harvest-size. Demand for the export of American glass eels and elvers to East Asian markets has increased since the export ban on European eels was imposed in 2010 (Gollock et al., 2018).
3. The construction of dams and locks throughout the eastern half of the North American continent has prevented American eels from reaching upstream areas in many river systems thereby greatly reducing their historical range, and hydro-electric power stations produce turbine mortality for downstream migrants.
4. Contaminants from urban waste water sources as well as industrial and agricultural effluents may negatively impact eels by reducing survival and impairing reproduction (see review in COSEWIC, 2012). Eels inhabiting polluted waters are heavy bio-accumulators because they are a long-lived benthic species with a high body fat content that accumulates lipophilic contaminants such as polychlorinated biphenyls (PCBs), trace metals, polycyclic aromatic hydrocarbons (PAHs), and dioxins.
5. The swim bladder nematode *Anguillicola crassus* spread from Asia into Europe during the 1980s and then into North America by 1995. Heavy parasitic infections can lead to hemorrhagic lesions, swim bladder fibrosis, skin ulceration, decreased appetite, and reduced swimming performance which affects migration capacity (Barse and Secor, 1999).
6. Migrating adults are subject to predation from large pelagic fishes such as porbeagle sharks *Lamnus nasus* and Atlantic bluefin tuna *Thunnus thynnus* (Béguer-Pon et al., 2015).

Local

Bermudians were not known to catch and eat American eels, at least during the first half of the 19th century (Jones, 1859) and there is no written evidence which suggests that they have been consumed since then either. However, this species is thought to be locally affected by habitat degradation associated with habitat loss and water pollution. Many wetlands across Bermuda have been greatly reduced in area as a consequence of development and land reclamation. Since Bermuda's permanent settlement from 1612, humans have filled, drained, denuded, and polluted the mangrove swamps, ponds, and inland marshes in an effort to create more arable land or residential and commercial building sites and to eliminate mosquitos, while also disposing of unwanted waste material. Records indicate that at the beginning of the 20th century approximately 169.2 ha, or roughly 3% of Bermuda's total land area, comprised wetlands which included 20.4 ha of mangrove swamp, 29.6 ha of ponds and 119.2 ha of inland marsh. By 1980, these wetland areas had been reduced to an estimated 94.3 ha (16.7 ha of mangrove swamp, 29.2 ha of ponds, and 48.4 ha of inland marsh), representing a decrease of 44.5% (Sterrer and Wingate, 1981) and contributing to major losses of biodiversity in those areas (Sterrer et al., 2004). The entire Pembroke Marsh complex (i.e. both west and east basins) historically extended some 2.3 km inland from Mill Creek, prior to the extensive reclamation activities which took place during the 1920s. It transitioned from a mangrove swamp to a tidal salt marsh and finally to a network of freshwater marshes at the eastern most end. These wetlands covered approximately 120 acres and represented over one third of the total marshland area on Bermuda (Wingate, 1986a). Frequent flooding and persistent mosquitos, which were historically major vectors of human disease, prompted the government to initiate marsh reclamation using landfill. By the end of the 1940s, almost the entire west basin had been reclaimed. The east basin was used for the disposal of municipal waste during the 1930's and its use accelerated in the 1960's when all of Bermuda's garbage (more than 100 tons a day) was channeled into this site at Marsh Folly. By 1985 the Marsh Folly dump had grown to a huge mound filling the entire eastern end of the marsh basin (Wingate, 1986b). Garbage disposal in this area ceased in 1994 when the Bermuda Government began using a mass burn waste-to-energy incinerator. What remains of the former Pembroke Marsh East Basin is a 19.5 acre Government-owned Nature Reserve, of which approximately 13% comprises open water within a predominantly cattail *Typha augustifolia* and sawgrass *Cladium mariscus jamaicense* marshland.

Although not industrialised, Bermuda is characterised by high levels of localised anthropogenic pollution (Jones, 2011). Recent investigations of the health status of the pond environment on Bermuda suggest there is a suite of contaminants of concern that are having detrimental effects on the resident fauna. Tissue residue analyses from a range of taxa, including cane toads *Rhinella marinus*, mosquitofish *Gambusia holbrooki*, killifish *Fundulus* spp., and red-eared sliders *Trachemys scripta elegans* collected from a variety of contaminated wetlands across Bermuda have shown that petroleum hydrocarbons, polycyclic aromatic hydrocarbons and trace metals are being accumulated and induce developmental malformations, endocrine disruption, liver and gonad abnormalities plus immunological stress (Fort et al., 2006; Fort et al., 2006; Bacon, 2010; Bacon et al., 2012). Entry of contaminants into the wetlands comes through storm-water run-off from adjacent roadways, aerial deposition, and leachate from nearby landfills, septic tanks, and bore holes (Fort et al., 2006). Hydrogeological studies of Pembroke Marsh have indicated that the peat layer beneath it acts as an impermeable seal between the historical municipal dump and the surrounding bedrock, thus polluted leachate tends to drain into the surface water of Pembroke Pond and out to sea via Pembroke Canal (Wingate 1986b). Thomas (1996) reported very high levels of faecal coliform bacteria throughout the canal and visible oil pollution between Cemetery Road and Mill Creek. Furthermore, significant portions of the canal (particularly the western half) presently pass through industrial areas and analyses of canal water and sediment have shown the presence of a variety of chemicals resulting from contamination (Anon, 1987; Anon, 1991; Cooke, 1995; Simmons, 1996; Doughty, 2011).

F. Current Conservation Actions

Global

Much of the conservation and management initiatives over the past two decades have focused on fisheries and barriers to migration. In the U.S.A., the species is managed by the Atlantic States Marine Fisheries Commission which has harvest quotas for yellow eels. Glass eel fisheries are prohibited in all states except Maine and South Carolina (where they are subjected to harvest quotas). Increasing access to historical habitats via dam removal and the installation of eel ladders along the U.S. portion of the species range is now a common restoration strategy. Protection of downstream silver eel migrants through hydroelectric facilities can also be achieved by shutting down turbines at night (Eyler et al., 2016). The Recovery Strategy in Ontario, Canada, emphasizes restoring, protecting, and diversifying suitable habitats, enhancing recruitment, and reducing other anthropogenic sources of stress (MacGregor et al., 2013). There are few known management measures in place in the southern part of the species range, and what exists appears to be fisheries related in nature.

<u>Local</u>

There are no direct conservation actions for this species on Bermuda at present; however wetland restoration efforts over the past 60 years have increased the acreage of open fresh/brackish water habitat so that the total area is now higher than at any time since the start of the 20th century. New ponds are still occasionally created in nature reserves which give American eels the opportunity to inhabit them after recruiting to Bermuda. Additionally, in 2014, a collaborative study involving the Bermuda Zoological Society, Fort Environmental Laboratories and the Bermuda Government was initiated to apply simple remediation techniques (e.g. aeration) to a select number of ponds over a 12 month period. Significant decreases in the total levels of detectable polycyclic aromatic hydrocarbons within the benthic sediment were observed (J. Bacon, pers. comm.). This project is still ongoing at the time of writing.

PART II: MANAGEMENT

A. Management Goal

The principal aim of this plan is to address knowledge gaps and enable more effective conservation and management of American eels within Bermuda's waters. This can primarily be achieved by understanding which wetlands are capable of supporting American eels and what the species' present distribution is, monitoring the resident sub-population for changes in distribution and abundance, restoring the wetland habitats they inhabit to maximize species survival, and facilitating international research on the epi-pelagic stages of life.

<u>Short-term goals (5 years):</u> To ensure that all habitat related studies are completed, that the population assessment surveys have been undertaken to establish a baseline on modern distribution and demographic characteristics, designate suitable wetlands as "Critical Habitat" under the Protected Species Act (2003), and include eel conservation in all environmental impact assessments on wetland habitats and any future offshore marine spatial planning processes.

<u>Long-term goals (30 years):</u> The restoration of Bermuda's wetlands currently and historically used by eels, including the remediation of existing ponds and excavation to create new ponds. It is hoped that this will lead to an increase in both area of occupancy and local abundance.

B. Management Objective and Criteria

More favourable conservation status for Bermuda's sub-population of American eels will be achieved when:

- There is evidence of an increasing or stable sub-population,
- Both the quality and quantity of Bermuda's wetland habitats are enhanced,
- Critical habitats are identified and protected,
- Threats have been identified and adequately addressed.
- The public is better informed about the local sub-population of American eels, where they live, and the threats they face.

These overall objectives translate into specific actions outlined below:

1. Support scientific investigations of the biology and ecology of larval and benthic life stages.
2. Undertake population assessments in wetlands where eels are found in order to understand current distribution, abundance and demographic characteristics.
3. Survey the biotic and physical characteristics of Bermuda's wetlands to determine the quality and quantity of available habitat suitable for American eel survival.

4. Remediate wetland habitats where eels are found.
5. Designate suitable wetland(s) as 'Critical Habitat' for American eels as described under the Protected Species Act (2003).
6. Include conservation of eels during all life history stages when conducting the Marine Spatial Planning process and Environmental Impact Assessments.
7. Raise community awareness about American eels and their protected status.

C. Management Strategy

The oceanic life stages of both the silver eels and the leptocephali are difficult to study, thus regional plans tend to focus on improving conditions for American eels within coastal and interior wetlands. However, protection of their only spawning area is vitally important to the species. Numerous deleterious human activities occur within the Sargasso Sea (see review in Laffoley et al., 2011) but initiatives to protect and manage it, like those proposed by the Sargasso Sea Alliance, will have tremendous benefits to the species found within it – including the American eel. The Bermuda Government's Department of Environment and Natural Resources is one of the Alliance's partner agencies and it also plays a role in facilitating international research within Bermuda's territorial waters. More should be done to encourage and promote research into factors that affect eel survival in the pelagic environment, particularly with regards to spawning, larval development, and larval movement.

Negative impacts to Anguillid eels should also be included in Bermuda's offshore marine spatial planning process (a public procedure that organizes human activity in marine areas to meet environmental, economic, and social objectives). The Bermuda Ocean Prosperity Programme (BOPP) is one such way of achieving this. Furthermore, eel conservation can be included in the Environmental Impact Assessment of future proposed projects or developments to any wetland inhabited by eels (e.g. the Pembroke Canal). Such assessments should also include mitigating actions which offset potential harm caused by the proposed activity.

Assessment of the biotic (i.e. resident flora and fauna) and physical characteristics (i.e. levels of contamination and seasonal fluctuations in temperature, salinity, and dissolved oxygen) of Bermuda's wetlands is required in order to determine which are capable of supporting American eels. Wetland remediation activities may be needed to reduce the levels of contamination, especially within the benthic sediment. Priority should be given to the Pembroke Canal, given that this body of water historically contained relatively large numbers of eels.

Some of the management actions in this plan are applicable to other protected species that reside within the same wetlands (e.g. killifishes, endemic freshwater molluscs, marine cave fauna). For example, stopping or reversing the environmental damage to Bermuda's ponds will benefit a number of native and endemic species. Furthermore, undertaking biotic assessments within Pembroke Marsh and Devonshire Marsh will also help to determine if the imperiled and endemic freshwater limpet *Ferrissia bermudensis* and the freshwater pea clam *Pisidium volutabundum* are still extant.

D. Tools Available for Strategy

Presence/absence survey and population assessment
The capture of yellow eels can be accomplished using baited traps which should be monitored daily. A wide variety of traps exist, the most common being the cylindrical eel pot with funnel openings. Fresh bait, such as fish or meat, must be large enough to ensure good scent dispersion. If the captured eels need to be kept temporarily for examination they should be placed either in perforated floating boxes within the waters they are being fished from or transferred into well oxygenated holding tanks. Overcrowding should be avoided to prevent stress and injury. Estimates of abundance are calculated through capture-mark-recapture surveys. Marking eels can be accomplished using various methodologies to create identifiable features. Visible implant elastomer (VIE) has been used to mark American eels in Maine (Johnson, 2018), Passive Integrated Transponder (PIT) tags have been used with success in small American eels ranging in size from 205-370 mm total length (Zimmerman and Welsh, 2008), and coded wire tags have been successfully implanted in the dorsal musculature of very young European eels (Tomassen et al., 2000).

Wetland remediation
Some simple yet effective remediation techniques for ponds and marshes include phytoremediation, in which plants are used to extract persistent contaminants from surrounding substrate, as well as employing various chemical and biological remediation techniques. A variety of wetland plants have been shown to sequester petroleum hydrocarbons (Lin and Mendelssohn, 1998), polycyclic aromatic hydrocarbons (Lin and Mendelssohn, 2009) and trace metals (Weis and Weis, 2004) from benthic sediment and store them below ground in roots or concentrate them in aerial tissues (e.g. leaves and stems). Chemical remediation methods include reducing or eliminating inputs of contaminants from point sources, natural sediment remediation by biodegradation and chemical degradation, and active sediment remediation by removal or by in-situ treatment; biological remediation methods include enhancing populations of target organisms (see reviews in Wilcox and Whillans, 1999). Depositing clean sediment (e.g. diatomaceous earth) over contaminated sediment is yet another technique of wetland remediation that can diminish the risk of biological contact, however it should not be considered without first assessing its impact on the water column and aquatic biota of the ponds. Additionally, the creation of buffer zones (e.g. road-side reed beds) between road drains and freshwater wetlands would help to reduce direct in-put of pollutants by serving as a filter for contaminants entering as road runoff (see Revitt et al., 1997; Cooper, 1999). Introduction of oxygenated air into the organic sediment of contaminated areas promotes natural biological degradation of some contaminants (e.g. polycyclic aromatic hydrocarbons) by increasing the activity of indigenous bacteria that are capable of metabolizing pollutants (D. Fort, pers. comm.). This has been recently trialed in some of Bermuda's ponds and appears to significantly reduce the level of polycyclic aromatic hydrocarbons after one year (J. Bacon, pers. comm.).

E. Step-Down Narrative of Work Plan

Abbreviations:
DENR – Department of Environment and Natural Resources
PW – Department of Public Works
BZS – Bermuda Zoological Society
FEL – Fort Environmental Laboratories (U.S.A.)
DCI – Department of Communications and Information
Planning – Department of Planning

The actions needed are as follows:

1. Support scientific investigations of the biology and ecology of larval and benthic life stages.

   Actions proposed:
   - Promote research into factors that affect eel survival in the pelagic environment, particularly with regards to spawning, larval development, and larval movement,
   - Undertake studies to find out if additional Anguillid species are also present on Bermuda (i.e. European eel *Anguilla anguilla*).

   Work Team: DENR and collaborative institutions
   Team Leader(s): Principal investigators from the collaborative institutions
   Assistance: Students, volunteers
   Outputs: Better awareness about what is happening to the species during these particular life stages.

2. Undertake population assessments in wetlands where American eels are found in order to understand current distribution, abundance and demographic characteristics.

   Actions proposed:
   - Undertake presence/absence study across Bermuda's wetlands in order to understand current species distribution,
   - Undertake capture-mark-recapture surveys.

   Work Team: DENR
   Team Leader: DENR
   Assistance: Students, volunteers
   Outputs: Report establishing a baseline assessment of Bermuda's sub-population of American eels
   List of equipment required: Truck, row boat, eel traps, bait, life support system for eels (e.g. buckets, Scuba tank, air stones, dip nets), anesthetic, tagging materials.

3. Survey the biotic and physical characteristics of Bermuda's wetlands to determine the quality and quantity of available habitat suitable for American eel survival.

   Actions proposed:
   - Perform surveys using transect tape, quadrats, and camera/video recorder,
   - Use nets, dredges, and baited traps to collect fauna and flora,
   - Monitor temperature, salinity, and dissolved oxygen,
   - Collect sediment and water for eco-toxicological analyses.

   Work Team: DENR
   Team Leader: DENR
   Assistance: Students, volunteers
   Outputs: Report on the biotic and physical characteristics for each wetland, including toxic burden, and a prioritized list of sites identified as being suitable for eel survival
   List of equipment required: Truck, row boat, multi-parameter water quality probe (eg. Sonde or YSI meter), quadrats, transect tape, underwater camera, nets, traps, dredges, sterile bottles for sediment collection.

4. Remediate wetlands where American eels are found.

   Actions proposed:
   - Identify appropriate wetlands to remediate,
   - Identify suitable remediation methods to employ,
   - Initiate remediation activities.

   Work Team: DENR, BZS, and FEL, PW, land owners of wetlands identified for remediation
   Team Leader: DENR
   Assistance: Students, volunteers
   Outputs: Less polluted habitats

5. Designate suitable wetland(s) as 'Critical Habitat' for American eels as described under the Protected Species Act (2003).

   Actions proposed:
   - Create maps of wetland(s) showing boundaries,
   - Publish notice in the official gazette for public inspection,
   - Create new order.

   Work Team: DENR, land owners of wetland(s)
   Team Leader: DENR
   Assistance: Attorney General's Chambers
   Outputs: Amended legislation for protection of habitat

6. Include conservation of eels during all life history stages when conducting the Marine Spatial Planning process and Environmental Impact Assessments.

   Actions proposed:
   - Include specific consideration in criteria for any Marine Spatial Planning process, particularly Bermuda's offshore waters,
   - Include specific consideration in criteria for all future Environmental Impact Assessments of Bermuda's wetlands.

   Work Team: DENR, Planning, and partner agencies
   Team Leader: DENR
   Outputs: Negative impacts on eel survival are effectively mitigated.

7. Raise community awareness about American eels and their protected status.

   Actions proposed:
   - Publicize the protected status of eels,
   - Promote the appreciation of eels and their wetland habitats,
   - Create maps of wetlands where eels are found and share with neighbouring properties,
   - Encourage the public to report sightings to the Department of Environment and Natural Resources.

   Work Team: DENR, DCI
   Team Leader: DENR
   Outputs: Bermuda's public, especially the land owners of wetlands inhabited by eels and the adjacent properties, know about American eels, where they live, and the threats they face.

F. Estimated Date of Down Listing

Recovery of Bermuda's sub-population is dependent on the recovery of other regional sub-populations, which is heavily reliant on the cooperation of numerous jurisdictions across the species range. Local actions will not be enough to positively affect the status of the global population. Down listing can only be considered when the species has shown signs of recovery throughout its geographical range, which is likely to take many eel generations. Generation length ranges from four years (in the Caribbean) to more than 20 years (within the St. Lawrence River system), thus recovery of the American eel will be a long-term prospect.

PART III: IMPLEMENTATION

<u>Priority 1</u>: An action that must be taken to prevent extinction or to prevent the species from declining irreversibly.
<u>Priority 2</u>: An action that must be taken to prevent a significant decline in the species population/habitat quality, or some other significant negative impact short of extinction.
<u>Priority 3</u>: All other action necessary to provide for management of the species.

Priority #	Task #	Task description	Task Duration	Responsible Party
2		**Wetland surveys**		
	1	Assess physical characteristics	12 months	DENR
	2	Assess biotic characteristics	12 months	DENR
2		**Population assessments**		
	3	Presence/absence surveys	12 months	DENR
	4	Capture-mark-recapture surveys	12 months	DENR
2		**Remediate wetlands**		
	5	Identify appropriate wetlands	1 day	DENR
	6	Identify remediation method(s)	3 months	DENR
	7	Initiate remediation method(s)	12 months (min) per wetland	DENR
3		**Designate 'Critical Habitat'**		
	8	Create maps	1 day	DENR
	9	Gazette notice	1 month	DENR
	10	Create Order	6 months	AG Chambers
3		**Support scientific investigations**		
	11	Promote research needs	ongoing	DENR
3		**Ensure eels are included in planning processes**		
	12	Include eel conservation in the MSP	ongoing	DENR
	13	Include eel conservation in EIAs	ongoing	public
3		**Raise community awareness**		
	14	Publicize protected status	ongoing	DENR
	15	Promote appreciation of species and habitats	ongoing	DENR
	16	Create distribution maps	1 week	DENR
	17	Encourage public to report sightings	ongoing	DENR

BIBLIOGRAPHY

Anon, 1987. Report on trace organics and heavy metal pollution survey. First study. Produced by Clayton Consultants Ltd. (Birmingham, UK) for the Ministry of Works and Engineering, Bermuda Government.

Anon, 1991. Report on trace organics and heavy metal pollution survey. Second study. Produced by Clayton Consultants Ltd. (Birmingham, UK) for the Ministry of Works and Engineering, Bermuda Government.

Bacon, J.P. 2010. Progress report for the Bermuda Amphibian Project. Bermuda Zoological Society. 38 pp.

Bacon, J.P., Outerbridge, M.E., Fent, G.M., Mathias, M., Fort, C.E., Fort, H.M., and Fort, D.J. 2012. Paradise Lost? The effects of anthropogenic contaminants on wetland species in Bermuda. SETAC Europe. 23rd Annual Meeting. Glasgow, Scotland.

Bacon, J.P. Personal Communication. Principal Investigator, Bermuda Amphibian Project.

Barbour, T. 1905. Notes on Bermudan fishes. Bulletin of the Museum of Comparative Zoology 46(7):109-134.

Barse, A.M. and Secor, D.H. 1999. An exotic nematode parasite of the American eel. Fisheries 24(2):6-10.

Beebe, W. 1934. American fresh-water eels in Bermuda. Bulletin of the New York Zoological Society 37(6):181-183.

Beebe, W., and Tee-Van, J. 1933. Field book of the shore fishes of Bermuda and the West Indies. G.P. Putnam's Sons, N.Y. 337 pp.

Béguer-Pon, M., Castonguay, M., Shan, S., Benchetrit, J. and Dodson, J.J. 2015. Direct observations of American eels migrating across the continental shelf to the Sargasso Sea. Nature Communications DOI: 10.1038/ncomms9705

Boëtius, I. and Boëtius, J. 1967. Eels, *Anguilla rostrata*, LeSueur, in Bermuda. *Videnskabelige Meddelelser Fra Dansk Naturhistorisk Forening,* 130:63-84.

Cooke, J.E. 1995 Report on Pembroke Marsh and Canal sediment and water monitoring, June 1995. Produced by Clayton Consultants Ltd (Birmingham, UK) for the Ministry of Works and Engineering, Bermuda Government.

Cooper, P.F. 1999. A review of the design and performance of vertical flow and hybrid reed bed treatment systems. Water Science and Technology 40(3):1-9.

Copeland, A. Personal Communication. Biodiversity Officer. Department of Environment and Natural Resources.

COSEWIC, 2012. COSEWIC assessment and status report on the American Eel *Anguilla rostrata* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. 121 pp.

Doughty, L.A. 2011.Report on water quality in Pembroke Canal and the inner part of Mill Creek, Bermuda. BSc dissertation. Cardiff University. 130 pp.

Ellison, J.C. 1993. Mangrove retreat with rising sea-level, Bermuda. Estuarine and Coastal Shelf Science 37:75-87.

Ellison, J.C. 1996. Pollen evidence of Late Holocene mangrove development in Bermuda Global Ecology and Biogeography Letters 5(6):315-326.

Eyler, S., Welsh, S., Smith, D.R., and Rockey, M.M. 2016. Downstream passage and impact of turbine shutdowns on survival of silver American eels at five hydroelectric dams on the Shenandoah River. Transactions of the American Fisheries Society 145(5):964-976.

Fort, D. J., Rogers, R. L. and Bacon, J. P. 2006. Deformities in cane toad *Bufo marinus* populations in Bermuda: Part II. Progress towards characterization of chemical stressors. Applied Herpetology 3:143-172.

Fort, D. J., Rogers, R. L., Buzzard, B. O., Anderson, G. D. and Bacon, J. P. 2006. Deformities in cane toad *Bufo marinus* populations in Bermuda: Part III. Microcosm-based exposure pathway assessment. Applied Herpetology 3:257-277.

Fort, D.J. Personal Communication. President of Fort Environmental Laboratories Inc.

Gagnaire, P.A., Normandeau, E., Côté, C., Hansen, M.M., and Bernatchez, L. 2012. The effect of spatially varying selection on locally adaptive alleles in the panmictic American eel (*Anguilla rostrata*). Genetics 190: 725–736.

Gibbons, D.A. 2003. An environmental assessment of Bermuda's caves. MSc thesis. Texas A&M University. 150 pp.

Glasspool, A. 2014. Management plan for Bermuda's critically endangered cave fauna. Department of Conservation Services, Government of Bermuda. 38 pp.

Gollock, M., Shiraishi, H., Carrizo, S., Crook, V., and Levy, E. 2018. Status of non-CITES listed anguillid eels. Report. 176 pp.

Goode, G.B. 1876. Catalogue of the fishes of the Bermudas. Based chiefly upon the collections of the United States National Museum. Bulletin of the United States National Museum 1(5):1-82.

Greene, K.E., Zimmerman, J.L., Laney, R.W., and Thomas-Blate, J.C. 2009. Atlantic coast diadromous fish habitat: A review of utilization, threats, recommendations for conservation, and research needs. Atlantic States Marine Fisheries Commission Habitat Management Series No. 9, Washington, D.C. 465 p.

Geer, P. J. 2003. Distribution, relative abundance, and habitat use of American eel *Anguilla rostrata* in the Virginia portion of the Chesapeake Bay. American Fisheries Society Symposium 35:101-115.

ICES. 2010. International Council for the Exploration of the Sea. Report of the ICES/EIFAC Working Group on Eels. ICES CM 2010/ACOM:18.

Iliffe, T.M., Jickells, T.D., and Brewer, M. 1984. Organic pollution of an inland marine cave from Bermuda. Marine Environmental Research 12:173-189.

Johnson, C.D. 2018. Report on American eel (*Anguilla rostrata*) mark recapture study: Year 1. Maine Sea Grant Publications 134:17 pp.

Jones, J.M. 1859. The naturalist in Bermuda; a sketch of the geology, zoology, and botany of that remarkable group of islands; together with meteorological observations. London, Reeves and Turner. 200 pp.

Jones, R. J. 2011. Spatial patterns of chemical contamination (metals, PAHs, PCBs, PCDDs/PCDFS) in sediments of a non-industrialized but densely populated coral atoll/small island state (Bermuda). Marine Pollution Bulletin 62:1362-1376.

Laffoley et al., 2011. The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic Ocean. Summary science and supporting evidence case. Sargasso Sea Alliance, 44 pp.

Lin, Q. and Mendelssohn, I. A. 1998. The combined effects of phytoremediation and biostimulation in enhancing habitat restoration and oil degradation of petroleum contaminated wetlands. Ecological Engineering 10:263-274.

Lin, Q. and Mendelssohn, I. A. 2009. Potential of restoration and phytoremediation with *Juncus roemerianus* for diesel-contaminated coastal wetlands. Ecological Engineering 35:85-91.

MacGregor, R., Casselman, J., Greig, L., Allen, W.A., McDermott, L., and Haxton, T. 2010. Draft recovery strategy for the American Eel (*Anguilla rostrata*) in Ontario. Ontario Recovery Strategy Series. Prepared for Ontario Ministry of Natural Resources, Peterborough, Ontario. 78 pp.

MacGregor, R., Casselman, J., Greig, L., Dettmers, J., Allen, W.A., McDermott, L. and Haxton, T. 2013. Recovery Strategy for the American Eel (*Anguilla rostrata*) in Ontario. Ontario Recovery Strategy Series. Prepared for Ontario Ministry of Natural Resources, Peterborough, Ontario.

Miller, M.J. and R. Hanel. 2011. The Sargasso Sea Subtropical Gyre: The Spawning and Larval Development Area of both Freshwater and Marine eels. Sargasso Sea Alliance Science Report Series, No 7, 20 pp.

Oliveira, K., and Hable, W.E. 2010. Artificial maturation, fertilization, and early development of the American Eel (*Anguilla rostrata*). Canadian Journal of Zoology 88:1121–1128.

Pratt, T.C., Bradford, R.G., Cairns, D.K., Castonguay, M., Chaput, G., Clarke, K.D., and Mathers, A. 2014. Recovery Potential Assessment for the American Eel (*Anguilla rostrata*) in eastern Canada: functional description of habitat. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/132. 49 p.

Revitt, D.M., Shutes, R.B.E., Llewellyn, N.R., and Worrall, P. 1997. Experimental reed bed systems for the treatment of airport runoff. Water Science and Technology, 36(8-9):385-390.

Rouja, P.M. Personal Communication. Custodian of Historic Wrecks. Department of Environment and Natural Resources (formerly Department of Conservation Services). Government of Bermuda.

Rulifson, R.A., Cahoon, C., and Cudney, J.L. 2004. Critical habitat assessment and population demographics of the American eel fishery in Northwestern Pamlico Sound, North Carolina. Final Report for the North Carolina Sea Grant Fishery Resource Grant Program, Project No. 02-EP-13.

Scott, D.A. and Carbonell, M. 1986. A directory of neo-tropical wetlands. IUCN, Cambridge and IRWB, Slimbridge. 684 pp.

Silfvergrip, A.M.C. 2009. CITES Identification Guide to the Freshwater eels (Anguillidae)

Simmons, K. 1996. Hazardous assessment of marine contaminants June 16-July 6, 1996. Final Report. Bermuda Biological Station for Research. 75 pp.

Smith-Vaniz, W.F., Collette, B.B., and Luckhurst, B.E. 1999. Fishes of Bermuda: History, Zoogeography, Annotated Checklist, and Identification Keys. American Society of Ichthyologists and Herpetologists. Special Publication No. 4. 424 pp.

Sterrer, W.E. and Wingate, D.B., 1981. Wetlands and Marine Environments. In Bermuda's Delicate Balance. (Eds. S.J. Hayward, V.H. Gomez & W.E. Sterrer) pp. 107-112. Bermuda Biological Station for Research, Inc. Special Publication No. 20. Island Press, Hamilton, Bermuda.

Sterrer, W.E., Glasspool. A.F., De Silva, H. and Furbert, J. 2004. Bermuda and island biodiversity transported. In: Davenport, J. and Davenport, J.L. (eds.) The effects of human transport on ecosystems: cars and planes, boats and trains. Dublin. Royal Irish Academy. Pp 118-170.

Thomas, M.H.L. 1996. Report on the ecological conditions of Pembroke Canal and the inner part of Mill Creek. 40 pp.

Thomas, M.L.H., and Wassmann, P. 1992. Characteristics of Spittal Pond, a unique, polluted, marine pond in Bermuda. Caribbean Journal of Science 28:81-88.

Thomas, M.L.H., Eakins, K.E., and Logan, A. 1991. Physical characteristics of the anchialine ponds of Bermuda. Bulletin Marine Science, 48:125-136.

Thomas, M.L.H., Eakins, K.E., Logan, A. and Mathers, S.M. 1992. Biotic characteristics of the anchialine ponds of Bermuda. Bulletin Marine Science, 50(1):133-157.

Thomassen, S., Pedersen, M.I., Holdensgaard, G. 2000. Tagging the European eel *Anguilla anguilla* (L.) with coded wire tags. Aquaculture 185:57-61.

Tomie, J.P.N. 2012. The ecology and behaviour of substrate occupancy by the American Eel. M.Sc. Thesis. University of New Brunswick, Fredericton, New Brunswick.

Thompson, M. Personal Communication. Environmental Engineer for the Ascendant Group Limited Company.

Westerberg, H., Pacariz, S., Marohn, L., Fagerström, V., Wysujack, K., and Miller, M.J. 2018. Modeling the drift of European (*Anguilla anguilla*) and American (*Anguilla rostrata*) eel larvae during the year of spawning. Canadian Journal of Fisheries and Aquatic Sciences 75:224–234.

Weis, J. S. and Weis, P. 2004. Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. Environmental International 30:685-700.

Wiley, D.J., Morgan II, R.P., Hilderbrand, R.H., Raesly, R.L., and Shumway, D.L. 2004. Relations between physical habitat and American eel abundance in five river basins in Maryland. Transactions of the American Fisheries Society 133: 515–526.

Wilcox, D. A. and Whillans, T. H. 1999. Techniques for restoration of disturbed coastal wetlands of the Great Lakes. The Society of Wetland Scientists 19(4):835-857.

Wingate, D.B. 1986a. The history of drainage and land fill operations in the Pembroke marsh Basin and its implications for future management and use of the area. Department of Agriculture and Fisheries Monthly Bulletin. 57(6):45-47.

Wingate, D.B. 1986b. The history of drainage and land fill operations in the Pembroke marsh Basin and its implications for future management and use of the area. Department of Agriculture and Fisheries Monthly Bulletin. 57(7):53-56.

Wingate, D.B. Personal Communication. Former Conservation Officer. Department of Agriculture and Fisheries.

Zimmerman, J.L. and Welsh, S.A. 2008. Pit tag retention in small (205-370 mm) American eels, *Anguilla rostrata*. Proceedings of the West Virginia Academy of Science 79(2):1-8.

APPENDIX

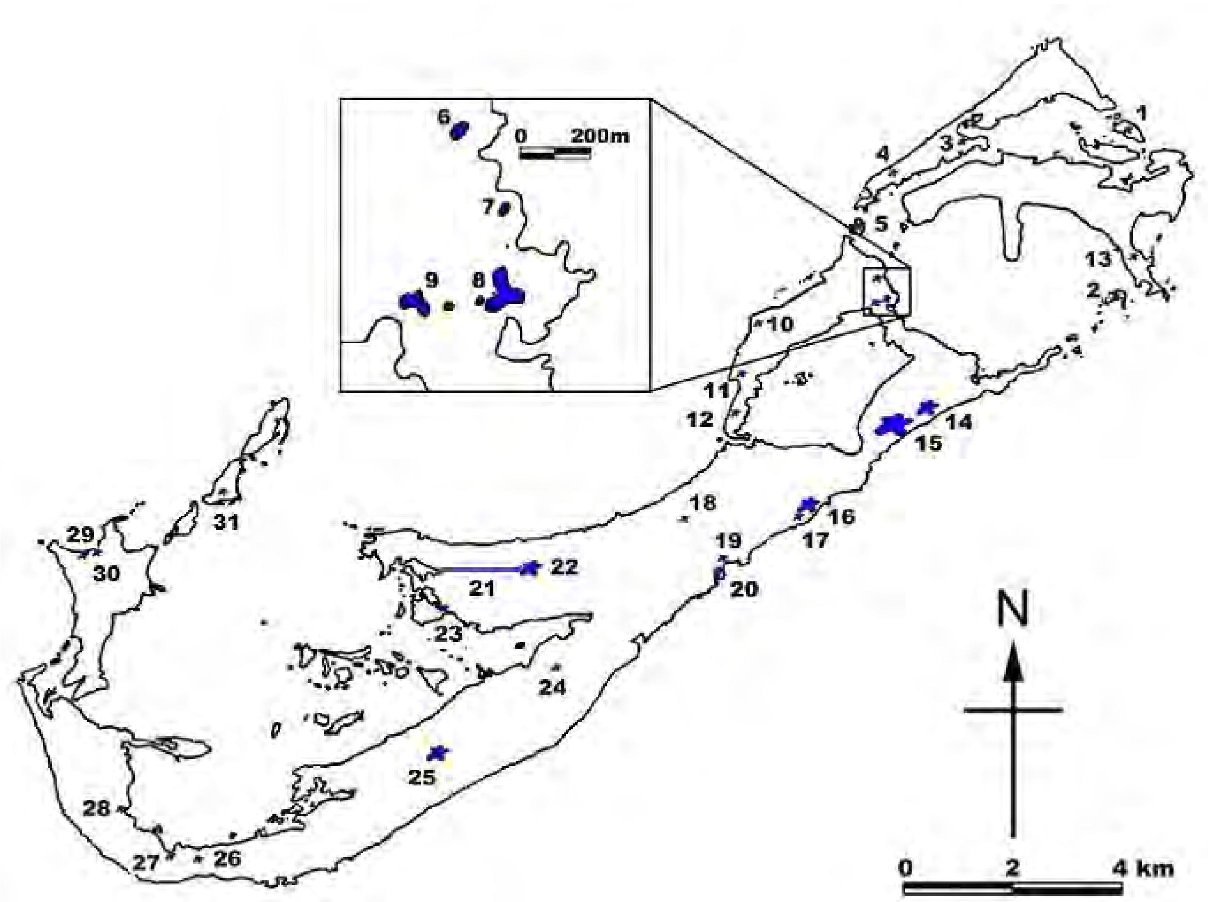

Figure 5. Map showing the locations of various ponds across Bermuda

Legend:
1. Paget Island Lagoon
2. Nonsuch Island Pond
3. Bartram's Pond
4. Lover's Lake
5. Coney Island Pond
6. Blue Hole Bird Pond
7. Blue Hole Grotto
8. East Walsingham Ponds
9. West Walsingham Ponds
10. Davis Pond
11. Shelly Bay Pond
12. Eve's Pond
13. Cooper's Island Pond
14. Trott's Pond
15. Mangrove Lake
16. Spittal Pond
17. Heron & Round Ponds
18. Devonshire Marsh Pond
19. Cloverdale Pond
20. Gibbon's Nature Reserve Pond
21. Pembroke Canal
22. East Pembroke Marsh Pond
23. Fairyland's Bridge Pond
24. David's Pond (Paget Marsh)
25. Warwick Pond
26. Seymour's Pond
27. Sea Swept Farm Pond
28. Evan's Pond
29. Somerset Long Bay Pond (west)
30. Somerset Long Bay Pond (east)
31. Ireland Island Lagoon

Table 2. Summary of physical characteristics for 30 ponds across Bermuda

Pond Name	Salinity*	Temp. (^{0}C) range (mean)	Dissolved Oxygen (mg/L)	Area of open water (acres)	Pollution profile available?	Ownership
†Bartram's Pond	M	13.9-31.7 (23.3)	unknown	0.56	N	BDA Audubon Soc.
Φ Lover's Lake	M	18.0-28.5 (23.7)	unknown	1.01	Y	BDA Government
†Paget Island lagoon	M	unknown	unknown	0.46	N	BDA Government
†Coney Island	M	unknown	unknown	0.97	N	BDA Government
†Blue Hole Bird Pond	M	16.2-28.3 (23.2)	unknown	0.22	N	BDA Government
Φ Blue Hole Grotto	M	unknown	unknown	0.08	N	BDA Government
Φ West Walsingham Ponds	M	12.4-37.9 (23.7)	unknown	0.87	N	Wilkinson Trust
Φ East Walsingham Pond	M	19.0-27.7 (23.2)	0.7-19.7	1.95	N	Walsingham Trust
Φ Trott's Pond	BR	16.0-31.0 (24.5)	unknown	2.88	N	Private
Φ Mangrove Lake	M	13.7-33.6 (24.6)	unknown	9.89	Y	BDA Government
Φ Davis Pond	M	unknown	unknown	0.47	N	Private
†Shelly Bay Marsh Pond	M	unknown	unknown	0.10	N	BDA Government
Φ Spittal Pond	BR	16.0-37.5 (32.0)	unknown	7.42	N	BDA National Trust
†Round Pond	BR	unknown	unknown	0.25	N	BDA National Trust
†Heron Pond	BR	unknown	unknown	0.18	N	BDA National Trust
†Cloverdale Pond	FW	17.0-32.0	unknown	0.35	Y	Private
Gibbons Nature Reserve Pond	FW	unknown	unknown	0.20	N	BDA Audubon Soc.
†Devonshire Marsh Pond	FW	unknown	unknown	0.22	N	Private
†East Pembroke Marsh Pond	FW	unknown	unknown	4.07	N	BDA Government
†Fairyland's Bridge Pond	M	unknown	unknown	1.75	N	Private
†David's Pond (Paget Marsh)	FW	13.6-31.6 (17.7)	unknown	0.20	Y	BDA Audubon Soc.
Warwick Pond	BR	10.8-39.6 (24.0)	unknown	2.76	Y	BDA National Trust
†Seymour's Pond	BR	18.7-30.9	unknown	0.79	Y	BDA Audubon Soc.
†Sea Swept Farm Pond	BR	unknown	unknown	0.45	N	Private
Φ Evan's Pond	M	17.0-32.0 (24.6)	0.1-10.2	1.79	Y	Private
†Somerset Long Bay Pond (west)	FW	unknown	unknown	0.51	N	BDA Audubon Soc.
†Somerset Long Bay Pond (east)	FW	19.0-33.0	unknown	0.72	Y	Buy Back BDA
†Ireland Island Lagoon	M	unknown	unknown	3.97	N	Wedco
†Cooper's Island Pond	M	unknown	unknown	0.24	N	BDA Government
†Eve's Pond	BR	unknown	unknown	unknown	N	Buy Back BDA

† ponds that have been significantly modified by humans (often entirely man-made); Φ natural ponds
*FW = freshwater <2 psu; BR = brackish water 2-29 psu; M = marine water >30 psu

Physical and abiotic descriptions of the various wetlands on Bermuda inhabited by American eels

Pembroke Canal

The Pembroke Canal (Fig. 6) comprises approx. 3 km of waterways between Mill Creek and Glebe Road. It was constructed between 1837 and 1840 to facilitate the drainage of the Pembroke Marsh complex and a sluice gate was installed at the mouth of the canal to prevent back-flooding of tidal waters. Temperature throughout the canal has been reported to range from 25.4 - 32^{0}C (mean 28.6^{0}C), pH from 6.1-8.3 (mean 6.5), and oxygen reduction potential 8.0-118.7 mV (mean 62.1 mV) (Doughty, 2011). Salinity ranges from ca. 32 psu (where the canal joins Mill Creek) to >1 psu (pond in the eastern portion of the marsh) (Boëtius and Boëtius, 1967). Some sections of the canal are filled with invasive aquatic plants (e.g. water hyacinth *Eichhornia crassipes* and water lettuce *Pistia stratiotes*). Mosquito fish *Gambusia holbrooki* and red-eared sliders *Trachemys scripta elegans* are abundant throughout.

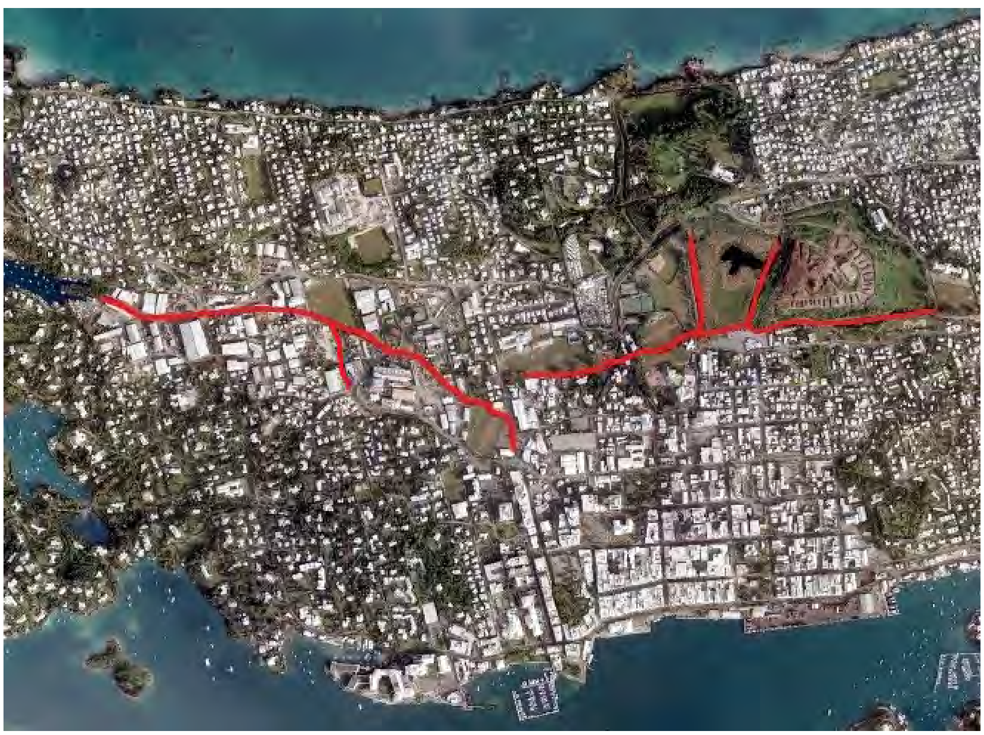

Figure 6. 2012 aerial image of the Pembroke Canal system (red lines)

Pembroke Marsh East

The relative sterility of the east basin is owing to the history of reclamation and re-submergence which destroyed the original diversity of peat marsh flora, leaving only cattail and saw-grass (Wingate, 1986b). What remains of the former Pembroke Marsh East Basin is a 19.5 acre Government-owned Nature Reserve, of which approximately 13% comprises open water within a predominantly cattail *Typha augustifolia* and sawgrass *Cladium jamaicense* marshland (Fig. 7). A 3 km canal connects Pembroke Marsh East with Mill's Creek (the terminal end of the marsh basin); however sections are filled with invasive aquatic plants (e.g. water hyacinth *Eichhornia crassipes* and water lettuce *Pistia stratiotes*) and much of it traverses through industrial land. The east basin is being slowly encroached upon by the Horticultural Waste Facility as it expands in area over time. Salinity in the pond was reported to be >1 psu (Boetius and Boetius, 1967).

Figure 7. Aerial photograph of Pembroke Marsh East.

Bartram's Pond

Bartram's Pond (Fig. 8) was originally about 0.75 acres in size and bordered by mangroves, prior to being filled with garbage by the middle of the 20th century. Dredging began in 1983 which resulted in the creation of a half-acre marine pond containing two small islets. The new pond is situated in a 2.4 acre nature reserve in St. George's Parish. Mosquito fish *Gambusia holbrooki* were introduced in 1985 and Bermuda killifish *Fundulus relictus* were introduced in 1986. In 1987 red mangroves *Rhizophora mangle* were planted on the two islets which have since self-seeded around the pond edges. Widgeon grass *Ruppia maritima* and American eels have naturally colonized the pond. This pond is connected to Mullet Bay by a tidal channel which runs under the road. The mean depth is 123 cm and the depth range was 32-178 cm. Average annual surface water temperatures is known to range from 13.9-31.7°C (mean 23.3°C) and salinities can vary from 27-37 psu (mean 31 psu) (Outerbridge and Thomas, unpublished data).

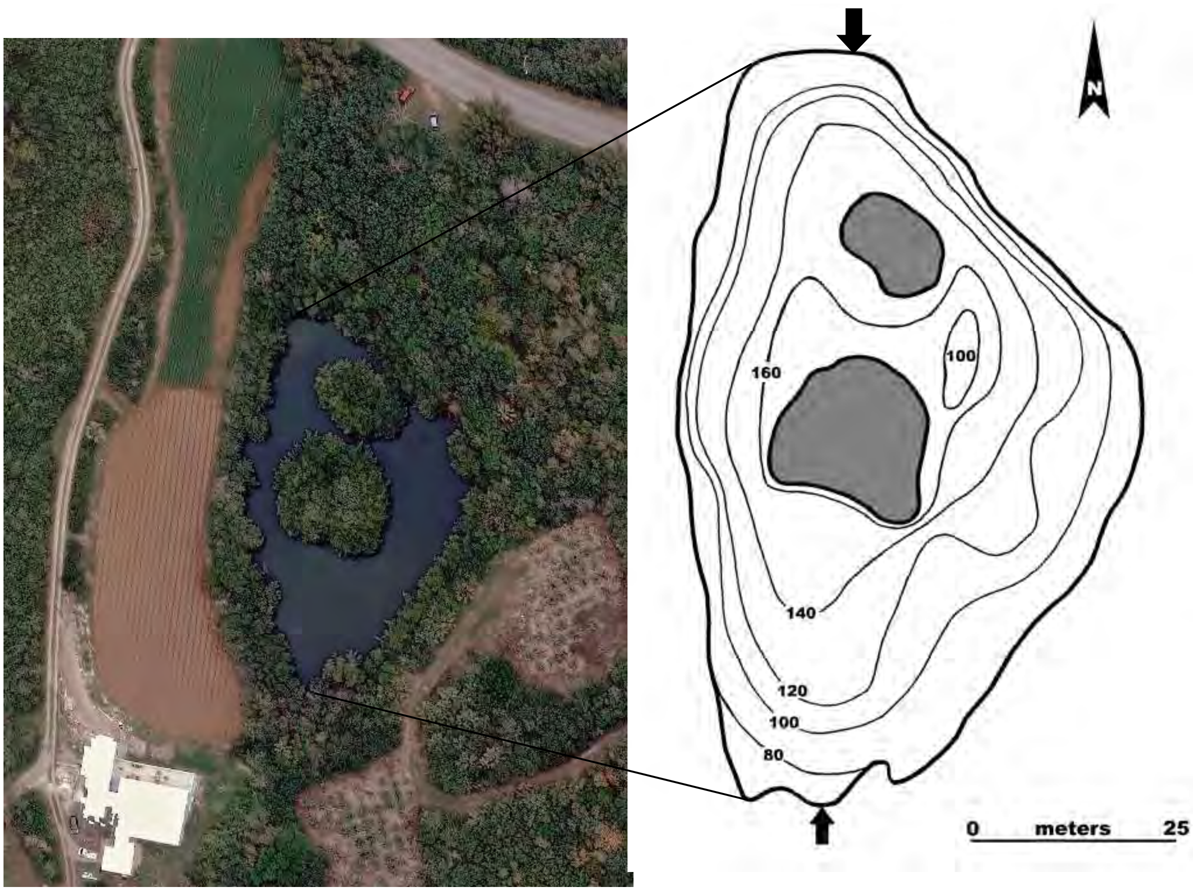

Figure 8. 2012 aerial photograph of Bartram's Pond (left) and map of bathymetry (right) (Depth is in cm. Black arrows indicate areas of tidal exchange)

Spittal Pond

Spittal Pond (Fig. 9) is a 7.4 acre brackish water pond located within 64 acres of nature reserve co-managed by the Bermuda National Trust and the Bermuda Government. The pond comprises two shallow basins separated by a very shallow sill. Mean depth was reported to be 38 cm and the maximum was 95 cm (Thomas and Wassmann, 1992) but the water level varies according to rainfall patterns. Sea water typically enters the pond at the western and eastern ends during exceptionally high tides or during southerly storms. Salinity and temperature show tremendous variation, ranging from 6.5 to 42.5 psu (mean 19.7 psu) and 16.1 to 37.5°C. Dissolved oxygen concentrations in the water exhibit a diurnal pattern; saturation during the day and falling to near zero by the early morning (Thomas and Wassmann, 1992). Biotic diversity is very low, although mosquito fish, widgeon grass, and American eels are found within the pond. The latter are occasionally found dead after anoxic events; Thomas and Wassmann (1992) reported encountering individuals >350 mm TL during the 1980s. Animal waste from a neighboring dairy farm frequently enters the ponds as run-off, especially during periods of high rainfall.

Figure 9. 2012 aerial image of Spittal Pond

Hungry Bay

Hungry Bay is a shallow water embayment with a contiguous forest of red and black mangroves ca. 6 acres in area (Fig. 10). The mangrove swamp is zoned as nature reserve and has a number of tidal sea water channels which run through it, providing access to the interior. It is presently considered to be the largest mangrove area on Bermuda, despite retreat of the seaward edge resulting in the loss of over two acres of mangroves, most of which has happened since 1900 (Ellison, 1993). This location is also a Ramsar site of international importance due to being the largest northerly mangrove swamp in the Atlantic Ocean, the many migratory bird species which visit during winter months, and the many native crustacean species which live there, including the endangered land hermit crab *Coenobita clypeatus* and giant land crab *Cardisoma guanhumi*. Refer to Ellison (1996) for a detailed ecological description of Hungry Bay.

Figure 10. 2012 aerial image of Hungry Bay

Walsingham Tract

Walsingham Tract is a strip of land that is approximately 400 acres in area and located between Castle Harbour and Harrington Sound (Fig.11). This tract consists of 22% protected lands (park land, coastal reserve, and nature reserve - the largest of which is the Walsingham Trust's Nature Reserve). The remaining lands are mainly a mixture of residential, industrial, recreation, tourism, agricultural and open space. It sits on top of the Walsingham geologic formation which consists of extensive systems of both dry and flooded caves. This cave system is a critically important habitat for many of the 22 cave-dwelling marine invertebrate species that are endemic to Bermuda (see Glasspool, 2014) and Smith-Vaniz et al. (1999) hypothesized that it may also act as a diurnal refuge for American eels. Temperature, salinity, pH, and dissolved oxygen values change with depth within Bermuda's marine caves (Iliffe et al., 1984; Gibbons, 2003). Most inland cave pools contain a thin (<1 m) brackish layer which varies in salinity (0-25 psu) followed by a sharp halocline, beneath which salinities increase with depth to >35 psu. Water temperature shows a similar gradient; temperatures are lowest at the surface but increase with increasing depth. Dissolved oxygen levels in the surface waters are slightly lower than saturation (70-90%) but fall rapidly to zero at the halocline, at which point they begin to increase at depths below 10 m. The average (i.e. summation through the water column to a depth of 30 m) dissolved oxygen concentration was found to be 3.13 ml/L (or 4.47 mg/L) (Iliffe et al., 1984). Organic pollution in these cave systems can rapidly lead to oxygen depletion and anoxic conditions. Gibbons (2003) reported that the highest pollutant concentrations (i.e. nitrates, ammonia, and bacterial contamination) were consistently found in surface waters; however most of the cave fauna live below the halocline and are therefore do not have direct contact with the highest levels of pollutants.

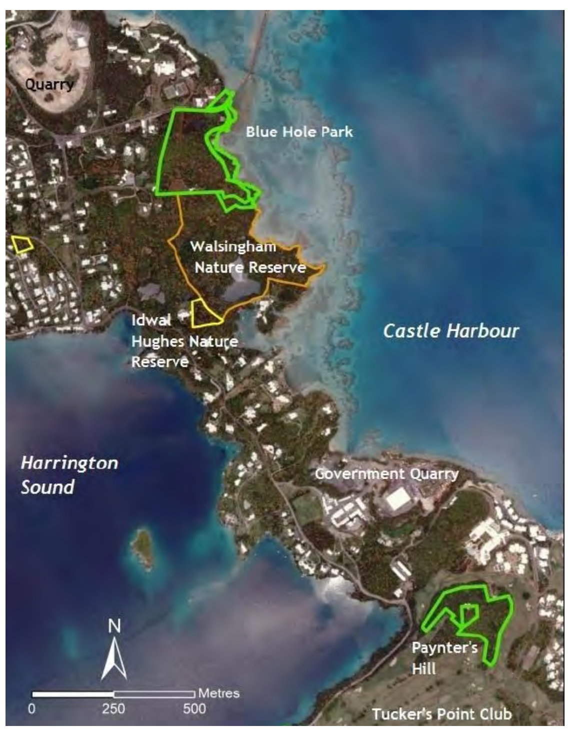

Figure 11. Aerial image of the Walsingham Tract and environs.
(Government owned park and nature reserves shown in green, Walsingham Trust property shown in orange and Bermuda National Trust properties shown in yellow.)

Devonshire Marsh

Devonshire Marsh (Fig. 12), Bermuda's largest peat marsh, is situated above Bermuda's largest freshwater lens, and is bisected by Barker's Hill into eastern and western sections. This marshland is almost entirely privately owned, of which nearly 21 acres comprises lands managed by the Bermuda Audubon Society and the Bermuda National Trust (e.g. the Watlington, Winifred Gibbons, Freer Cox, and Firefly Nature Reserves). The marsh was originally a tree-dominated environment (notably cedar and palmetto trees) but a series of large fires from 1914–2018, in conjunction with the scale insect epidemic during the 1940s, windfall during severe hurricanes and episodic inundation of salt water due to sea level rise, has resulted in the loss of the majority of these trees and the transformation to a bracken and grass-dominated landscape (D. Wingate, pers. comm.). A sliver of relatively high, dry land in the Marsh Lane area enabled building for industrial use during the 19th century. An open-water ditch system was created in the 1940s in an attempt to manage mosquitoes and mosquito-borne diseases and there are still presently a number of ditches and one small pond located within the marsh, all totaling less than one acre in area. The salinity of Devonshire Marsh was reported to be 4 psu in the mid-1980s (Scott and Carbonell, 1986) and only 0.2 psu in the spring of 2017 (A. Copeland, pers. comm.).

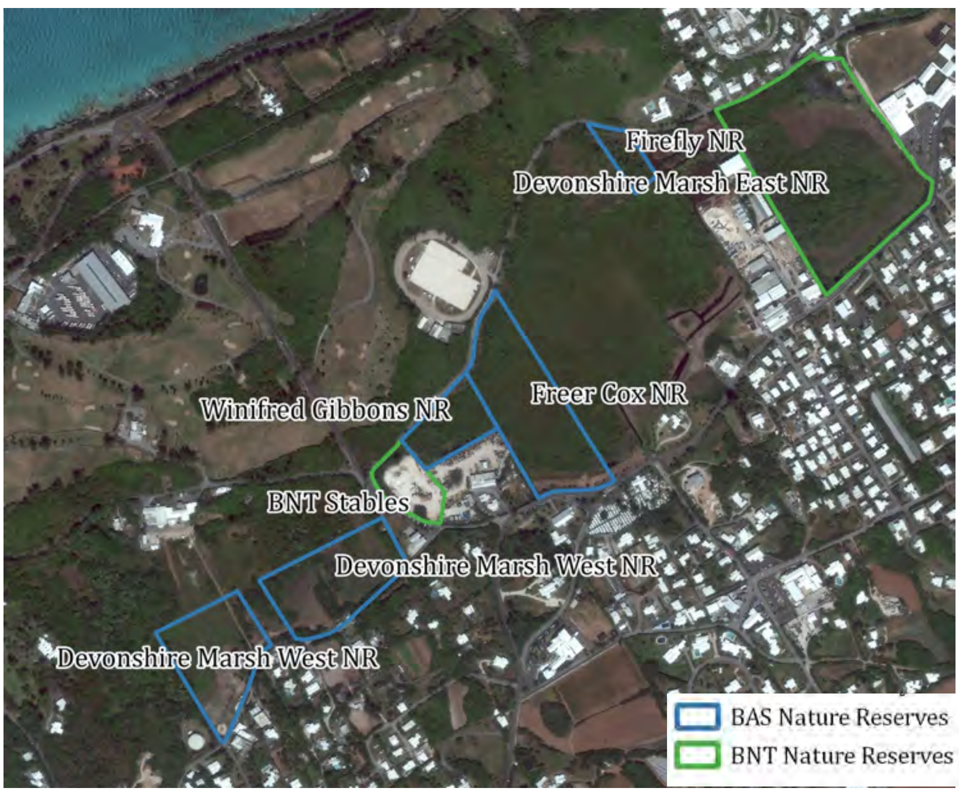

Figure 12. Aerial photograph of Devonshire Marsh.