Environmental Management Plan

North Windermere Island Boat Basin REV. 2

Eleuthera, The Bahamas

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Submitted on Behalf of North Windermere Island
To: Department of Environmental Planning and Protection

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Eleuthera, The Bahamas

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1 Executive Summary

This Environmental Management Plan (EMP) pertains to the boat basin at North Windermere Island, Eleuthera, The Bahamas. An Environmental Management Plan is a guide that identifies relevant management techniques, including Best Management Practices (BMPs) and Emergency Response Plans, based on site-specific physical and biological conditions.

North Windermere Island development is located on Windermere Island, Eleuthera, The Bahamas. The 3.82 acre boat basin will be comprised of a timber pile boardwalk capable of berthing 26 vessel while accommodating a maximum vessel size of 37 and three (3) foot draft. Excavated depth of the boat basin and entrance channel is five (5) feet below mean low sea level. Total volume of excavated materials is estimated at 14,500 cubic yards. This material will be used for land building purposes. A bridge will span the boat basin to allow access to homes on the western portion of the peninsula.

Vessels will access the boat basin from a southern approach. The boat basin is located immediately upon entrance with additional docks beyond the bridge to the north for use by adjacent private homes. Two (2) large culverts result in 85% flushing in 24 hours meeting DEPP policy. Moreover, boat basin and channel walls will be constructed using natural ridge sloped with vegetated and boulders. Total build-out of the boat basin is expected to take four and half months (4 ½) months.

Vegetation land classes within the general vicinity of the boat basin include mangrove and buttonwood formations; sawgrass, saltwort, cattail, and bay marigold formations; dry broadleaf evergreen formation; and human altered. The boat basin will result in the loss of the interior saltwort and buttonwood formation and disturbance to the dry broadleaf evergreen formation. To mitigate the loss of waterfowl habitat, the developer will create 0.8 acres of waterfowl habitat in the vicinity of the agricultural area. The southern entrance channel and northern flushing culverts will result in the loss of individual red mangroves and black mangroves. Prior to construction, mangroves identified in the immediate area of impact will be removed and replanted for reuse as part of the overall mitigation measures.

Detailed mitigation measures are found within this report under the section titled Mitigation. The proposed 3.82 acre boat basin will result in the loss of wetland habitat including individuals of red and black mangrove. Minimal disturbance to the hydrological regime is recommended. To mitigate this loss it is recommended that:

- Removal of mangrove individuals only where necessary for culvert installation.
- Use of Best Management Practices during construction to limit sediment impacts and hydrological changes.
- Planting of mangrove seedlings immediately following culvert installation.
- Long-term goal for mangrove self-recruitment to achieve optimal replanting and resilience.
- Installation of 0.8 acre of waterfowl habitat in the agricultural area.

Recommendations

Recommended Best Management Practices for the boat basin at Windermere Island:

- **Sediment and Erosion Controls**. Land clearing activities require use of best management practices (BMPs) to limit impacts to the environment. BMPs reduce the potential for sediment transport during storm events and entry into subsurface caverns and marine environment. Potential best management practices to consider include a drainage plan, silt fencing and dewatering away from wetland features.
- **Turbidity and Environmental Monitoring.** Construction will employ the use of turbidity barriers and monitoring to ensure turbidity does not exceed 29 NTU above background levels. Turbidity barriers shall be placed in the area of excavation for culvert installation and southern marina entrance. The interior of the boat basin will be excavated while maintaining land plugs at the northern culverts and southern entrance. Turbidity monitoring will ensure the effectiveness of the turbidity barrier.

- **Materials Storage and Fuel Storage**. Materials storage should be kept away from sensitive environmental features. Fuel storage and refueling should adhere to best practices, including raised storage with either 110% containment mechanism or doubled walled tanks in the event of spill. While no commercial fueling is anticipated to take place during boat basin operation, construction equipment refueling will require adherence to an Environmental Management Plan (EMP) to minimize spill potential and threats to the ground and surface waters.
- **Handling of Waste Materials, Materials Storage including Fuel Storage**. Materials storage should be kept away from sensitive environmental features. Materials stored on site will be in a single location and remain tidy. Petroleum products will be stored in a designated area identified prior to construction activities. All waste materials will be taken to a designated landfill approved by the Department of Environmental Health Services.
- **Spill Prevention and Fuel Containment**. Construction activities shall adhere to best management practices to prevent oil spills or leaks and in the event of a spill or leak, a plan to contain and mitigate dispersal into the ground and surface waters. Refueling of equipment will occur in a designated area away from open water bodies with impervious ground cover and containment area. Spill kits will be available on site at all times.
- **Sensitive Environmental Features – Mangrove & Waterfowl Mitigation**. Two types of mangroves, black and red, fringe the coastline of the peninsula at North Windermere Island. Boat basin design entails two (2) culverts for flushing to mitigate impacts to the mangrove community. Flushing design and employment of best management practices will mitigate adverse impacts. To mitigate the loss of waterfowl habitat, the developer will create 0.8 acres of waterfowl habitat in the vicinity of the agricultural area.
- **Planting with Native Tree species.** Removal of invasive species considered a threat to small island nations will slow the proliferation of unwanted plant species. It is recommended that the developer perform routine removal of saplings to prevent recolonization. A landscaping program that uses a palate of native trees will encourage visits by native fauna.

2 Environmental Management Overview

Environmental management is a systematic approach that integrates environmental, health and safety policies with continuous monitoring to ensure environmental compliance. These policies entail international best management practices to avoid and minimize known and unforeseen adverse impacts stemming from the project. Hazards to human health and safety and the environment can be managed through careful planning, vigilance and strong communication during works, and continual improvement to the overall environmental management program.

As such, an EMP should be consulted during construction planning and used during construction and operation. The preferred management approach is to avoid, minimize, and control adverse impacts to human health, safety, and the environment. Where adverse impacts cannot be avoided, best management practices should be employed to mitigate human and environmental harm.

The EMP shall be continually revised to reflect any changes on site. The EMP outlines measures that are to be implemented in order to minimize potential adverse environmental and social impacts and safety hazards. A copy of the DEPP approved EMP will be available on site at all times.

3 Purpose and Scope

An Environmental Management Plan (EMP) is a guide that identifies relevant management techniques, including BMPs and Emergency Response Plans, based on site-specific physical and biological conditions. The purpose of this EMP is to control environmental impacts associated with construction and operation of the boat basin at North

Windermere Island, Eleuthera. Please note that all references to 'site' herein constitute the boat basin and its immediate vicinity.

The EMP shall be continually revised to reflect any changes on site. The EMP outlines measures to be implemented in order to minimize potential adverse environmental and social impacts and safety hazards. A copy of the DEPP approved EMP will be available on site at all times.

4 Corporate Environmental Policy

Windermere Operations Environmental Policy Statement

Windermere Operations ("WOL") has a deep respect and appreciation for the natural environment and seeks to be a diligent guardian in pursuit of this belief wherever possible. It is WOL's policy to carry out all activities in a manner that minimizes environmental impacts, conserves natural resources and provides effective stewardship of the environment. WOL has implemented Design Guidelines that formalize the responsible development of the site. To that end, WOL is committed to making environmental management an integral core value and vital part of the Windermere culture by:

- Utilize a way of building that is deferential to the natural environment and context, integrating structures with landscape rather than imposing on it;
- Protect and enhance the existing marine and land ecologies, the coastline, and the ground water quality;
- Preserve the views of untouched natural landscape for all community members by building low and compact relative to the vegetation;
- Preserve the dense, mature natural vegetation that is a defining characteristic of North Windermere as much as possible;
- Preserve the island's greatest asset of pristine waterfront in its natural state as much as possible
- Respect protected plant species and habitats and minimize tree and brush removal as well as grading and site disturbance;
- Utilize plant palettes that are sensitive to water conservation;
- Encourage owners utilize green building technique wherever possible;

- Informing employees and associates of applicable environmental regulations and WOL requirements;
- Providing the resources necessary for employees and associates to conduct their work in accordance with applicable environmental regulations and WOL requirements;
- Developing environmental goals and targets relevant to WOL operations and taking actions to achieve those goals and targets;
- Promoting pollution prevention, waste minimization, and conservation;
- Promoting the effective use of innovative environmental technologies and practices;
- Fostering a work environment in which employees and associates are encouraged to report and raise environmental issues without fear of retaliation;
- Continually improving the effectiveness and efficiency of environmental management through assessments and performance and cost metrics, and;
- Complying with applicable laws, regulations and other promulgated environmental requirements.

In addition, every individual at WOL is expected to:

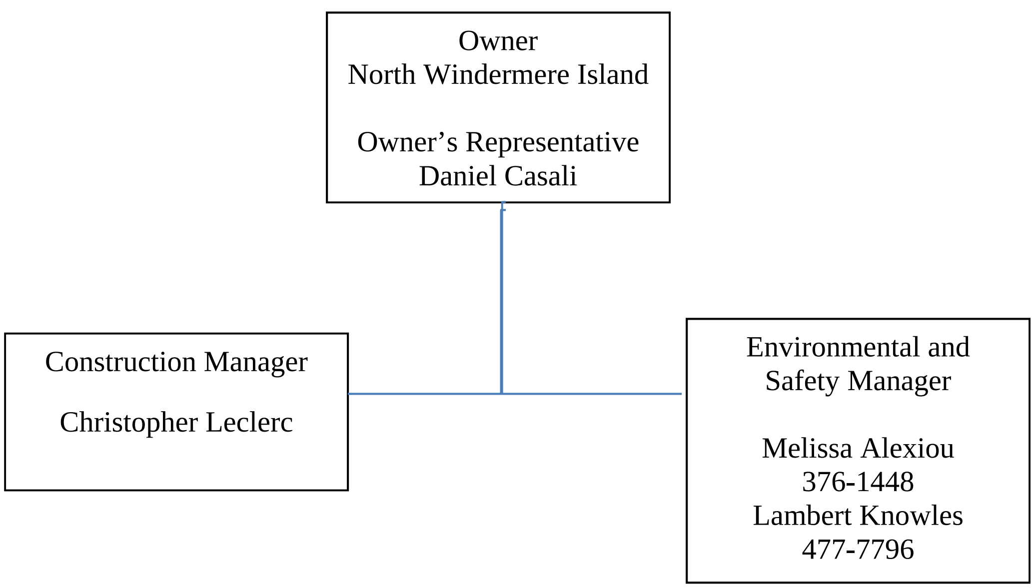
- Conduct their assigned duties in a manner that complies with applicable environmental regulations and WOL requirements;

- Continually strive to improve environmental performance in their work area;
- Be aware of the potential environmental consequences of their actions at all times and take care to minimize any adverse consequences;
- Promptly report or otherwise address conditions that could result in a spill or release of hazardous or regulated material to the environment;
- Promptly report environmental incidents, i.e., events in which a spill or release of hazardous or regulated material to the environment occurred or could have occurred;
- Participate in the conduct of incident investigations;
- Effectively disseminate information and lessons learned from any incidents; and
- Correct deficiencies and take actions to prevent incidents from occurring.

5 Organization Chart

An organizational chart and communication plan facilitate a network of strong internal and external communication. It also establishes protocols for emergency response and community grievance redress. The project team will have a designated Environmental Manager and Safety Manager, the position can be combined.

Weekly site meetings will highlight items of immediate environmental concern; a compilation of environmental issues will be highlighted in monthly reports presented to DEPP. The Environmental Manager will engage in frequent communication with the DEPP. Additionally, coordination of construction activities will entail notification and meetings with local government, community leaders, and the public.



6 Environmental Training and Awareness

The EMP is a written guide for the workforce and the Employer that outlines roles and responsibilities for human health and safety, and the protection and preservation of the natural environment. All personnel will be required to attend an environmental induction session followed by on-going training to reinforce environmental stewardship. On-going training may include a weekly Toolbox talk to address specific concerns and preparation for future works.

The Environmental Induction booklet contains information specific to construction procedures.

7 Geographical Setting

The Bahamas is an archipelagic nation comprising 700 islands and cays situated over 100,000 square miles of the Atlantic Ocean. Located east of Florida and north of Cuba, The Bahamas has a population of 351,461 persons of which 70% reside on New Providence. Collectively New Providence, Grand Bahama, and Abaco represent 90% of the population.

Eleuthera is located east of the capital island of New Providence. The narrow island is 110 miles long from the settlement of Current in the North to the Bannerman Town in the south. The boat basin at North Windermere Island is located on Windermere Island which rests directly east of the island of Eleuthera. Windermere Island is connected to mainland Eleuthera via a private access bridge.

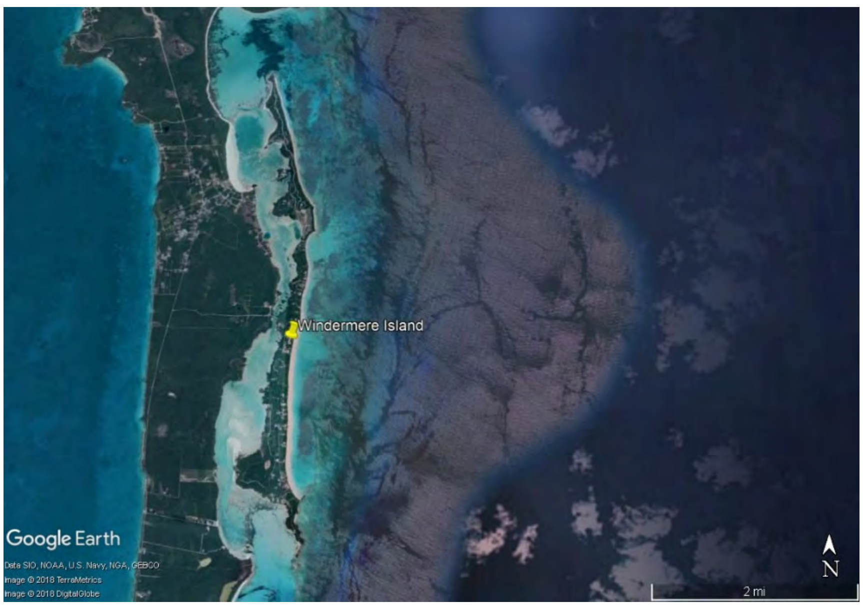


Figure 7-1 Windermere Island

Figure 7-2 North Windermere

8 Project Description

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9 General Climate and Site Characteristics

The climate of The Bahamas is considered sub-tropical; it lies in a transition zone between the temperate and tropical zone. The archipelago spans 450 miles in longitudinal extent from 21°N to 27.5°N. The northern Bahamas experiences cooler winters and higher amounts of rainfall compared to the southern Bahamas where annual temperatures deviate less and the climate is markedly drier. The climate of The Bahamas is influenced by the sea particularly, the Gulf Stream which lies between Florida and the Great Bahama Bank. (Sealey, 2006)

Average High and Low Air Temperature is given in degrees Fahrenheit for Nassau (Sealey, 2006)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
High	77.3	77.5	79.7	81.8	84.6	87.3	89.1	89.3	88.4	85.4	81.8	78.7
Low	62.1	62.5	63.8	66.2	69.8	73.3	74.7	74.8	74.4	71.9	68.0	63.8

Rock Sound, Eleuthera can expect 50 inches and 99 rain days compared to New Providence which can expect 57.1 inches and 137 rain days (Sealey, 2006). Rainfall is highest between the months of May and November with peaks during June and October. Generally, prevailing winds are from the northeast with a rotation to the southeast during the summer months, May to September. In winter, wind may shift to the northwest due to cold fronts emanating from North America. According to the Bahamas Department of Meteorology, the average wind speed is eight (8) knots.

9.1 Climate Change

Climate change will contribute to greater climate variability where changes may occur to precipitation patterns, increase in frequency and intensity of storm events, extreme heat, global sea level rise, and alteration of wave patterns leading to shoreline erosion. Given this climate variability, engineering and building designs should plan for a scenario for future high anthropogenic greenhouse gas emissions.

The boat basin design provides for breakaway docks and floating docks to accommodate climate change effects and storm surge.

9.2 Topography

The peninsula ranges in elevation from sea level to nearly fifty (50) ft. A narrow ridgeline extends along the northern site boundary where the land meets the sea; elevations here average ten (10) feet. Overall, the site features diverse topography with numerous changes in elevation from interior depressions to isolated hill top knobs.

9.3 Baseline Biological Survey

9.3.1 *Vegetation Survey*

In terms of vegetation community classification, the site contains ten (10) vegetation types including for which seven (7) are wetlands: Beach Strand, Black Mangrove (*Avicennia germinans)*, Red Mangrove Formation (*Rhizophora mangle)*, Buttonwood Formation *(Conocarpus erectus)*, Sawgrass *(Cladium jamaicense)*, Saltwort *(Salicornia bigelovii)*, Bay Marigold *(Borrchia aerborescens)*, Cattail *(Typha domingensis)*, Dry broadleaf evergreen formation (DBEF), and Human Altered.

A total of 84 vascular plant species were observed on during the site field investigation occurring from 2nd to 3rd of November 2018. *Guapira discolor* (Narrow leaf blolly) was the only species observed on site listed on the Protected Tree Order contained within the Conservation and Protection of the Physical Landscape Act. Four (4) invasive species were identified with one (1) white inkberry *(Scaevola taccada)* being recommended for eradication.

9.3.2 *Avian Survey*

The Avian Survey identified eleven (11) avifauna during three (3) hours of observation. All species identified are permanent residents with the exception of the Cape May Warbler *(Setophaga tigrine)*, Lesser Yellowlegs *(Tringa flavipes)*, and Blue Wing Teal *(Anas discors)* which are winter non-breeding residents. Also of note is the observance of the White-cheeked Pintail (*Anas bahamnesis)* which is prohibited for hunting.

Overall, species numbers for the site are considered moderate with a majority of the activity occurring within the fresh/brackish wetlands. To note, bird nests were observed in the wetlands and DBEF vegetation.

9.3.3 *Marine Assessment*

The Marine Benthic Assessment identified benthic habitats and marine flora and fauna within the vicinity of the proposed boat basin. A majority of the substrate can be classified as sand and silt bottom dominated by manatee grass *(Syringodium filiforme)* and various algal types. Thirteen (13) species of marine flora, one (1) coral specie, starlet coral *(Siderastrea radians)*; and three (3) sponge species were observed. In addition, eight (8) other marine species including sea cucumber *(Holothuria Mexicana)* and a juvenile queen conch *(Lobatus gigas)* were observed. Ten (10) species of fish including the commercially important Mutton Snapper *(Lutjanus analis)* were identified. Site investigations also noted Green turtle *(Chelonia mydas)* and Caribbean spiny lobster which are endangered and protected species. Overall, a majority of marine activity occurred within the protection of the mangrove roots close to shore rather than the open flats.

9.4 National Parks

At present, there are no National Parks or Protected Areas in the vicinity of the proposed boat basin. However, under the Bahamas Protected Project, the Bahamas National Trust proposes expanding the existing marine protected area network. This expansion would include the proposed Savannah Sound and Plantation Reef marine protected area encompassing 3,469 acres immediately adjacent to the boat basin.

A Rapid Ecological Assessment was conducted in August 2017 and identified the mangroves within Savannah Sound to be highly productive. This area has a high species diversity and fish density, and supports a number of juvenile species including Nassau Grouper, queen conch, snappers, grunts, and parrotfish. While it is noted that reef systems off-shore show degradation, Plantation Reef is in superior condition.

Figure 9-1 Savannah Sound & Plantation Reef Proposed MPA

10 Environmental Laws, National Environmental Policies and International Conventions

The boat basin at North Windermere Island is within the constituency of Central and South Eleuthera which is represented by Member of Parliament Hank Johnson.

10.1 Environmental Laws of The Bahamas

Environmental Law, Regulation, Policy	Subject	Summary
Bahamas National Trust Act, 1959 Bahamas National Trust Amendment, 2013 Bahamas National Trust Amendment, 2019	Designation and management responsibility for National Parks	This Act and Amendment founded the Bahamas National Trust and grant it authority for the provision and oversight of National Parks in The Bahamas. The 2019 Amendment expands the duties of the Bahamas National Trust; to revise the constitution of the council; and to expand its authorized capital investments; and for connected purposes.
Conservation and Protection of the Physical Landscape of The Bahamas, 1997 Chapter 260	Excavation, Landfill, Quarrying, Mining, Protected Trees Listing	This Act makes provisions for the regulation of activities including excavation, landfill, quarrying, mining, and harvesting of protected trees in The Bahamas for the purpose of conservation of maintenance of the environment. The Regulations include a list of protected tree species in The Bahamas.
Environmental Health Services (Collection and Disposal of Wastes) Regulations 2004	To administer and outline waste collection and management facilities	Environmental Health Services (Collection and Disposal of Wastes) Regulations 2004 establish the collection and control of waste including waste facilities and other matters relating to wastes.
Environmental Health Services (Fees and Services) Regulations 2000	To establish fees and services performed by the Department of Environmental Health Services	The Fees and Services regulations outline services and associated fee rates performed by the Department of Environmental Health Services. The Department may provide testing for air quality, water quality, and radioactive materials.
Environmental Health Services Act 1987	To promote and protect the public health and to provide for the conservation and maintenance of the environment	An Act to promote the conservation and maintenance of the environment in the interest of health for proper sanitation in matters of food and drinks, and generally for the provision and control of services, activities, and other matters connected therewith or incidental thereto.
Environmental Planning and Protection Act 2019	To establish the Department of Environmental Planning and Protection	An Act to establish the Department of Environmental Planning and Protection; and to provide for the prevention or control of pollution, the regulation of activities, and the administration, conservation and sustainable use of the environment and for connected purposes. The Act defines procedures for environmental impact assessments and environmental reporting requirements for protection of natural resources.
Environmental Impact Assessment Regulations, 2020	To provide procedures for a Certificate of Environmental Clearance (CEC).	The Regulations provide procedures for the review proposed projects inclusive of monitoring and compliance requirements. The Regulations dictate the requirements for a Certificate of Environmental Compliance (CEC).
Forestry Act of 2010	To protect the forests and make declarations to use	The Act provides for utilization of forest products and non-timber forest products from the forest estate. It sets forth the management and conservation of the Forest estate and associated industries.
Health and Safety at Work Act 2002 Health and Safety at Work Amendment, 2015	To protect human health and safety at work	The purpose of the Act is to secure the health, safety and welfare of persons at work- protect persons other than persons at work against risks to health or safety arising out of or in connection with the activities of persons at work- control the storage and use of explosive or highly flammable or otherwise dangerous substances, and generally preventing the unlawful acquisition, possession and use of such substances.

Planning and Subdivision Act, 2010 Planning and Subdivision Regulations (Application Requirements), 2011	To regulate the built environment	This Act regulates the development of the built environment though physical planning protocols across the archipelago of The Bahamas. The Act stipulates the process for subdivision approval subject to specific conditions with respect to the features of the proposed development or project including the preparation of an Environmental Impact Assessment/Statement.
Public Works Act 1963	To provide for the physical development of The Bahamas	An Act to provide for the construction, management and development of public works, buildings, and road.
Water and Sewerage Act 1976	To establish the Water and Sewerage Corporation and to control water resources	An Act to establish a Water and Sewerage Corporation for the grant and control of water rights, the protection of water resources, regulating the extraction, use and supply of water, the disposal of sewage and for connected purposes
Wild Animals Protection Act 1968	To protect wild animals of The Bahamas	The Act provides a listing of protected animal species in The Bahamas
Wild Birds Protection Act 1987 Wild Bird Protection Act (Reserves)	To protect wild birds of The Bahamas	The Act protects the wild birds of The Bahamas and makes provision for the dedication of time periods for the hunting of specific species.

10.2 National Environmental Policies

Relevant National Policies	Subject	Summary
National Policy for the Adaptation to Climate Change 2005	Climate change assessment for the immediate and project adaptation techniques for The Bahamas	The National Policy for the Adaptation to Climate Change outlines a national framework to meet the goals and objectives of the United Nations Framework Convention on Climate Change (UNFCC). The Bahamas is committed to reduce greenhouse gases and address climate change impacts.
National Invasive Species Strategy for The Bahamas, 2013	Identifies and recommends a management framework for the control and eradication of invasive species.	The National Invasive Species Strategy for The Bahamas originally published in 2003, was updated in 2013 as part of the Global Environment Facility funded project, Mitigating the Threats of Invasive Alien Species in the Insular Caribbean (MITIASIC). It sets forth a management framework for the control and eradication of invasive species.
National Biodiversity Strategy and Action Plan, 1999	A plan to maintain biodiversity through sustainable development for a small island developing nation.	The Bahamas Government is committed to conserve biodiversity and to pursue sustainable development. This document highlights the role of biodiversity in the Bahamian social and environmental context and recommends measures to ensure its compatibility with future development.

10.3 International Conventions of Relevance

International Convention/Organization	Subject	Summary
Cartagena Convention Ratified: June 24, 2010	An agreement for the protection and development of the marine environment in the wider-Caribbean region	The Convention provides a legal framework for cooperation in the wider Caribbean region. Three technical agreements support the Convention which include: - Protocol for Co-Operation in Combating Oil Spills - Protocol for Specially Protected Areas and Wildlife (SPAW) - Protocol Concerning Pollution from Land-based Sources and Activities (LBS)
Convention on Biological Diversity Signed: June 12, 1992	To preserve species diversity	The Bahamas is a signatory to the Convention on Biological Diversity which came into force December 1993. It has three main goals: a) The conservation of biological diversityb) The sustainable use of components of biological diversityc) The fair and equitable sharing of the benefits arising out of the utilization of genetic resources
Convention on Wetlands of International Importance Especially as Waterfowl Habitat (Ramsar Convention) Signed: June 7, 1997	This convention provides a framework for the international protection of wetlands as contributors for human resources and moreover, for avifauna which do not adhere to international boundaries.	The Bahamas is a signatory to the Convention on Wetlands of International Importance, also known as the Ramsar Convention. This convention provides a framework for the international protection of wetlands as contributors for human resources and moreover, for avifauna which do not adhere to international boundaries. Ramsar defines wetlands as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters'.
Convention to Combat Desertification & Drought Signed: Nov. 10, 2000	To combat desertification and to mitigate the effects of drought	The Convention is a proponent for sustainable development by addressing social and economic issues that directly impact land degradation.
United Nations Framework on Climate Change Signed: June 1992 Kyoto Protocol Signed: April 9, 1999 Paris Agreement Ratified: August 22, 2016	To stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with climate systems	The Bahamas is a signatory to UNFCC which entered into force in March 1994. The UNFCC was the culmination of climate negotiation at the Rio Earth Summit in 1992. This summit established a framework with an aim to stabilize atmospheric greenhouse gas. The Kyoto Protocol was developed under the UNFCC to provide emissions targets and timetables for developed countries. The Paris Agreement as put forth at the Conference of the Parties (COP21) in December 2015. The agreement has not yet come into force as it requires at least 55 parties to have ratified the agreement.
Basel Convention on the Control of Transboundary Movement of Hazardous Wastes Signed: August 12, 1992	To regulate the transboundary movement of hazardous wastes	The Convention regulates the transboundary movements of wastes and ensures that parties to the Convention manage and treat waste according to sound environmental practices. Main Principles: - Transboundary movement of hazardous wastes should be reduced to a minimum - Hazardous wastes should be treated and disposed of as close as possible to the source - Hazardous waste generation should be reduced at the source

10.4 Government Departments and Local Non-Governmental Organizations

- Ministry of Public Works
- Ministry of the Environment and Housing
- Department of Environmental Planning and Protection
- Port Department
- Department of Physical Planning
- Department of Environmental Health Services
- Water and Sewerage Corporation
- Bahamas Power and Light

11 Register of Environmental Issues

Register of Environmental Issues: Boat basin at North Windermere Island			
Aspect	Ecological Value	Impacts	Recommendations for Mitigation & Management
Botanical	Ten (10) vegetation types were identified including: - Beach Strand - Black Mangrove - Red Mangrove - Buttonwood - Sawgrass - Saltwort - Bay Marigold - Cattail - Dry Broadleaf Evergreen Formation - Human Altered Of note, the site has seven (7) wetland communities. Red and black mangroves fringe the coastline and the other wetland types are present inland. One (1) protected species, narrow leaf blolly and four (4) invasive species were observed.	The boat basin design has a primary entrance to the south with additional but non-navigable flushing channels to the north. Construction of the boat basin will result in the loss of the interior wetland communities' sawgrass formation, saltwort formation, and buttonwood formation. The majority of the peninsula and immediate areas are covered by DBEF. Red mangrove communities are not expected to incur long-term adverse impacts. The black mangrove community fringes the area of the southern boat basin entrance with select species removed for basin construction. Coastal vegetation along the southern perimeter as noted in the botanical study and confirmed by historic aerial imagery was previously disturbed. Land clearing and site preparation activities should focus on the avoidance and minimization of sediment and erosion, pollution prevention, waste management, materials storage, refueling, and BMPs included in the EMP.	- Erosion and Sediment BMPs - Prevention of Pollution of Waterbodies - Mangrove and Wetland Mitigation - Removal of Invasive Species - Landscaping with Native Species - Waste Management Program
Avian	Eleven (11) avian species were observed. The white-crowned pigeon is listed as a near threatened (NT) species on the IUCN red list. Avifauna activity was greatest in the fresh/brackish wetlands and in the DBEF with a moderate number of species observed. Breeding on site is likely with observance of nests in wetlands and DBEF.	Removal of wetland features, sawgrass formation, saltwort formation, and buttonwood formation for the basin will result in the loss of some waterfowl avifauna due to the loss of habitat. Planting with native species and a natural shoreline may encourage visits by shorebirds.	- Mangrove and Wetland Mitigation - Removal of Invasive Species - Landscaping with Native Species - Air and Noise Quality BMPs - Waterfowl habitat creation
Marine	Benthic substrate can be described as sand and silt bottom dominated by manatee grass and various alga types. The manatee grass and alga substrate extended ten (10) to twelve (12) meters from shore.	A previously dredged area exists to the immediate south of the site. A majority of the activity occurred within the mangrove roots. Disturbance to red mangroves is anticipated to be limited to the area of	- Erosion and Sediment BMPs - Prevention of Pollution of Waterbodies - Mangrove and Wetland Mitigation - Landscaping with Native Species

	One (1) coral species and three (3) sponge species were identified. Other notable fauna included sea cucumber, juvenile conch, Caribbean spiny lobster, and string ray. Ten (10) fish species were observed included commercially important Queen Conch, Mutton Snapper, and Caribbean Spiny Lobster. Green turtle was also observed.	the northern flushing channels and basin entrance. Greatest impacts will occur at the southern boat basin entrance. Placement and construction of northern flushing channels will employ BMPs to limit removal of individuals trees. Once flushing channels are in place, it is expected that mangroves will naturally recolonize the area. Activity was limited in the open flats.	- Waste Management Program - Educational signage in boat basin on species using mangroves

12 Environmental Management & Mitigation

Environmental management is a systematic approach that integrates environmental policy and planning with continuous monitoring of implementation techniques to improve environmental compliance in order to achieve the goals of sustainable development. Hazards to human health and safety and the environment can be managed through careful planning, vigilance and strong communication during works, and continual improvement to the overall environmental management program.

The preferred management approach is to avoid, minimize, and control adverse impacts to human health, safety, and the environment. Where adverse impacts cannot be avoided, best management practices should be employed to mitigate human and environmental harm.

Mitigation is considered when a project component is known to generate an adverse impact. To offset this unavoidable impact, mitigation techniques may include the creation, restoration, enhancement or preservation of the natural habitat.

Types of mitigation include:

- In-Kind Mitigation: A type of compensatory mitigation in which the adverse impacts to one habitat type are mitigated through the recreation, restoration, or enhancement of the same habitat type
- On-Site Mitigation: A mitigation project at or near the adversely affect site
- Out of Kind Mitigation: A type of compensatory mitigation in which the adverse impacts to one habitat type are mitigated through the creation, restoration or enhancement of another habitat type.
- Off-Site Mitigation: A mitigation project located away from the adversely affected site (PBS&J, 2008).

12.1 Coastal Construction Managerial Best Practices

Nonstructural operational and maintenance procedures can also be used to prevent or reduce environmental impacts and even reduce the need for more costly structural controls (PBS&J, 2008). The following managerial techniques for coastal construction activities should be considered:

- **Design, Siting Impact Avoidance and Minimization.** Impact avoidance may be achieved during the planning and design stage. Project siting and features should be reviewed for impacts and where practicable altered for impact avoidance, minimization and mitigation.
- **Personnel Qualifications**: Personnel responsible for implementation of the EMP should be evaluated prior to construction start. The qualified Environment, Health, and Safety Manager or position of the like may be required to perform water quality monitoring, turbidity monitoring, biological monitoring, wildlife monitoring, and additional technical tasks.
- **Construction Windows**. Construction may be best contained within a specific time period to avoid adverse wildlife impacts. Such construction windows may consider the presence of endangered species.
- **Buffer Zones**. Buffer zones are a defined area surrounding a site to allow a minimum distance between construction activities and marine resources.
- **Adaptive Management**. Adaptive management allows for the flexibility to change construction operations in response to particular events.

12.2 Good Housekeeping Practices

Good housekeeping practices help to maintain a safe and healthy workplaces by eliminating hazards. While seemingly simple, a well-kept site improves productivity and worker health thereby aiding in accident and fire prevention. A tidy work site, free of clutter and organized, allows for more effective use of the site.

General housekeeping should keep the work areas free of litter and ad-hoc construction debris. All solid waste materials will be placed in a designated dumpster or bin to be regularly emptied on schedule and disposed of at a facility as indicated by the Department of Environmental Health Services (DEHS). Sanitary conveniences will be emptied at regular intervals by an approved sewage disposal company. Hazardous materials such as contaminated soils with hydrocarbons will be identified, remediated, and disposed of in coordination with DEHS.

General guidelines for good housekeeping practices include but are not limited to the following:

- Identification and marking of physical hazards, such as open trenches
- A designated materials storage area with adequate space and organization for supplies
- Preventive maintenance on tools and machinery to reduce the threat of spills and accidents
- A waste management program that provides and frequently empties bins for litter, dumpsters, and a designated area for construction debris
- DEPP will be notified immediately of any oil spill and/or hazardous materials contamination

12.3 Site Safety and Health

Personnel on site will have access to sanitary conveniences, potable water, and personal protective equipment (PPE).

General site safety and health practices include:

- Sanitary conveniences will be available for use on site and regularly emptied.
- Hazards such as open trenches and utilities, will be marked by caution tape.
- All personnel will undergo an initial site safety and health training followed by weekly tool-box talks.
- A first aid kit and emergency contact list will be available at all times.
- Security and signage will identify hazards to public safety.
- Potable drinking water will be available on site at all times.
- Activities will cease during inclement weather.

Additional PPE will be available for work sites near water and will include ladders, safety harnesses, and training. PPE shall be inspected and maintained in good condition. If PPE becomes worn or broken, new PPE shall be distributed and used.

PPE will include but is not limited to the following:

- Steel toed boots
- Safety Vests
- Hard hats
- Gloves
- Eye Protection
- Boats
- Life jacket/preserver
- Ladders

12.4 Materials Storage

Materials stored according to best management practices prevent spills through hazard avoidance.

Materials shall be stored in a designated and secured area. Every material requires specific handling procedures as materials differ by composition, size, and weight. Materials shall be handled and stored according to specifications found in the Material Safety Data Sheet (MSDS). MSDS shall be kept on site at all times.

All fuel shall be stored away from waterbodies in a designated area. Flammable materials will be stored away from ignition sources to prevent fire. The Contractor shall have fire extinguishing equipment on site at all times.

12.5 Waste Management

Solid Waste Management

Waste management identifies a project's waste streams, makes provision for timely and effective removal, and allocates responsibility for waste disposal. General housekeeping should keep the work areas free of litter and ad-hoc construction debris.

All solid waste materials will be placed in a designated dumpster or bin to be emptied on a fixed schedule and disposed of at a facility as directed by the DEHS.

Additionally:

- No burning of debris is permitted.
- Debris may not be buried.
- Transport of materials to the designated landfill or transfer presents an opportunity for debris to enter the marine environment. All waste materials will be secured and covered, if possible, prior to marine and/or land transport. Record keeping will document the chain of command of waste movement to ensure proper disposal to the designated landfill or waste facility as determined by DEHS.

Liquid Waste Management

Liquid wastes includes wastewater, fuels, oils, lubricants, chemicals, and other contaminants that can enter the soil, ground water and surface water. Sanitary conveniences will be emptied at regular intervals by an approved sewage disposal company.

- Liquid waste on the property must be identified prior to construction.
- Any pipes or drains carrying liquid waste must be closed and drained prior to construction
- All UST/ASTs must be emptied prior to removal
- Designated wash-down area for equipment with no reuse of wash-down water
- No discharge of liquid wastes to waterbodies
- Proper storage and disposal of oil products

12.6 Hazardous Waste Materials

For the purpose of this EMP, hazardous materials are defined by the United States Environmental Protection Agency (US EPA) under the Resource Conversation and Recovery Act of 1976 (RCRA) as "a solid waste, or combination of solid wastes which because of its quantity, concentration, or physical, chemical, or infectious characteristics may – (A) cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness; or (B) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed."

Hazardous materials, if any, will be identified prior to construction to ensure implementation of best management practices during construction activity, debris storage, and debris removal. There are no anticipated hazardous materials; all materials will be stored in accordance to Material Safety Data Sheets.

There will be no refueling at the boat basin. Petroleum product storage is limited to above ground storage tanks to be used for the generator in the event of a power loss. Power is supplied via mainland Eleuthera.

All activities on site during the construction and operation of the property shall follow the Environmental Planning and Protection Act 2019 (Section 30 and 31) pertaining to Hazardous Substances and Hazardous Waste.

12.7 Equipment Refueling & Maintenance

Equipment should be kept in good working order with regularly scheduled maintenance. Preventative maintenance reduces the likelihood for unintentional spills or leaks during operation on site.

All fuel shall be stored away from waterbodies in a designated area. The tanks will be stored in a bermed area designed to hold 110% of the fuel tanks capacity. During construction the bermed area will be fully lined with impervious 32mil polyester liner. This bermed area location will be converted after construction into the permanent fuel storage location with concrete berm walls and slabs. During construction ISO double wall tanks will be stored in the lined berm area.

A designated refueling area shall be identified on site away from sensitive environmental features such as wetlands. Impervious sheeting should be on hand with a spill kit. Any spills should be cleaned according to the spill prevention plan.

Any heavy equipment stored on site will be placed in a designated area and on a geotextile membrane with a dune and catchment area to contain oil spills and mitigate potential contamination to the water lends.

In the event of an oil spill, the DEPP and the Department of Environmental Health Services should be notified within 24 hours. In the event that the spill is major, i.e. oil escapes a 55 gallon drum, the DEPP should be notified immediately. The spill response plan including remediation is found in Spill Response Plan appended to this document.

12.8 Prevention of Pollution of Groundwater Resources

Employment of best management practices will minimize adverse impacts to natural resources and ensure viability of sensitive environmental features such as wetlands and nearshore habitats. Erosion and sediment control measures will minimize sedimentation impacts and constitute a form of pollution control.

Spill prevention practices include

- A designated refueling and fuel storage area; with adequate containment measures (110% of capacity);
- Pump out of all UST/AST contents prior to container removal
- Preventive heavy vehicle and machinery maintenance and designated wash-down area;
- A waste management program, and;
- Spill clean-up kits on site.

12.8.1 *Erosion and Sediment Control*

Sediment and erosion control measures such as silt fencing, turbidity curtains, and revegetation will be deployed as required. Sediment impacts may occur during heavy storm events where flash flooding may erode surfaces and transfer suspended sediments to another location. Turbid conditions may adversely affect light penetration through the water column impairing photosynthesis for marine species.

Dredge Spoils

BMP dredge guidelines are provided in submitted dredge plan included in the Appendices. Dredge spoils will be stockpiled on the existing land area. The dredge fill will be allowed air dry sufficiently to remove moisture, salt and consolidate fines. The fill will be reused to form a “dry” beach to the east of the boat basin which is contained by silt fabric and natural stones. The silt fabric will prevent any sediment from the fill material into the surrounding waters. This is a flat area away from the water where BMPs will be implemented to control sediment transfer during inclement weather events.

No beach nourishment activity will be required. The slope of the interior beach is sufficiently flat to deter erosion. The interior beach will incur no wave action.

BMPs for erosion and sediment control include but are not limited to the following:

- Dewatering hoses will be placed away from sensitive environmental features and allow time for suspended sediment to fall out.
- Installation and on-going maintenance for sediment and erosion control devices such as silt fencing and/or turbidity curtains
- Revegetation and/or sodding of a cleared area
- Turbidity barriers selected are appropriate for water conditions
- Construction debris will be placed away from surface waters and with containment measures
- Excavated materials, if any, and/or fill stockpiles will be stored in pre-approved locations
- Equipment wash-down will occur in a pre-approved location to capture runoff

12.8.2 *Controls for Elevated Site Conditions*

The culverts will be installed within a northern ridge that separates Savannah Sound from the upland interior. These culverts allow an exchange of water between the boat basin and the sound. The placement of these culverts will occur at the end of the boat basin construction; this land plug will eliminate turbid conditions during the excavation of the larger boat basin. Engineering controls will stabilize the land with runoff prevention BMPs such as silt fencing and a vegetation buffer to reduce runoff during storm events.

Homeowners must follow a homeowner manual titled "North Windermere Island: Single Family Private Residences - Design Guidelines". Seventy-five percent (75%) of the lot land must be reserved with a 25' vegetation buffer on the property's perimeter. Retaining vegetation cover will reduce the potential for runoff during construction and operation.

See next page.

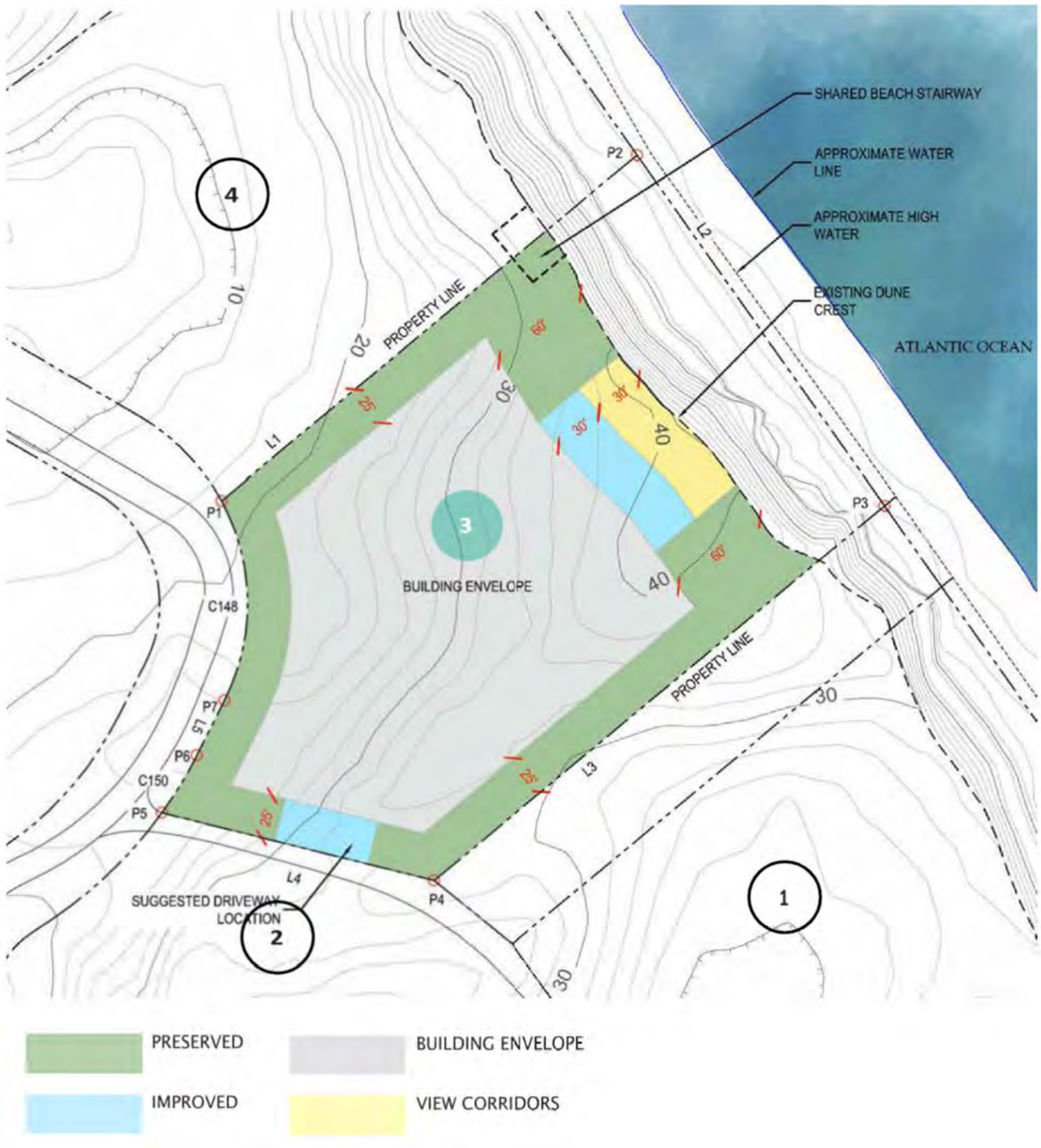


Figure 12-1 Design Guidelines Lot Restrictions

12.8.3 *Turbidity Control*

Turbidity control will be achieved through a combination of BMPs, turbidity barriers, and continuous monitoring. North Windermere Island shall use floating turbidity barriers for moving water, Type 2 or Type 3, to prevent the dispersal of suspended sediment. This temporary in-water sediment barrier consists of a geotextile fabric curtain suspended from a flotation device and held in vertical position with a ballast at the bottom. Turbidity skirts should never rest on the bottom and maintain at least one (1) foot above sea floor. In areas of high tidal flow and wave action, curtains and anchoring devices must be installed according to manufacturer's recommendations.

Important Considerations:

- Turbidity barrier will be placed across marina entrance for the duration of construction activities
- Faults occurring along the turbidity barrier will be corrected immediately. Construction will be halted when curtains are not correctly installed and functional.

Turbidity Monitoring

During basin construction notably, excavation of the culverts and southern entrance, turbidity readings will be taken at several predetermined locations three times per day and recorded in a daily log. Prior to construction, turbidity levels will be recorded to determine the background level. This background level will be approved by DEPP for use as the control.

Elevated Turbidity Levels

If turbidity readings measure 29 NTU above the background level the Environmental Manager on site will issue a cease and desist order for all construction operations. Operations will not resume until turbidity readings return to satisfactory levels, the cause is identified and construction methods are altered to prevent recurrence of elevated turbidity levels. The Construction Manager and Environmental Manager will work together to revise construction methods.

DEPP will be notified upon non-compliance of turbidity levels and a corrective action report filed. The Environmental Manager will indicate when activities can resume.

12.9 Air Quality and Noise

Air

The Contractor shall implement measures to maintain ambient air quality. Fine sediment may become airborne during the dry season which typically begins in November and ends in late May. Dust mitigation strategies include periodic dampening and street cleaning of the marina perimeter and/or construction access roads.

Additional practices for management of air quality include but are not limited:

- Tarpaulins used on dump trucks
- Vehicle speed restrictions
- Frequent site watering during the dry season
- Daily road cleaning and sweeping
- Perimeter fencing may include a tarp to capture dust particles

Noise

The Contractor shall work between normal business hours beginning not before 7am and ending not after 6pm. The project is located in a residential neighbor. Noise prevention and mitigation begins at the source of noise. Noise reduction at the source prevents extraneous noise output.

Noise reduction option include but are not limited to the following:

- Selecting equipment with lower sound power levels
- Installing suitable mufflers on engine exhaust and compressor components
- Installing acoustic enclosures for equipment casing radiating noise
- Installing vibration isolation for mechanical equipment
- Limiting hours of operation for specific pieces of equipment or operations, especially mobile sources operating through community areas

Noise impacts should not exceed the following:

Noise Level Guidelines		
	One Hour L_{Aeq} (dBA)	
	Daytime 07:00 – 22:00	Nighttime 22:00 - 0:700
Residential; Institutional; Educational	55	45
Industrial; Commercial	70	70

Table 12.9-1 IFC Noise Level Guidelines

12.10 Fire and Hurricane Risks

The North Atlantic tropical cyclone season begins June 1st and ends November 30th. However, tropical disturbances may form prior to the start and after the close of this time period. The Bahamas lies within the hurricane zone, it is expected that tropical disturbances, tropical depressions through Category 5 Hurricane, may periodically make landfall. Risks associated with tropical cyclones include storm surge, high winds, and heavy rainfall. Given the low elevation of the site and the surrounding areas, the drainage system must be able to effectively dispose runoff during heavy storm events.

Fire-fighting equipment such as a fire extinguisher must be available on site at all times. The inventory of materials shall dictate any substances requiring additional specialty fire-fighting equipment. A list emergency numbers should be available on site at all times.

12.11 Site Security

Mariners will be advised of construction activity occurring in the vicinity of the North Windermere Island boat basin.

Signage will alert residents and visitors of danger. Fencing may be used to secure the site and all trenches will be marked.

Additionally, the site will be gated and have security during working hours. When security is not present, the site will be inaccessible.

12.12 Transportation and Traffic Management

While North Windermere Island is a private development and located away from populated areas, vehicles, employees, and residents/guests on island must be well informed of the project schedule and sequencing of construction works. For human, health, and safety, BMPs will be employed for adequate signage, flagmen, speed control, and designated heavy vehicle entry and exit. Works will take place during normal hours unless advised otherwise.

Workmen will be on site whenever heavy duty vehicles are approaching and leaving the site.

General BMPs for traffic management include:

- **Signage**. Site access entry and exit will be identified by a visible sign. One way roads, if any, will be marked.
- **Flagmen**. Entry and exit on to roadways with vehicle traffic will be provided with a flagman. Flagman will aid safe truck entry and exit and secure site entry with a visitor list.
- **Overhead Clearance**. For areas with overhead obstruction, i.e. powerlines, a clearance trap will be provided prior to the obstruction for oversized heavy vehicles and equipment.

- **Drainage and Wet conditions**. Weather events may flood roadways and create dangerous operating conditions. Areas that do not have adequate drainage will be identified and graded with additional fill.
- **Operator Training**. Operators will undergo continuous driver safety training. Drivers and workers will be aware of emergency medical plans, fire suppression, and oil spill plans in the event of an accident.
- **Equipment Maintenance**. Routine maintenance deters machinery malfunctions during use. Routine maintenance should include checks for oil leaks, hydraulic fluid leaks, tire pressure, back-up alarms, lights and indicators, and other inspections required for roadworthiness.

12.13 Special Environmental Conditions

Employment of best management practices will minimize adverse impacts to natural resources and ensure viability of sensitive environmental features such as wetlands and nearshore habitats. Excavation works will take place adjacent to and within coastal wetland areas. Savannah Sound is a functional wetland and nursery habitat for juvenile fish species. As such, special care is to be taken to maintain the ecological viability of Savannah Sound.

Erosion and sediment control measures will minimize sedimentation impacts and constitute a form of pollution control. Spill prevention practices include designated refueling and fuel storage areas with adequate containment measures, preventive heavy vehicle and machinery maintenance, and spill clean-up kits on site, and waste management. No equipment wash down will occur on site.

13 Mitigation

Wetlands exist in a transition zone between the aquatic and terrestrial environments. Neither terrestrial nor aquatic, wetlands have unique characteristics that allow for a distinct classification. The Bahamas is a signatory to the Convention on Wetlands of International Importance for Waterfowl Habitat, also known as the Ramsar Convention. Ramsar defines wetlands as ‘areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters’.

Ecosystem services provided by wetlands include: storm surge and flood protection, water quality improvement, nursery and feeding habitat, waterfowl habitat, inherent aesthetic and cultural values, and recently discovered, mangroves are prolific natural carbon sinks. Anthropogenic alterations to existing marine and vegetation communities are threatening coastal ecosystems; in the case of the Bahamas mangroves are particularly affected. Threats to wetland communities include: coastal development, aquaculture, nutrient loads, ecosystem change, and climate change.

The proposed 3.82 acre boat basin will result in the loss of wetland habitat including individuals of red and black mangrove. To mitigate this loss of habitat, management protocols for waterfowl habitat and mangrove/vegetation habitat are provided below.

13.1 Waterfowl/Avian Habitat Management Plan

Avifauna can be considered indicator species for ecosystem health. Highly visible and subject to movement, avifauna provide a relatively easy opportunity to monitor seasonal fluctuations and adaptations to changes in habitat. Climate change presents a host of unknown effects to waterfowl and shorebirds with increasing sea surface temperatures, ocean acidification, sea level rise, higher intensity tropical disturbances, and changing rainfall patterns.

A study performed by Ogden et al, 2014, quantified the level of impact to waterbirds based on a series of drivers and pressures including vulnerabilities to climate change. Those drivers resulting in the greatest impact include altered water and air temperature due to climate change, contaminant releases, threats due to invasive species, human disturbance, and land-based activities resulting in changes of habitat (Ogden, 2014)[1]. Wintering shorebirds have incurred reduced numbers due to loss of coastal habitat. Increasing recreational use of coastal habitat results in unintentional disturbance to nesting and foraging areas. Provided herein are management protocols to address changes in the environment for the development of a boat basin at North Windermere Island.

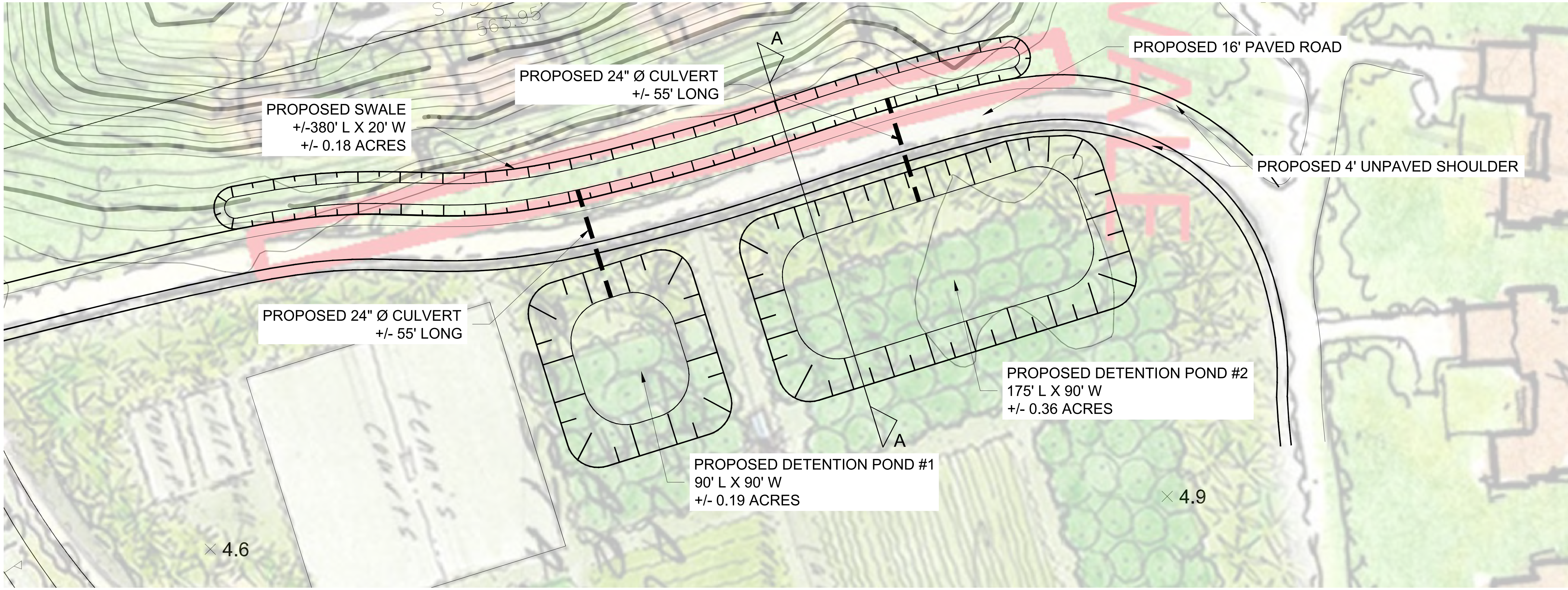
13.1.1 *North Windermere Boat Basin Waterfowl Habitat Creation*

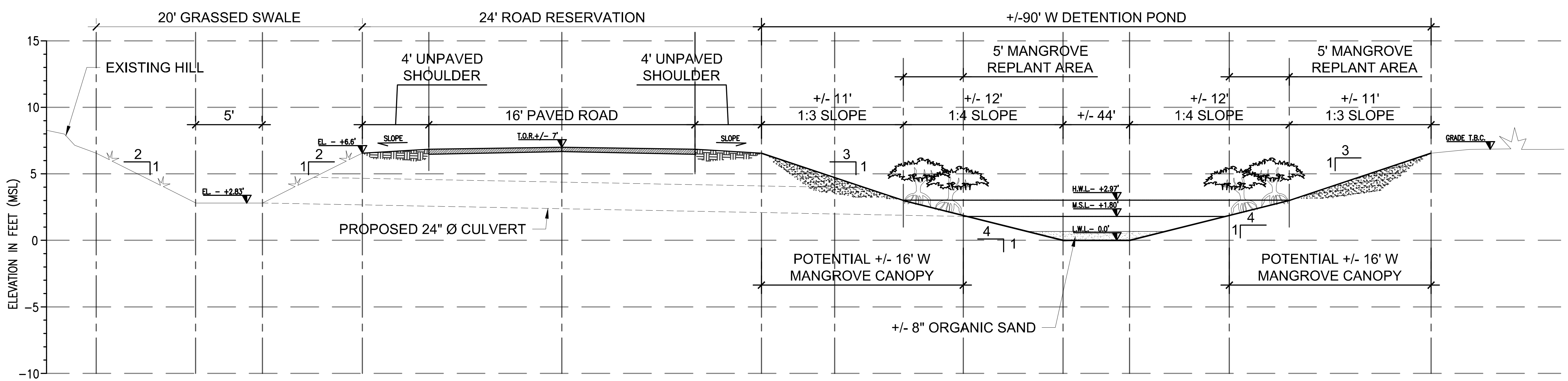
Avifauna were observed on 2nd to 3rd of November 2018 capturing the fall migrants and beginning of the winter residents. Avifauna observed at North Windermere Island were either permanent residents or winter non-breeding residents with the White Crowned pigeon the only near-threatened species observed with many individuals. It is highly likely that additional avifauna utilize the site but were not observed during the bird survey.

The boat basin and adjoining culvert system will result in the direct loss wetland utilized by waterfowl. To mitigate this loss, 0.8 of waterfowl habitat will be created on-site in the vicinity of the agricultural area. This area will be planted with native vegetation to replicate to the extent possible wetland formations loss during the boast basin and culvert excavation.

Please see proposed design schematic on the next page.

[1] Ogden, John C.; Baldwin, John D.; Bass, Oron L.; Browder, Joan A.; Cook, Mark I.; Frederick, Peter C.; Frezza, Peter E.; Galvez, Rafael A.; Hodgson, Ann B.; Meyer, Kenneth D.; Oberhofer, Lori D.; Paul, Ann F.; Fletchet, Pamela J.; Davis, Steven M.; and Jerome J. Lorenz. Waterbirds as indicators of ecosystem health in the coastal marine habitats of Southern Florida: 2 Conceptual ecological models. Ecological Indicators. 44 (2014) pages 128-147.





SECTION A - TYP. ENBANKMENT DETAIL

SCALE: 1/8" = 1'-0"

PROJECT	WINDERMERE ISLAND DEVELOPMENT
DRAWING	PROPOSED CATCHMENT AREAS
DATE	JANUARY 2021

13.1.2 *North Windermere Waterfowl Conservation Goals*

It is recommended that North Windermere Island establish conservation goals specific to waterfowl that are embraced by homeowners to mitigate habitat loss. These conservation goals will be upheld through the management protocols as recommended.

Conservation goals:

- To assess the seasonal status of avifauna by documenting annual trends and fostering citizen science through participation in seasonal bird counts.
- To produce educational materials specific to avifauna for use by the residential community, visitors, and community of Savannah Sound.
- To provide opportunities to attain information via training, literature review, or funding original research.

Management Protocols

- Vector Control Program. Avifauna are highly vulnerable to mammalian nest predators including raccoons. Raccoons, feral cats, and rats should be controlled and eradicated at the first sign of occupation. A single raccoon can disrupt an entire colony of avifauna.
    - Traps should be kept on island with education provided to homeowners for BMPs for vector control.
    - All domesticated cats should be kept predominantly indoors.
    - Invasive plant species should be controlled and eradicated according to the National Invasive Species Strategy 2013. Invasive plants crowd out native plants that provide foraging and nesting areas for avifauna.

- Prevention of Pollution (Point and non-point sources). The installation of a channel to Savannah Sound introduces the potential for point source nutrient enrichment from the outflows of the boat basin. Nutrient enrichment may result in change to macroalgal biomass, zonation, and herbivory.
    - It is important that a strong landscaping policy is developed to lessen impacts from fertilizers and/or pesticides used by homeowners for the beautification of lots. Many contaminants are bioaccumulative leading physiological and neurophysical effects resulting in lower fecundity.
    - Native tree plantings will reduce the need for fertilizer.

- Education. Humans are drawn to nearshore and coastal habitat frequented by shorebirds and waterfowl. Unintentional disruption to these species warrants educational outreach to homeowners and visitors to be respectful to these habitat types.
    - It is recommended that the developer produce an avifauna pamphlet that identifies avifauna species, important habitat, and pollution prevention measures.
    - Limited disturbance should occur to the beach wrack line which provides foraging to shorebirds and other coastal species.
    - It is recommended that the developer participate and encourage seasonal avifauna counts with homeowners and the local birding community. A formal association with the Bahamas National Trust to support continued avifauna education and research is highly recommended.
    - Bird counts and avifauna observations by residents are recommended to be added to the internationally recognized database eBird by Cornell University https://ebird.org/home.

- Habitat Preservation. Habitat loss and human disturbance greatly influence avifauna visits.
    - No fishing. No fishing or netting within the boat basin to protect juvenile fishes and food source for avifauna.
    - No harvesting of shellfish/bivalves. No removal of shellfish or bivalves from the boat basin.

- Preservation of the dune. A coastal setback and dune preservation policy will lessen impacts to shorebirds utilizing the beach. Dunes provide avian habitat and protection for homeowners during storm events. Coastal beach erosion due to sea level rise and/or habitat loss for construction will result in the loss of foraging habitat.
- Preservation of the wrack line. The wrack line also referred to as seaweed, accumulates on the beach during high tide and remains onshore during the low tide. Avifauna and shore creatures forage in the wrack line.
- Noise ordinance. It is recommended that noise attenuation polices are in place to limit disturbance. For example, landscaping equipment such as blowers should be banned.
- Preserving the night skies. It is recommended that the developer follow guidelines developed by the International Dark Skies Association to reduce light pollution at night. Dark skies are imperative for species such as turtles to enable successful transition to the sea following hatching should any utilize the beach for nesting.

13.2 Vegetation Management & Mangrove Wetland Protection Plan

The proposed 3.82 acre boat basin will result in the loss of wetland habitat including individuals of red and black mangrove. Coastal communities are particularly vulnerability to the effects of climate change namely, sea level rise and increased severity of storm events. Mangrove wetlands and tidal creeks such as Savannah Sound, attenuate these impacts and provide habitat for wildlife species, marine and avian. Curtailing wetland loss is a cornerstone of the Ramsar Convention for the promotion of waterfowl habitat. Impacts associated with the proposed boat basin include an unavoidable loss of wetland vegetation, the potential for turbid conditions, and land instability.

13.2.1 *Vegetation Management*

There will be an unavoidable loss of vegetation in areas slated for development, namely the boat basin. The developer shall take care to ensure that vegetation removal is kept at a minimum and only within the area of works.

Clearing and grubbing prepares the site for construction. Clearing removes the above surface foliage and trees whereas grubbing removes the roots that remain in the soil. This process requires heavy machinery and adherence to BMPs for sediment and erosion control, prevention of pollution to ground water resources, and protection of sensitive of environmental features, namely mangroves.

There shall be no burning of material on site.

Construction BMPs:

- Protection of Sensitive Environmental Features.
  - Fencing shall be placed along sensitive environmental features such as wetlands and protected tree species to protect from encroachment, illegal dumping, and damage from machinery.
  - The workforce will receive training on protected tree species and the importance of wetland habitat and mangroves.
  - Mangrove individuals in the area of the culvert will be removed by hand to be replanted.
  - A walkover survey shall be performed prior to the commencement of works. Protected trees, if any, in the area of the work site shall be removed only upon receipt of a Permit to Harvest a Protect Tree as permitted by the Forestry Unit.
  - Mangrove restoration shall occur quickly following culvert installation.
  - Heavy machinery will undergo routine maintenance to prevent leaks, spills, and/or other mechanical failure which may cause environmental harm.

- Cleared Vegetation.
  - Vegetation that is cleared and cannot be replanted shall be used as mulch in landscaping. Invasive species should not be used as mulch and should be sent to a government approved landfill.

  - Landscaping debris shall be stockpiled in a designated location away from the coastline.
  - There shall be no burning on site.

- Landscaping & Planting
  - All areas cleared for construction should be replanted as soon as possible to mitigate sediment and erosion impacts.

13.2.2 *Mangrove Wetland Protection BMPs*

Construction of the boat basin will result in the loss of several interior wetland communities including sawgrass formation, glasswort formation, and buttonwood formation. The majority of the peninsula and immediate areas are covered by DBEF. Red mangrove communities are not expected to incur long-term adverse impacts. The black mangrove community fringes the area of the southern boat basin with select species removed for construction. As confirmed in aerial imagery, the coastal vegetation along the southern peninsula perimeter was previously disturbed given the present atypical species composition.

This section documents techniques to mitigate wetland loss at North Windermere Island resulting from construction of the boat basin.

Construction BMPs

- Sediment and Erosion BMPs. Turbidity can be controlled through best management practices including the use of turbidity curtains and dredging during low tide when the area and surrounding wetlands are above the waterline. The majority of boat basin excavation will be performed prior to a connection with the sea by maintaining a plug to eliminate unnecessary sedimentation.

- Shoreline Stability. The canal extension will introduce increased water flow into the area potentially resulting in erosion impacts to the shoreline and to the mangrove wetland.

- Mangrove replanting 2:1. Mangroves are carbon sinks and protect against coastal erosion by lessening the severity of storm surge. To mitigate the loss of wetland species, it is recommended that invasive species are removed within the shoreline and replaced with native vegetation.
  - Mangrove seedlings are recommended to come from Eleuthera.

- Individual mangrove removal.
  - Removal of mangrove individuals only where necessary for culvert installation.

13.2.3 *Wetland Mitigation Techniques for North Windermere Island*

The objective for the wetland mitigation program for North Windermere Island is to enable self-recruitment of mangrove individuals following installation of the culverts and initial mangal planting. With adequate biophysical conditions, self-recruitment is the long-term goal for North Windermere Island. Substantial alteration of water flow to achieve perceived optimal flushing time may impede self-recruitment due to changes in the critical hydrological regime.

1. **Boat basin Design.** The boat basin design incorporates natural walls and slopes to encourage recolonization of shoreline vegetation and use by local marine benthic species. Given the shallow depths of Savannah Sound, the boat basin will be excavated to a depth of five (5) ft below mean low.

2. **Flushing Channels.** Access to the boat basin is via the southern basin entrance channel. The two (2) northern culverts will allow for water circulation while eliminating high velocity water flow associated with tide changes to encourage natural recolonization of the existing mangrove community. A semi-annual flushing and flow rate will be provided to DEPP for the first three (3) years.

3. **Natural Coastline.** Homeowners will be discouraged from removing existing coastal vegetation around the boat basin and peninsula. Invasive species will be removed and replaced with native vegetation.

4. **Mangrove Planting.** Individual mangroves to be affected by construction will be removed and allocated for revegetation following construction completion. Where needed, additional mangroves will be planted as propagules to supplement natural recolonization.

5. **Waste Management.**
    a. Solid Waste Management. Trash will be collected, stored, and sorted at a designated location. Covered waste bins may be provided on and around the property to prevent litter.
    b. Liquid Waste Controls. All homes and facilities will Boats will must use pump out services if required.
    c. Pesticides, Fertilizers, and Herbicide Use. The community will discourage the application of pesticides, fertilizers, and herbicides to limit pollution into the waterbodies.
    d. Fuel. No fueling services will be provided at the boat basin.

Important considerations for wetland creation and restoration (Mitsch 2007):

1. **Local Wetland Ecology**. Mangroves will flourish in environments with suitable hydrology, biochemical, and wave energy conditions.
2. **Self-Design to Avoid Over-Engineering**. Self-design means that the ecosystem created or restored contains the properties that will allow mangroves and the wetland system to grow naturally. Whether through human or natural seeding a successful self-designed mangrove habitat will adjust and change over time. The system should be self-sustaining. Mangrove success should not be determined solely on the number of plants or animals present.
3. **Mangal Planting**. Where a mangal formation has been decimated completely, the physical planting of trees may be required to reintroduce the species into the greater ecosystem. A December 2016 article in Smithsonian notes the excessive costs associated with planting as in the case of the Philippines where the World Bank spent $35 Million to plant three (3) million mangrove seedlings between 1984 and 1992. By 1996, less than twenty (20) survived. Natural colonization is a cost-efficient mechanism if mangroves are present within the area of restoration and the biophysical and biochemical properties remain the same.

Mangal planting while a popular mitigation technique may not yield satisfactory results. Research indicates that natural recolonization of mangroves is the preferred approach for effective mangrove restoration. According to Wetlands International, when the enabling biophysical and socio-economic conditions are in place, nature will do rest resulting in optimal placement, better survival, and a more resilient mangrove forest. Planting efforts fail due to poor understanding of the hydrological and biochemical needs for mangrove survival. However, planting can assist or enrich the natural regeneration process.

13.2.4 *Spill Response in Mangroves*

The United States National Ocean and Atmospheric Administration (NOAA) published guidance for planning and response considerations for oil spills in mangrove systems. It is recommended that the developer use this guide during construction and operation. While no fueling operations are anticipated, equipment refueling will occur on site during construction operations. This manual combined with an Environmental Management Plan and the above wetland mitigation techniques should facilitate a functional wetland habitat in association with the proposed boat basin. This manual is provided within the appendix.

14 Grievance Redress

Grievance redress is a management tool to identify, assess, and provide resolution of complaints during a project cycle. Implementing a system of grievance redress early in a project's cycle allows for resolution of minor issues before escalation to high-profile and expensive disputes at the local and national level. Support is garnered from local communities which have access to a system for complaint filing and resolution. Grievance redress mechanisms (GRMs) are a core component of managing project operational risk. A system to receive, catalogue, and respond to community concerns is important.

According to the *World Bank's Approach to Grievance Redress in Projects* the following steps should be taken:

Step 1 Assessment of Risks and Potential Grievances and Disputes
Step 1 is the identification of potential issues, stakeholders, and existing institutional capacity for dispute resolution.

Step 2 Capacity Assessment

Step 2 reviews the capacity for local and national institutions to address and resolve project concerns. Institutions will be reviewed through a credibility assessment with the following criteria: legitimacy, accessibility, predictability, fairness, rights compatibility, transparency, and capability.

Step 3 Action Plan
Step 3, the Action Plan, creates tangible steps to be implemented during project planning and execution to enable effective grievance management for dispute resolution. Successful grievance management systems contain the following components:

- Access Point(s) for Complaints, i.e. Help Desk
- Grievance Log Database
- Assessment, Acknowledgement, and Response to Complaint(s)
- Appeals Process
- Resolve and Follow-Up

14.1 Grievance Contact Information

During the construction and operation of the North Windermere Boat Basin, members of the public will be able to submit comments and questions to the Owner's representative, Daniel Casali, via an email address, dan@northwindermere.com. These comments will be acknowledged and responded to in an appropriate timeframe.

15 Environmental Monitoring & Reporting

Environmental compliance is achieved through frequent and consistent site inspection and strong communication with the Contractor. The monitoring checklist is the mechanism within the environmental management system to document onsite practices, provide recommendations, and note when corrective action is required.

Should corrective action not take place, the Environmental Manager will file a non-conformance report to effect corrective action. The Environmental and Manager will have the authority to cease and desist installation works. Environmental monitoring will be performed daily with electronic copies provided to DEPP. All daily environmental monitoring checklists will be compiled into a monthly report and provided to DEPP.

Construction
Construction monitoring documents Contractor compliance to the EMP with respect to but not limited to: site safety and health, protection of ground water, general housekeeping, hazardous waste disposal, noise and air quality control, and protection of sensitive environmental features.

Operation
Environmental monitoring and reporting will continue through the operational phase of the project. During the project's operational phase, the developer will produce a semi-annual environmental report.

Please refer to a sample Environmental Monitoring Checklist on the following page.

Environmental Monitoring Checklist – North Windermere Boat Basin

Environmental Specialist: ___________________________ Date:_____________________

Site Description:___________________________________ Time: _____________________

Weather (Circle One): Sunny Partly Cloudy Cloudy Rain Temperature (°F): _______

Special Weather Notes: ______________________________

1	**Site Safety and Health**			
		In Compliance with EMP		
		YES	Corrective Action Required	Comments
1a	Personal Protective Equipment Used			
1b	Proper safety requirements signage for Safe Road and Hazardous Sites			
1c	Traffic management and site access			
1d	Sanitary facilities are clean and convenient			
1e	Adequate Freshwater drinking supplies			
2	**Ground Water Management**			
		In Compliance with EMP		
		YES	Corrective Action Required	Comments
2a	All diesel, fuels, and other toxic materials securely bundled in welded steel trays whose capacities are at least 110% of max. stored vol.			
2b	Refueling area next to storage tanks and on concrete apron in case of spillage			
2c	All mobile machinery is in good condition and free from engine, lubrication, and oil leaks with drip trays when not in use			
2d	Spill kits, adsorbents, emergency kits on site			
2e	Wash-down area away from waterbodies and contained			
3	**Erosion and Sediment Control**			
		In Compliance with EMP		

		YES	Corrective Action Required	Comments
3a	Silt-traps and turbidity barriers adequately place			
3b	Erosion Control Measures: silt fencing, check dams, sediment basins, sodding and other measures			
3c	Control of dewatering activities and runoff			
3d	Stabilization of slopes and excavated areas			
3e	Turbidity Measures are in compliance			
4	**Vegetation**			
		In Compliance with EMP		Comments
		Yes	Corrective Action Required	
4a	Vegetation removed as needed			
4b	Site Restoration			
5	**Materials Storage & Solid Waste Management**			
		In Compliance with EMP		
		Yes	Corrective Action Required	Comments
5a	Construction material storage area secured and appropriately stockpiled			
5b	Minimum 1 dumpster and 2 litterbins			
5c	General Tidiness of the Site			
5d	Ground surface debris disposed of at proper facility			
5e	Hazardous materials identified, stored, and disposed of properly			
6	**Dust & Air Pollution/Noise Control/Odour**			
Monitoring Checklist		In Compliance with SMP		
		Yes	Corrective Action Required	Comments
6a	Roadway watering and daily site clean up to mitigate airborne dust			

6b	Speed restrictions adhered to				
6c	Dump trucks fitted with tarpaulins				
6d	No incineration along road corridors				
6e	Noise levels within recommended decibels for day/night				
6f	Observation of foul odours				
7	**Miscellaneous**				
7a	Accident Log - Any reported Environmental Incidents or Safety Accidents? Personnel Involved and Accident Details				

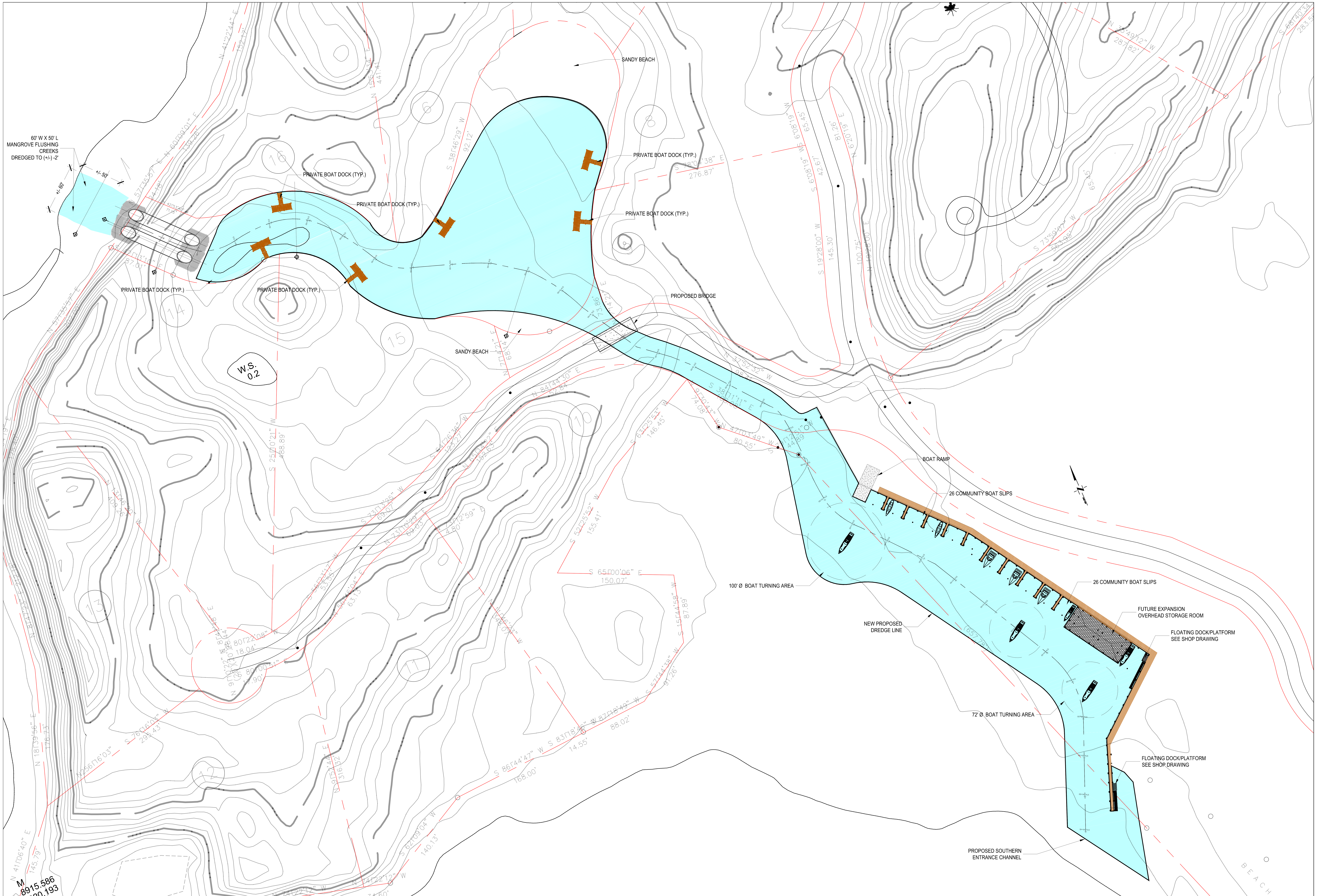
* To note, the monitoring checklist is limited to observations at a specific time and place and cannot account for activities occurring outside the time of inspection unless such activity or the results thereof are observed during inspection.

16 References

1. BEST Commission, National Invasive Species Strategy for The Bahamas, 2013.
2. Sealey, Neil E. *Bahamian Landscapes.* 3rd Edition. Macmillan Caribbean. 2006
3. IFC. Environmental, Health, and Safety (EHS) Guidelines. Noise Management. April 30, 2007
4. U.S. Army Corps of Engineers. Water Resources Assessment of The Bahamas. 2004. Available for download at http://www.sam.usace.army.mil/en/wra/Bahamas/Bahamas.html
5. Ogden, John C.; Baldwin, John D.; Bass, Oron L.; Browder, Joan A.; Cook, Mark I.; Frederick, Peter C.; Frezza, Peter E.; Galvez, Rafael A.; Hodgson, Ann B.; Meyer, Kenneth D.; Oberhofer, Lori D.; Paul, Ann F.; Fletchet, Pamela J.; Davis, Steven M.; and Jerome J. Lorenz. Waterbirds as indicators of ecosystem health in the coastal marine habitats of Southern Florida: 2 Conceptual ecological models. Ecological Indicators. 44 (2014) pages 128-147.
6. Ogden, John C.; Baldwin, John D.; Bass, Oron L.; Browder, Joan A.; Cook, Mark I.; Frederick, Peter C.; Frezza, Peter E.; Galvez, Rafael A.; Hodgson, Ann B.; Meyer, Kenneth D.; Oberhofer, Lori D.; Paul, Ann F.; Fletchet, Pamela J.; Davis, Steven M.; and Jerome J. Lorenz. Waterbirds as indicators of ecosystem health in the coastal marine habitats of Southern Florida: 2 Conceptual ecological models. Ecological Indicators. 44 (2014) pages 128-147.

17 Appendix

17.1 Master Plan/Dredge & Excavation Plan



LAGOON LAYOUT PLAN

SCALE: 1:600

REVISIONS	BY

ENGINEERING & TECHNICAL SERVICES
P.O.BOX SS 5589 NASSAU, N.P. BAHAMAS.
Tel: (242) 394-3219 Fax: (242) 394-4488

PROPOSED BOAT BASIN
WINDERMERE ISLAND, BAHAMAS

SHEET NAME: LAGOON OVERVIEW PLAN

DRAWN :	CHECKED :
J.V.	L.K.

DATE : JAN. 2020

SCALE : AS NOTED

JOB NO. :

SHEET

S - 9

17.2 Town Planning Master Plan Approval

CURVE TABLE				
CURVE	LENGTH	RADIUS	TANGENT	DELTA
C106	35.46'	205.00'	17.78'	N9°54'42"
C107	172.94'	300.00'	88.95'	N33°01'43"
C108	144.11'	250.00'	74.12'	N33°01'43"
C109	141.94'	130.00'	78.98'	N62°33'28"
C110	140.75'	180.00'	74.19'	N44°48'03"
C111	138.09'	205.00'	[illegible]	N38°35'43"
C112	55.79'	180.00'	28.12'	N17°45'25"
C113	104.41'	155.00'	54.27'	N38°35'43"
C114	139.73'	500.58'	70.32'	N[illegible]59'74"
C115	143.86'	550.00'	75.40'	N15°36'4[illegible]"
C116	128.41'	205.00'	66.39'	N35°53'21"
C117	100.90'	155.13'	51.97'	N37°02'44"
C118	62.75'	155.00'	[illegible]	N23°1[illegible]'46"
C119	82.83'	205.00'	41.99'	N23°09'06"
C120	142.68'	430.00'	[illegible]	N19°00'43"
C121	100.29'	380.00'	50.44'	N15°07'17"
C122	53.21'	430.00'	26.64'	N7°05'24"
C123	72.94'	380.00'	36.58'	N1[illegible]
C124	86.34'	124.18'	45.[illegible]	N39°50'09"
C125	121.10'	174.18'	63.[illegible]	[illegible]
C126	107.08'	110.00'	58.21'	N55°46'3[illegible]"
C127	58.84'	60.00'	32.[illegible]	N56°11'30"
C128	32.00'	25.00'	15.6[illegible]	N73°20'49"
C129	33.57'	15.00'	30.90'	N128°13'08"
C130	66.90'	73.24'	35.98'	N52°19'47"
C131	22.95'	43.24'	11.75'	N30°24'48"
C132	52.03'	33.34'	33.00'	N89°25'01"
C133	98.94'	63.34'	62.79'	N89°29'52"
C134	27.64'	250.00'	13.84'	N6°20'06"
C135	30.96'	280.00'	[illegible]	N6°20'06"
C136	14.90'	17.00'	7.96'	N50°12'29"
C137	43.89'	33.00'	25.88'	N76°12'42"
C138	71.90'	33.00'	63.16'	N124°49'41"
C139	45.72'	33.00'	27.39'	N79°22'36"
C140	14.90'	17.00'	7.96'	N50°12'29"
C141	94.25'	60.00'	60.00'	N90°00'00"
C142	172.79'	110.00'	110.00'	N90°00'00"
C143	228.49'	125.00'	162.[illegible]	N104°43'48"
C144	26.73'	75.00'	13.51'	N20°25'21"
C145	110.36'	75.00'	67.90'	N84°18'27"
C146	68.63'	125.00'	35.20'	N31°27'29"
C147	113.05'	75.00'	70.39'	N86°21'54"
C148	119.79'	125.00'	64.94'	N54°54'25"
C149	101.58'	200.00'	[illegible]1.81'	N29°02'39"
C150	38.69'	250.00'	19.39'	N8°52'05"
C151	88.03'	250.00'	44.48'	N20°10'33"
C152	43.23'	50.00'	23.07'	N49°32'25"
C153	86.46'	100.00'	46.14'	N49°32'25"
C154	83.74'	360.00'	42.06'	N13°19'41"
C155	72.11'	310.00'	36.22'	N13°19'41"
C156	125.58'	325.00'	63.58'	N22°08'22"
C157	84.32'	375.00'	42.34'	N12°52'57"
C158	119.14'	50.00'	125.40'	N136°31'20"
C159	122.61'	120.00'	67.26'	N58°32'28"
C160	62.82'	90.00'	32.75'	N39°59'32"
C161	120.28'	195.00'	62.12'	N35°20'32"
C162	156.54'	155.00'	85.68'	N57°51'51"
C163	76.65'	195.00'	38.83'	N22°31'18"
C164	18.76'	195.00'	9.39'	N5°30'46"
C165	52.52'	195.00'	26.42'	N15°25'50"
C166	56.66'	155.00'	28.65'	N20°56'36"
C167	22.27'	165.00'	11.15'	N7°43'54"
C168	27.56'	205.00'	13.85'	N7°43'54"
C169	39.35'	155.00'	19.78'	N14°32'48"
C170	49.51'	195.00'	24.89'	N14°32'48"
C171	73.12'	165.00'	37.17'	N25°23'32"
C172	21.99'	165.00'	11.01'	N7°38'04"
C173	52.61'	48.49'	29.23'	N62°09'55"
C174	95.13'	48.49'	72.45'	N112°25'00"
C175	115.56'	48.49'	121.63'	N136°13'04"
C176	55.48'	205.00'	27.91'	N15°30'26"
C177	66.12'	205.00'	33.30'	N18°27'08"
C178	267.01'	325.00'	141.56'	N47°04'22"
C179	205.52'	375.00'	105.41'	N31°[illegible]
C180	126.01'	1546.27'	63.04'	N4°4[illegible]
C181	128.64'	1596.27'	64.35'	N4°37'02"
C182	40.83'	955.71'	20.42'	N2°26'5[illegible]"
C183	35.37'	905.71'	17.69'	N2°14'1[illegible]"
C184	19.02'	185.33'	9.52'	N5°52'44"
C185	13.99'	60.00'	7.03'	N13°21'25"
C186	116.94'	185.33'	60.49'	N36°09'04"
C187	88.01'	135.33'	45.63'	N37°16'03"
C188	70.11'	100.00'	36.57'	N40°10'17"
C189	105.17'	150.00'	54.85'	N40°10'17"
C190	150.22'	5973.83'	75.12'	N1°26'27"
C191	151.48'	6023.83'	75.74'	N1°26'27"
C192	59.81'	300.00'	30.01'	N11°25'24"
C193	49.84'	250.00'	25.00'	N11°25'24"
C194	44.68'	895.28'	22.34'	N2°[illegible]'33"
C195	42.18'	845.28'	21.09'	N2°5[illegible]'33"
C196	134.14'	300.00'	68.21'	N25°37'09"
C197	111.78'	250.00'	56.84'	N25°37'09"
C198	85.68'	456.93'	42.97'	N10°44'37"
C199	76.56'	406.93'	38.39'	N10°46'47"
C200	211.59'	2299.10'	105.87'	N5°16'2[illegible]"
C201	212.57'	2370.88'	106.36'	N5°08'14"
C202	52.47'	82.69'	27.15'	N36°21'16"
C203	88.95'	132.69'	46.22'	N38°[illegible]
C204	63.37'	163.99'	32.40'	N22°20'59"
C205	87.77'	212.99'	44.51'	N23°29'57"
C206	64.76'	400.00'	32.45'	N9°16'35"
C207	56.67'	350.00'	28.40'	N9°16'35"
C208	179.18'	105.51'	119.89'	N97°17'59"
C209	34.27'	55.51'	[illegible]	N97°17'59"

SURVEY PLAN

SHOWING

"WINDERMERE ISLAND NORTH"

SITUATE

ABOUT 1,500 FT. NORTH OF THE BRIDGE
IN THE NORTHERN SECTION OF
WINDERMERE ISLAND

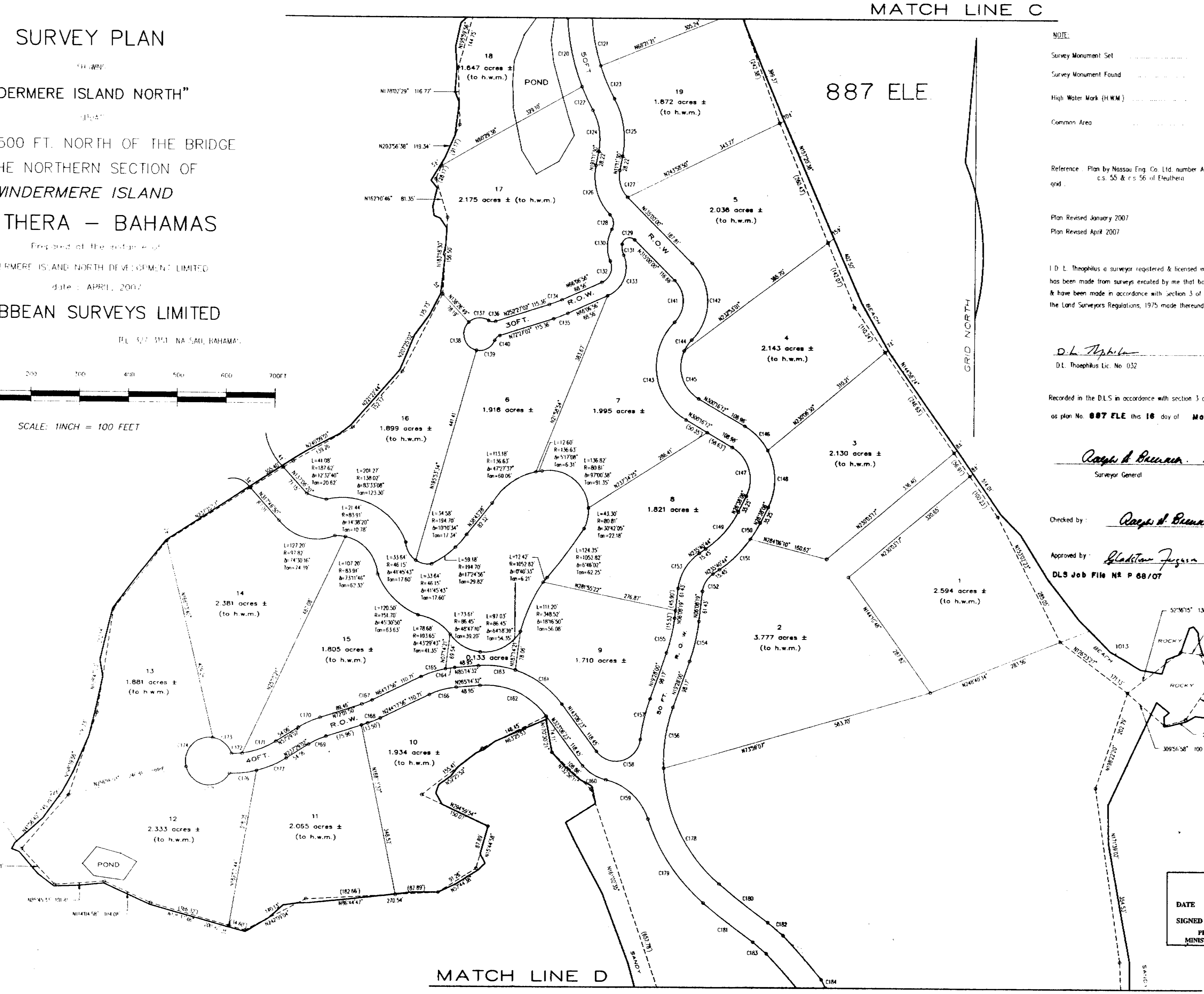
ELEUTHERA – BAHAMAS

Prepared at the instance of
WINDERMERE ISLAND NORTH DEVELOPMENT LIMITED
date : APRIL, 2007

CARIBBEAN SURVEYS LIMITED

P.O. BOX N 8153 TEL 3[illegible] NASSAU, BAHAMAS

SCALE: 1INCH = 100 FEET



NOTE:

Survey Monument Set

Survey Monument Found

High Water Mark (H.W.M.)

Common Area

Reference : Plan by Nassau Eng. Co. Ltd. number A486
c.s. 55 & c.s. 56 of Eleuthera
and

Plan Revised January 2007

Plan Revised April 2007

I D. L. Theophilus a surveyor registered & licensed in the Bahamas certify that this plan has been made from surveys excuted by me that both the plan & the survey are correct & have been made in accordance with section 3 of the Land Surveyors Act, 1975 and the Land Surveyors Regulations, 1975 made thereunder.

D.L. Theophilus Lic. No. 032

Recorded in the D.L.S in accordance with section 3 of the Land Surveyors Act, 1975 as plan No. **887 ELE** this **16** day of **May** 2007.

Surveyor General

Checked by :

Approved by :

DLS Job File Nº P 68/07

APPROVED FOR SALE OF LOTS

DATE 2/3/09

SIGNED

PERMANENT SECRETARY MINISTRY OF THE ENVIRONMENT

SHEET 4 OF 5

Windermere Island North
Boast Basin Master Plan

17.3 Turbidity Monitoring Form

Turbidity Monitoring Report
North Windermere Island Boat Basin
Windermere Island, Eleuthera, The Bahamas
(Turbidity testing to occur before work begins and every three (3) hours until dredging stops)

Name of Tester__________________________ Date: _______________ Time: __________

Site Conditions		**Background Turbidity** _________		**0 NTU**
Weather	**Clear**	**Partly Cloudy**	**Cloudy**	**Rain**
Tide	**High**_______	**Low**___________		
Wind	**Speed**______	**Direction**_______		

SAMPLING

Sample 1 Before Daily Dredge Operation Begins

1A	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
1B	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
1C	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	

Sample 2 Three Hours after Dredging Starts

2A	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
2B	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	

2C	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	

Sample 3 Six Hours after Dredging Starts

3A	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
3B	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
3C	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	

Sample 4 Nine Hours after Dredging Starts

4A	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
4B	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	
4C	**Location:**				
	NTU		**Time**		
	GPS Coordinates	**Latitude**		**Longitude**	

17.4 Spill Prevention, Control, and Countermeasure (SPCC) Plan

A Spill Prevention, Control, and Countermeasure Plan (SPCC) implements best managements to prevent the discharge of pollutants and/or petroleum products. It is a proactive measure to manage the storage, use in order to avoid a release of a pollutant into the environment. Key preventative measures include proper materials storage, material use, and equipment preventative maintenance.

At its core, SPCC is part of the environmental management system such as ISO14001 of Plan, Do, Check, Act.

Key SPCC Procedures:

1. Operating BMPs to Prevent Spills. Environmental awareness training and toolbox talks shall incorporate spill prevention practices to educate employees about standard operating procedures to avoid a spill event. These BMPs include:

- Materials Storage Information. Materials should be stored according to MSDS. Petroleum products should be stored on elevated surfaces or with an impervious layer separating the container from the ground. Appropriate containment and if needed, secondary containment should be capable of 110% storage. Oil sources shall not be stored near floor drains or sensitive environmental features, such as wetlands. Petroleum products should be stored in a secured area.
- Product Transfer and Refueling. Refueling and fuel transfer should use pads, drip pans, and/or funnels when using petroleum products. Any refueling done on site shall be in a previously agreed designated area with employed spill prevention techniques to prevent the release of a petroleum product to the environment. Tanks should be filled to no more than 90-95% due to the potential for overflow from expansion in hot weather. No smoking during equipment refueling or any fueling exercise.
- General Housekeeping. General housekeeping principles to keep a site clean and free of debris can contribute to culture of cleanliness and vigilance for storage and handling practices that may cause a release.

2. Control Measures - Spill Clean-up Kit. In the event of a spill, spill-kits should be easily identified and readily available on site. These kits should include absorbent products such as pad, sawdust, kitty litter, pillow and booms. All personnel on site should be aware of the spill clean-up kit location. All spills shall be reported immediately to the Environmental Manager or On-Site Manager.

3. Oil Spill. When an oil product is released to the environment, employees should be trained in first-response measures.

The following steps should be followed:

- Utilize oil spill response training prior to spill
- Immediate use of spill kit or measures to contain spill safely
- Contact Environmental Manager or On-site Manager at the time of spill
- Notification to DEPP within 24 hours or in the event of major spill (release from a 55 gallon drum), notification to DEPP immediately.

4. Clean up. Clean-up efforts are most effective when employed quickly following a spill.

- If a spill occurs on a paved surface, it is best to keep the spill contents away from drains. Use absorbent pads or socks to contain the spill.
- If a spill occurs on soil, it is best to keep the spill away from waterways. Use absorbent pads or socks to contain the spill. Spills to soils should be excavated immediately. All contaminated soils, by visual and odour detection, should be placed on an impervious surface such as a tarp and covered. DEHS should be contacted to determine proper method for disposal. The contractor should keep receipt of the disposal of contaminated materials by DEHS.

- Large spills may require sampling to determine extent and prolonged monitoring during remediation efforts. Major spills, release from a 55 gallon drum, will require clean-up in coordination with DEHS. Efforts using the spill kits including absorbent materials and containment measure should be employed while waiting instruction.

17.5 Inclement Weather & Hurricane Plan

Project Crisis Management Team Duties

The potential threat posed by a hurricane requires a prepared response of all site and project personnel.

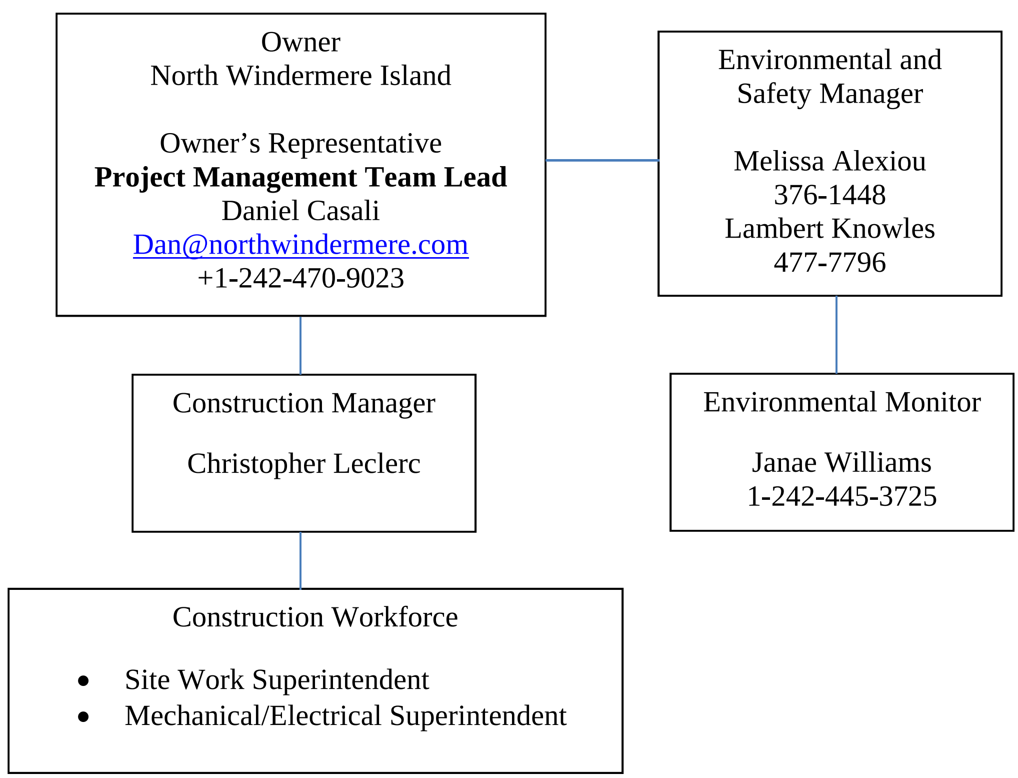
The Project Management Team (PMT) has reviewed all procedures and established the Project Hurricane / Specific Severe Weather. Keep in mind that no emergency follows a script. The Crisis Management Team (CMT) must continually gather information, assess the possible consequences and decide what should be done, who should do it, and how.

The PMT will monitor weather developments, communicate all required hurricane-related activity and oversee hurricane damage assessment and remediation.

Participation will be required from each project/business unit. Managers will be responsible for requesting participation of their subordinates as needed.

17.5.1 *Project Management Team Organizational Chart*

The Owner's Representative Daniel Casali will lead the Project Management Team. He will coordinate all inclement weather and hurricane preparation and response with the Environmental & Safety Manager, and Construction Manager. The Contractor will be responsible to securing equipment and safety his personnel with oversight and direction given by the Project Management Team Lead, Daniel Casali. The Environmental and Safety Manager will review policies and coordinate with the PMT Lead and Construction Manager to ensure the health and safety of the environment during inclement weather and compliance to this EMP.



Responsibilities of the PMT

Before Hurricane Season (Prior to June 1st)

1. Review the Hurricane Preparedness & Response Plan.
2. Review weather-monitoring resources including satellite television (Bahamas Department of Meteorology, The Weather Channel), AM/FM radio, weather radio, and any other radios recommended by the local government. Ensure that there are sufficient spare batteries stockpiled.
3. Maintain sufficient copies of the Hurricane Tracking Chart and tracking table.
4. Verify that the EOR is equipped as outlined in this plan and is ready for use. Provide necessary equipment; verify all equipment is in normal operating condition; and communicate to members of the CMT and all department heads the location and telephone number of the EOR.
5. Review and update list of emergency telephone numbers for PMT and all staff.
6. Survey all buildings and grounds to identify windstorm or flood related exposures that can be mitigated by repair or emergency measures before a storm. Repairs should be completed before June 1st.
7. Identify resources that would be needed if the site was flooded. Verify sandbag need and placement to protect possible water entry points and vital protection equipment.
8. Develop a Damage Survey and Repair Team (DSRT) that will be the first on site to assess damage and make the site safe enough for return of workforce.
9. Contract an external company to shoot aerial and fixed film images to update the property documentation for areas where changes have been made.
10. Contact off-island vendors and contractors of building materials, heavy equipment, generators, pumps, electrical transformers and switchgear equipment, motors, and other critical systems. Verify availability and obtain proposals. (if needed)
11. Inventory vital records including paper records, computer tapes or disks, or other media that will need to be moved to a safe and secure location.
12. Evaluate the need for any additional flood proofing of vital equipment.
13. Review inventories of emergency supplies and pursue acquisition of additional as needed.
14. Order hurricane supplies for post-hurricane clean up.
15. Begin removing coconuts from all coconut palms. Arrange for contractor to clean taller palms.
16. Check the condition of tall trees within 25 ft. to 75 ft. of any structure that may cause damage to nearby structures.
17. Remove all loose debris from landscape including limbs, loose 2 x 4's, trash etc.
18. Trim Vegetation around the property. Anchor trees that are not firmly rooted or remove. Remove all debris.
19. Identify locations of all essential BEC transformers and high voltage switchgear and liaise with BEC for any reasonable protection.
20. Verify that there are sufficient portable fuel containers to run pumps for an extended period (24 – 48 hours).
21. Identify potential vehicular access problems resulting from flooding or storm surge carried sand and debris.
22. Ensure that necessary road signs are ordered, for example; Detour, No Through Road, No Parking, Directional Signs, etc.

23. Inventory vehicles and update accordingly. Determine which vehicles are best suited for usage during and after the hurricane.
24. Keep the site continuously free from an accumulation of debris and scrap material to reduce the amount of time required for hurricane preparation.
25. Confirm availability of still and video cameras (plus film, tapes and batteries) to document property damage.
26. Verify that hurricane supplies are on-site or secure location.
27. Maintain constant communications with ALL EMPLOYEES – before, during and after a storm or hurricane, as regards the following:
    a. Safety features
    b. Communications from Management
    c. Scheduling concerns
    d. Any work related matters
    e. Storm updates
    f. Post storm updates

Follow the detailed procedures outlined in Hurricane Preparedness Plan.

HURRICANE PREPARATION AND REACTION PLAN

1. The PMT Area Superintendent is responsible for these preparations and implementation of these plans.
2. The site will **not be** occupied during the storm if it is in the hurricane path, only pre/ post hurricane.
3. Preparations will be made in time for personnel to prepare for the storm at their homes.

WHEN A HURRICANE APPROACHES

4. The PMT will decide when to prepare the project for a hurricane or tropical storm.
5. Check the supplies against the inventory list stockpiled at the beginning of the hurricane season.

HOUSEKEEPING:

6. Ensure that all loose scrap material is gathered up and disposed of in the dumpsters.
7. Ensure that the dumpsters are emptied. If the dumpster service is unable to pull the dumpsters they shall be securely covered with nets to prevent the debris in them from becoming windblown hazards.
8. Ensure that all loose forming materials are neatly stacked and banded.
9. Ensure that all materials, tools, tool sheds, gang boxes and small equipment that can be damaged by rising water are removed from excavations and low areas prone to flooding.

The Site Work Superintendent shall:

10. Ensure that continuous berms are installed at excavations.

11. Remove any non-essential barricades. Anchor essential barricades.
12. Ensure that incomplete underground piping and storm drain systems are protected against the infiltration of sand and silt.
13. Ensure that all equipment is relocated out of excavations.
14. Remove all mobile cranes off site.

15. Top off the fuel tanks of all equipment and ensure fill caps are properly secured.
16. Ensure dewatering, standby, and diesel powered equipment is ready to operate. Operate this equipment as conditions warrant.

The Mechanical, Electrical, Fire, Plumbing Superintendents shall:

17. Identify vulnerable material and work in progress and determine how to best protect it from the effects of flooding.
18. Ensure that all meter pits are outfitted with sump pumps so as to prevent damage to electronic equipment from rising water.
19. Ensure that all electronic equipment in storage is protected from rising water.
20. Ensure backup electrical generator power as required.
21. Turn off the power and water to the office trailers.
22. Be prepared to supply fuel tanks for de-watering pumps, portable generators and vehicles during the storm and remobilization after the storm.
23. Be prepared to anchor or restrain or dismantle and band anything that might blow away.
24. Loose tools and lumber should be tied down or placed in storage containers.
25. Tie erected form work together to make it more resistive to high winds.
26. Scaffold planking is to be dismantled, bundled and banded.
27. Anchor portable toilets or have them picked up.
28. Procure netting adequate to cover dumpsters that could not be emptied.

AFTER THE STORM IS OVER

29. PMT manager to give all clear.
30. Assemble the Damage Survey team. The Damage Survey Team will inspect the job site, identify and document the damage, prioritize repairs, complete Job Hazard Analysis and Safe Plans of Action, and then initiate repairs with a skeleton remobilization crew of skilled trades' persons.
31. Class A hazards will have priority and must be abated before calling in the whole workforce to resume construction.
32. Do not touch loose or dangling wires. Report such damages to the electrical Contractor, the utility company or police officers.

33. Stay clear of disaster areas where we may hamper first aid or rescue work. Be prepared to offer assistance with equipment
34. Stay alert as to prevent any fires. (Water pressure will be low).
35. Complete preparations for the return of the full workforce.
36. Implement the system to inform employees to return to work.
37. Be aware that we may need to care for some of our employees. Call the local RED CROSS and report persons needing assistance. Red Cross Bahamas Society -323-7370.

17.6 Hazard Communication & Hazardous Materials Management & Response Plan

Workers have a right to know hazard information as communicated through a global classification system. Information about the identities and chemicals must be available and understandable to workers.

All activities on site during the construction and operation of the property shall follow the Environmental Planning and Protection Act 2019 (Section 30 and 31) pertaining to Hazardous Substances and Hazardous Waste.

17.6.1 *Hazard Communication*

The United States Occupational Safety and Health Administration (OSHA) has aligned its Hazard Communication Standard (HCS) with the Globally Harmonized System of the Classification and Labelling of Chemicals (GHS). The integration of these two classification systems presents a coherent approval to classifying chemicals and communicating hazard information to workers. OSHA requires:

- All employers with hazardous chemicals in their workplaces must have labels and safety data sheets for their exposed workers, and train them to handle the chemicals appropriately.
- U.S. chemical manufacturers and importers are required to evaluate the hazards of the chemicals they produce or import, and prepare labels and safety data sheets to convey the hazard information to their downstream customers.

Employers should train employees to identify and understand hazard communication labels and maintain material safety data sheets (MSDS) on-hand in order to ensure correct handling of chemicals.

OSHA Hazard Communication Quick-Guide (See next page)

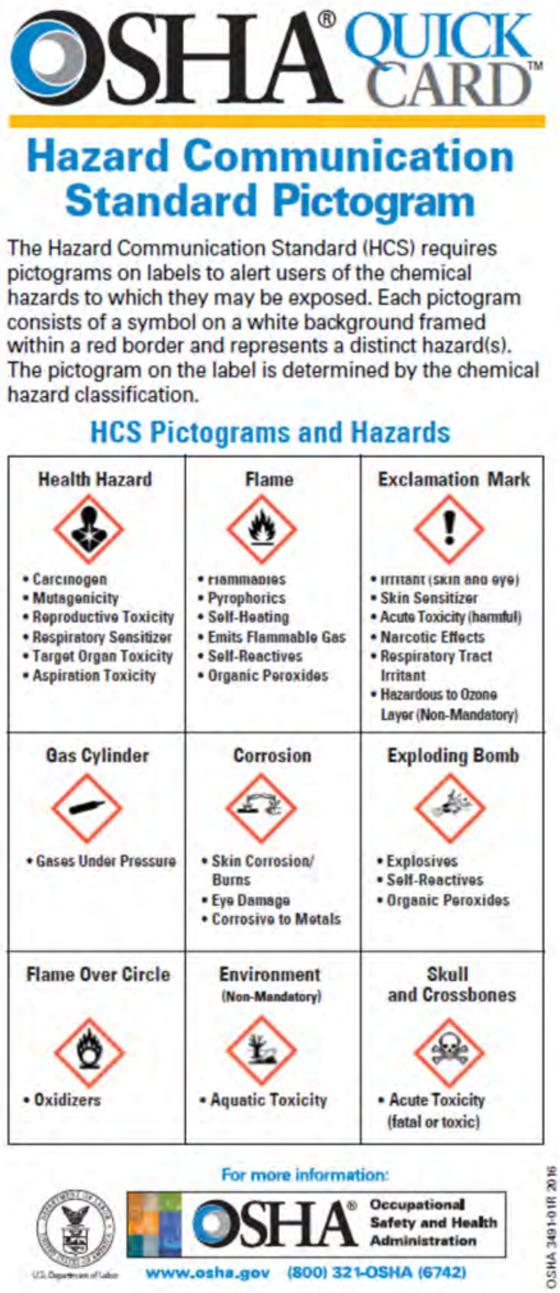


Figure 17-1 OSHA Hazard Communication

17.6.2 *Hazardous Waste*

For the purpose of this EMP, hazardous materials are defined by the United States Environmental Protection Agency (US EPA) under the Resource Conversation and Recovery Act of 1976 (RCRA) as “a solid waste, or combination of solid wastes which because of its quantity, concentration, or physical, chemical, or infectious characteristics may – (A) cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness; or (B) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed.”

Hazardous materials, if any, will be identified prior to construction to ensure implementation of best management practices during construction activity, debris storage, and debris removal. Hazardous material releases affect a range of stakeholders and may cause harm to people, the environment, critical infrastructure, and property.

17.6.3 *Hazardous Waste Response Plan*

Hazardous substance releases should be reported by the Designated On-Call Safety Officer as quickly as possible to local DEHS officials with precautions immediately taken to protect human life. Hazardous waste cleanup requires trained personnel, untrained personnel should remain safe and wait for instructions from the designated authorities. Human health and safety takes priority. First responders will use a risk-based response process such as APIE "Analyze, Plan, Implement, and Evaluate" by the United States Fire Protection Association (NFPA).[2]

The best method is prevention through hazardous materials storage and incident planning.

1. Notify the On-Call Safety Officer in the event of a hazardous material spill. [3]

2. Initiate an evacuation of an area or building by orders of the On-Call Safety Officer and secure the area to prevent access to authorized personnel; and

3. Notify additional resources to request assistance as determined by the On-Call Safety Officer. Call Local RBPF and DEHS officials or 919.

Responsibilities & Expectations

1. The On-Call Safety Officer will be available at all times.

2. Respond with appropriate action to control and remedy the event.

3. Respond to the event in a timely manner.

4. Maintain liaison with local Police and Fire Department.

5. Maintain status reports.

6. Provide a report of lessons learned.

---

[2] U.S. Department of Homeland Security. FEMA. Hazardous Materials Incidents: Guidance for State, Local, Tribal, Territorial, and Private Sector Partners. August 2019

[3] The University of Chicago: Environmental Health and Safety. Emergency Response Plan for Hazardous Materials. May 2020.

17.7 Environmental Manager CV – Janae Williams

Janae Williams

#44 Annas Close
Nassau, Bahamas
(242) 445-3725
janaedwilliams@gmail.com

Summary

Results-focused young professional with strength in critical thinking and problem solving. Proactive leader with experience in communication and collaboration. An adaptable learner proficient in leveraging social and cultural awareness to stimulate healthy conversation and action. Adept at managing concurrent objectives to promote efficiency and influence positive outcomes.

Skills

- Working collaboratively
- Time management
- Cultural and environmental competency
- Policy and procedure improvements
- Crisis intervention strategies

Experience

University of The Ozarks | Nassau, Bahamas
International Liaison to the Bahamas *01/2021 - Current*

- Managed orientation for 40+ international students.
- Coordinated accurate and timely immigration advising services for international students, including in-person, email, Zoom and telephone consultations.
- Defined strategies and created a plan to achieve ambitious operational objectives.
- Experience in proposal writing.
- Planned alternative and spring break trips.

University of The Ozarks | Clarksville, Arkansas
Assistant Director of Residential Life *01/2020 - 12/2020*

- Directed teams of professionals in special projects and daily operations.
- Established budgets and tracked expenses to maintain operational efficiency.
- Aided senior leadership during executive decision-making process by generating daily reports to provide data for consideration of corrective actions and improvements.
- Developed leadership and professional improvement activities for team members.
- Assisted residential living environments against compliance standards and safety requirements.

University of The Ozarks | Clarksville, Arkansas
Residence Hall Director *08/2019 - 12/2019*

- Responded to crisis situations quickly to maintain calm and immediately determine level of assistance needed.

- Conducted weekly meetings with directors and assessed and advocated resident needs; recommended solutions and strategies to improve resident care and satisfaction.
- Fostered relationships with residents and worked with new residents to optimize acclimation and ease transition to new living environment.
- Improved operations by working with team members and students to find workable solutions.

Bahamas Marine Mammal Research Organization | Abaco, Bahamas
Intern *06/2019 - 08/2019*

- Worked with a team on Marine Mammal research.
- Collected and analyzed biological data about relationships between organisms and their environment.
- Interpreted research findings and summarized data into reports.
- Delivered presentations to campers on related topics.
- Spent many hours in the field observing and interacting with animals.
- Conducted a Sea Turtle Rescue along with the team
- Worked in a cold and wet environment on a daily basis.
- Gained essential knowledge of ID and Wildlife Photography.

Bahamas Marine Mammal Research Organization | Abaco, Bahamas
Intern *07/2016 - 08/2016*

Education and Training

University of The Bahamas | Nassau, Bahamas
Bachelor of Science in BioChemistry with Concentration in Marine Biology

- Completed 2 years, then transferred to University of the Ozarks
- Field Work in Marine Biology
- Attended numerous Environmental and Leadership seminars and conferences.

University of The Ozarks | Clarksville, Arkansas
Bachelor of Science in Environmental Studies*12/2019*

- Minors in Political Science and Philosophy
- Cum laude graduate
- Thesis: Evaluating Climate Change Perceptions at University of The Ozarks
- Selected member of President's Advisory Council
- International Student Ambassador
- Resident Assistant

Shaw Academy
Professional Certificate in Project Management

- Currently pursuing.

Reference available upon request.

17.8 NOAA Oil Spills in Mangroves: Planning & Response Considerations

Oil Spills in Mangroves

PLANNING & RESPONSE CONSIDERATIONS

September 2014

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration • National Ocean Service • Office of Response and Restoration

Oil Spills in Mangroves

PLANNING & RESPONSE CONSIDERATIONS

September 2014

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration • National Ocean Service • Office of Response and Restoration

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Cover Photograph Credit: Felix Lopez, U.S. Fish and Wildlife Service

INTRODUCTION

This guide is intended to assist those who work in spill response and planning in regions where mangrove ecosystems are an important part of the coastline. By understanding the basic of the ecology of these forests and learning from past oil spills in mangroves, we can better plan for, protect, and respond to spills that may threaten them. Mangroves often border coastlines where coral reefs live offshore, and these two ecosystems are closely linked. Mangroves filter and trap excess sediment that could harm coral, and coral reefs protect shorelines where mangroves grow from excessive wave energy. Both habitats can be adversely impacted by oil spills, and spill responders must often consider tradeoffs between land-based and offshore resources during a response. This guide is a companion to Oil Spills in Coral Reefs: Planning and Response Considerations.

This guide is not intended to be a definitive guidance for choosing cleanup methods, as many comprehensive versions of these exist already. Rather, it is a summary of current research on mangroves from the perspective of those who may need to make decisions about oil spill response in mangroves and presents the information in an accessible format for people with some science or response background. Experienced responders unfamiliar with mangroves may want background on mangrove ecology, while biologists may want an overview of oil toxicity and response actions applied to mangrove ecosystems. The topics are organized by chapters, which can be read as a standalone, with additional references provided at the end of each chapter. A glossary defines specialized terms.

Chapter 1 provides an overview of mangrove ecology, forest biology, associated mangrove communities, and how they respond to various natural and human stresses. Chapter 2 reviews the research on oil toxicity and impacts to mangroves. Chapter 3 discusses general guidance for responding to spills in mangroves and provides specific considerations for cleanup measures. Chapter 4 discusses long-term recovery of mangroves from oil spill impacts and restoration techniques and approaches. Chapter 5 compiles case studies to illustrate a range of issues from oil spills.

Mangrove forests are in many ways very adaptable ecosystems. They have the ability to tolerate a wide range of physical changes in their environment. However, despite their hardiness, they are highly vulnerable to oil toxicity and the impacts from cleanup activities. Thus, we must undertake any type of response or restoration activities in mangroves with caution. The information in this document will is intended to help minimize impacts to mangroves from oil spills and associated cleanup activities.

CHAPTER 1. MANGROVE ECOLOGY

Mangrove – a tree or shrub that has evolved the adaptations for growing in the intertidal zone (specifically, adaptations to salinity and flooded conditions).

Key Points

- Mangroves worldwide cover an approximate area of 150,000 square kilometers of sheltered coastlines in the tropics and subtropics.
- Five of the most common ecotypes include fringe, basin, riverine, overwash, and dwarf forests.
- Mangroves are restricted to the intertidal zone.
- Mangroves in general have a great capacity to recover from major natural disturbances.
- Mangroves maintain water quality by trapping sediments and taking up excess nutrients from the water.
- Mangroves play an important role in shoreline protection and stabilization.
- Mangroves provide important habitat for a wide variety of species of commercial, recreational, subsistence, and conservation interests
- Mangrove conservation and restoration are now also valued for carbon sequestration.

What is a Mangrove?

Ecologically, mangroves are defined as an assemblage of tropical and semi-tropical trees and shrubs that inhabit the coastal intertidal zone. A **mangrove** community is composed of plant species whose special adaptations allow them to survive the variable flooding and salinity stress conditions imposed by the coastal environment. Therefore, mangroves are defined by their ecology rather than their taxonomy. From a total of approximately 20 plant families containing mangrove species worldwide, only two, *Pellicieraceae* and *Avicenniaceae*, are comprised exclusively of mangroves. In the family *Rhizphoraceae*, for example, only four of its sixteen genera live in mangrove ecosystems (Duke 1992).

Where are Mangroves and What do They Look Like?

Mangroves worldwide cover an approximate area of 150,000 square kilometers (km^2) of sheltered coastlines, which is about 50% of their historic range (Spalding et al. 2010). They are distributed within the tropics and subtropics, reaching their maximum development between 25°N and 25°S (Figure 1.1). Their latitudinal distribution is mainly restricted by temperature because perennial mangrove species generally cannot withstand freezing conditions. As a result, mangroves and grass-dominated marshes in middle and high latitudes fill a similar ecological niche.

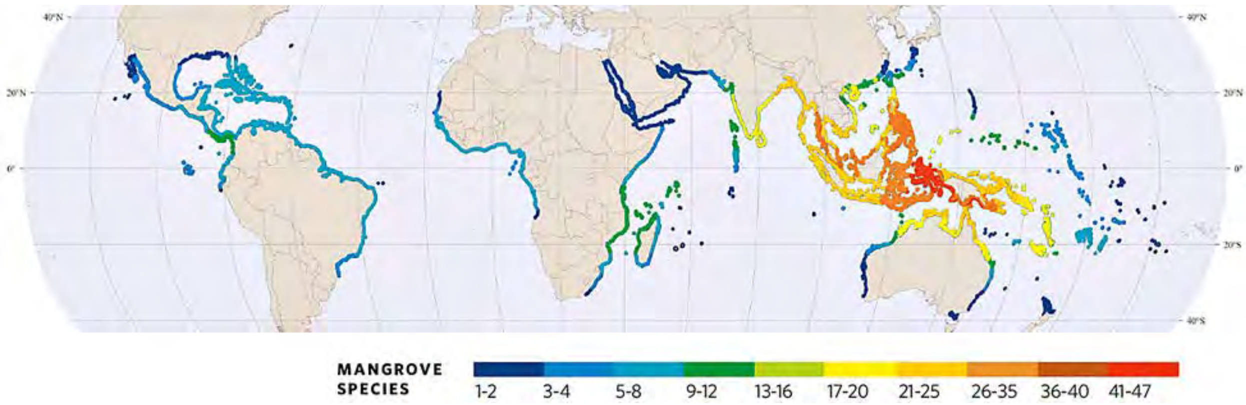

Figure 1.1. World map of the mangrove distribution zones and the number of mangrove species along each region (Deltares, 2014).

The global distribution of mangroves is divided into two hemispheres: the Atlantic East Pacific and the Indo West Pacific. As seen in Figure 1.1, the Atlantic East Pacific has fewer species than the Indo West Pacific (12 compared to 58 species, respectively). Species composition is also very different between the two hemispheres. Out of a total of approximately 70 mangrove species, only one, the mangrove fern, is common to both hemispheres.

In the continental United States, mangroves historically were distributed as distinct forests along the Atlantic and Gulf coasts of Florida. However, their range has expanded, with black mangrove forests now present in large numbers in southern Texas and Louisiana (Figure 1.2), mainly because of the decrease in the frequency and severity of hard winter freezes along the coast (Osland et al. 2013). More recently, red mangroves have started to appear in Texas. Mangroves also occur in Puerto Rico, the U.S. Virgin Islands, Hawaii, and the Pacific Trust Territories. There are 1,900 km^2 of mangroves along the Florida coast, with the most developed forest occurring along the southwest coast. The Gulf of Mexico and Caribbean regions are characterized by four dominant species (Table 1.1 and Figure 1.3): *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove), and *Conocarpus erectus* (button-mangrove or buttonwood). Black mangroves range further north than the other species because of their greater tolerance to low temperatures and ability to recover from freeze damage (Markley et al. 1982; Sherrod et al. 1986). Osland et al. (2013) predict that an increase in winter minimum temperatures may lead to black mangroves replacing salt marsh along portions of the Texas, Louisiana, and Florida coasts.

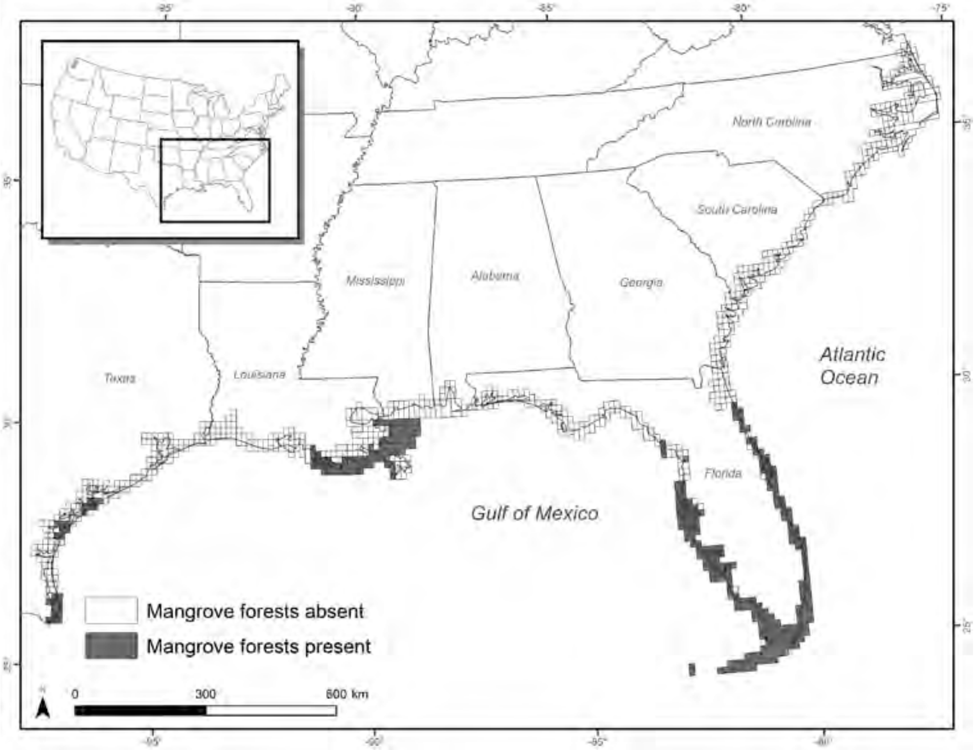

Figure 1.2. Distribution of mangrove forests in the continental United States based on data from 2006 for Texas and Louisiana and 2004 for Florida (Osland et al. 2013).

Table 1.1. Common mangrove species with common and scientific names and general distribution in the US and Caribbean regions.

Scientific name	Common name	Distribution
Rhizophora mangle	Red mangrove	Caribbean, FL, TX, HI (non-native)
Avicennia germinans	Black mangrove	Caribbean, FL, TX, LA, MS, American Pacific Trust Territories
Laguncularia racemosa	White mangrove	Caribbean, FL, American Pacific Coast
Conocarpus erectus	Buttonwood	Caribbean, FL
Acrostichum aureum	Mangrove fern	Caribbean, FL

Figure 1.3. Mangroves that occur in the U.S. and Caribbean. A) *Rhizophora mangel* (red mangrove) showing the classical tangle of prop roots. B) *Avicennia marina* (black mangrove) showing the diagnostic presence of pneumatophores. C) *Laguncularia racemosa* (white mangrove). D) *Conocarpus erectus* (buttonwood mangrove (A, B = Research Planning, Inc. and C, D = Robin Lewis), Lewis Environmental Services, Inc.).

Mangrove Ecotypes

Mangroves colonize protected areas along the coast such as deltas, estuaries, lagoons, and islands. Topographic and hydrological characteristics within each of these settings define a number of different mangrove ecotypes. Five of the most common ecotypes include fringe, riverine, basin, overwash and dwarf forests as shown in Figure 1.4 (Lugo and Snedaker 1974; Twilley 1998). A fringe forest borders protected shorelines, canals, and lagoons, and is inundated by daily tides. A riverine forest flanks the estuarine reaches of a river channel and is periodically flooded by nutrient-rich fresh and brackish water. Drainage depressions in the interior of mangrove areas harbor basin forests, characterized by stagnant or slow-flowing water. Overwash forests are islands frequently inundated or washed over by tides. Dwarf or scrub forests grow in areas where hydrology is restricted, resulting in conditions of high evaporation, high salinity, or low nutrient status. Low temperatures at the northern ranges of mangrove species distribution can also result in "scrub" mangrove areas in fringe, basin, riverine, and overwash settings. Such stressful environmental conditions stunt mangrove growth.

Each of these mangrove ecotypes is characterized by different patterns of forest structure, productivity, and biogeochemistry, all of which are controlled by a combination of factors such as hydrology (tides, freshwater discharge, rainfall), soil characteristics, biological interactions, and the effects of storms and other disturbances.

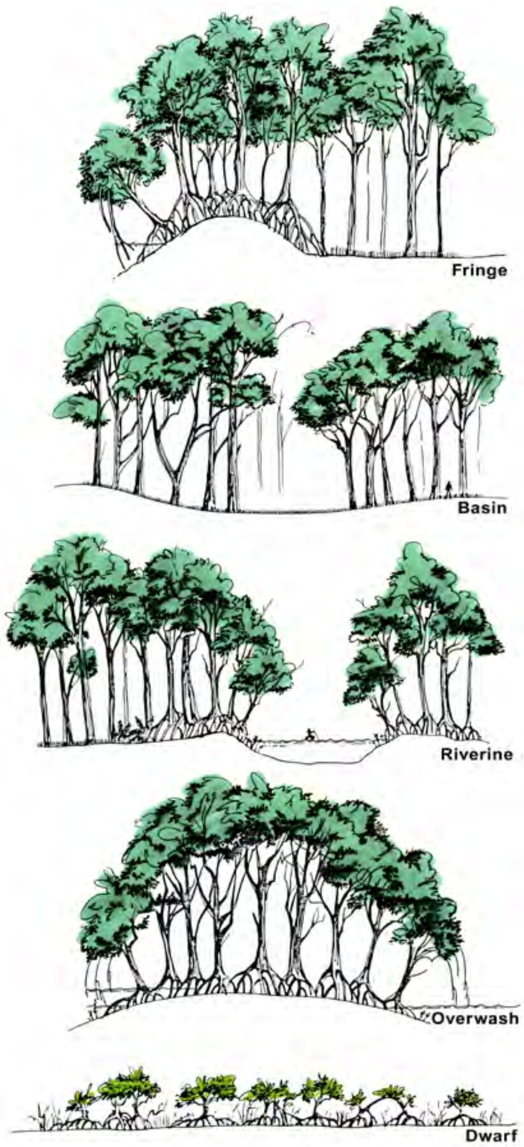

Figure 1.4. Various types of mangrove forests (modified from Lugo and Snedaker 1974).

Hermaphroditic – Both sexes present in an individual organism.

Vivipary – The condition in which the embryo (the young plant within the seed) germinates while still attached to the parent plant.

Propagule – Seedling growing out of a fruit; this process begins while the fruit is still attached to the tree.

Life History

Mangrove Reproduction and Growth

Most mangroves are **hermaphroditic** (both sexes are present in an individual organism). Mangroves are pollinated almost exclusively by animals (bees, small insects, moths, bats, and birds), except for *Rhizophora*, which is primarily self-pollinated (Lowenfeld and Klekowski 1992). In most mangroves, germination takes place while the embryo is still attached to the parent tree (a condition called **vivipary**). The embryo has no dormant stage, but grows out of the seed coat and the fruit before detaching from the plant. Because of this, mangrove **propagules** are actually seedlings, not seeds (Figure 1.5).

Vivipary as a life history strategy helps mangroves cope with the varying salinities and frequent flooding of their intertidal environments, and increases the likelihood that seedlings will survive. Since most non-viviparous plants disperse their offspring in the dormant seed stage, vivipary presents a potential problem for dispersal. Most species of mangroves solve this problem by producing propagules containing substantial nutrient reserves that can float for an extended period. In this way, the propagule can survive for a relatively long time before establishing itself in a suitable location (McMillan 1971; Tomlinson 1986).

Buoyancy, currents, and tides disperse mangrove propagules and deposit them in the intertidal zone. Once established, the numerous seedlings face not only the stresses of salinity and variable flooding, but also competition for light (Smith 1992). These, in addition to other sources of mortality, cause very low survival rates for seedlings and saplings. Determining the age of mangroves is difficult, but flowering individuals have been recorded as young as 1.5 years old. Tree growth, survival, and the ensuing forest structure are determined by the mangrove forests' ecotype.

There are few estimates of mangrove forest turnover (the time required for the forest to replace itself). Despite a precarious existence in the intertidal zone, Smith (1992) estimates mangrove turnover at 150-170 years. For comparison, an estimate for turnover in lowland tropical rainforests is about 118 years (Hartshorn 1978).

Figure 1.5. Examples of mangrove seedlings that occur in the U.S. and Caribbean. A) *Rhizophora mangle* (red mangrove). B) *Avicennia marina* (black mangrove). C) *Laguncularia racemosa* (white mangrove). D) *Conocarpus erectus* (buttonwood mangrove. (Robin Lewis, Lewis Environmental Services, Inc.).

Evapotranspiration – The transfer of water from the soil, through a plant, and to the atmosphere through the combined processes of evaporation and transpiration. Transpiration is a process of water loss through leaf stomatal openings.

Adaptations to Salinity

Mangroves can establish and grow under a relatively wide range of flooding and salinity conditions; however, they are generally restricted to the intertidal zone where there is less competition with freshwater plants. Mangroves have developed a series of physiological and morphological adaptations that have allowed them to successfully colonize these environments.

Mangroves do not require salt water to survive, but because of poor competition with freshwater vegetation and unique adaptations to the intertidal zone, they are generally found under the influence of salt water. Salinity is mainly determined by local hydrology, where input of salt water comes from the periodic tides and fresh water comes from rivers, rainfall, groundwater, and runoff. High **evapotranspiration** (water loss through the soil and plant leaves) in the tropics and subtropics can increase salinity considerably, especially under environments with restricted water flow. Thus, salinity can fluctuate widely within mangrove forests, both over time and space.

Mangroves have evolved different mechanisms to tolerate high salinities: salt exclusion, salt secretion, and tolerance of high salt concentrations within plant tissues are the main strategies. Most mangroves have developed all three mechanisms, although to varying extents. *Rhizophora*, *Bruguiera*, and *Ceriops* have root ultra-filters that exclude salt while extracting water from soils (Rützler and Feller 1996). In salt secretion, special organs or glands remove salts from plant tissues. For example, *Avicennia* and *Laguncularia* have special, salt-secreting glands that cause salt crystals to form on the leaf surfaces (Figure 1.6). These crystals then can be blown away or easily washed away by the rain. Leaf fall is another mechanism for eliminating excess salt in mangroves (Kathiresan and Bingham 2001).

Figure 1.6. Close-up of mangrove leaf showing salt crystals (C.E. Proffitt; Gulf of Fonseca, Honduras).

Adaptations to Flooding

Mangrove forests are periodically flooded, with the frequency and magnitude of flooding determined by local topography combined with tidal action, river flow, rainfall, surface runoff, groundwater, and evapotranspiration. As with salinity, hydrology in mangrove ecosystems varies greatly in time and space, and mangrove species differ in their ability to tolerate flooding.

At the intertidal scale, the magnitude and frequency of flooding decreases in a landward direction. Mangrove species often show a distinctive distribution across this gradient, which is the basis for classifying mangroves by lower, middle, and upper intertidal zones. The lower intertidal zone represents an area inundated by medium-high tides and is flooded more than 45 times a month. The middle intertidal is inundated by normal high tides and it is generally flooded from 20 to 45 times a month. The upper intertidal zone represents areas flooded less than 20 times a month (Robertson and Alongi 1992).

Figure 1.7. *Rhizophora* tree showing prop roots (C.E. Proffitt).

Flooded conditions can decrease soil oxygen, impacting root tissues that need oxygen to metabolize, and toxic substances such as sulfides can accumulate. Mangroves have evolved special morphological adaptations to cope with this lack of oxygen. First, mangroves have shallow root systems to avoid the lack of oxygen in deeper soils. As a result, most of the root biomass is found above 70-cm soil depth (Jimenez 1992). In some species (*Avicennia*, *Laguncularia*), roots form an extensive network close to the soil surface. Other species (*Rhizophora*) form extensive **aerial roots** (**prop roots** and **drop roots**) that help stabilize the tree in unconsolidated sediments (Figure 1.7). Second, above-ground root tissue such as aerial roots (*Rhizophora*) and **pneumatophores** (*Avicennia*, *Laguncularia*) transport oxygen from the atmosphere to the root system.

Aerial roots – Roots that are formed in and exposed to air. In mangrove species (e.g., *Rhizophora* spp.), aerial roots develop into stilt roots (prop roots and drop roots) that anchor into the sediment, offering mechanical support, nutrient absorption, and gas exchange.

Pneumatophore – A vertical extension of an underground root, with lenticels and aerenchyma to allow for gas exchange. Pneumatophores are characteristic of trees adapted to flooded conditions (such as *Avicennia* spp.).

Lenticel – A small, elliptical pore in the periderm that is a means of gaseous exchange.

Defoliation – The removal of the foliar tissues of a plant, resulting from mechanical (e.g., hurricanes), biological (herbivore), or chemical agents (e.g., plant hormones).

These specialized roots contain spongy tissue connected to the exterior of the root via small pores called **lenticels**. During low tide, when lenticels are exposed to the atmosphere, oxygen is absorbed from the air and transported to and even diffused out of the roots below ground. This diffusion of oxygen maintains an oxygenated microlayer around the roots that enhances nutrient uptake. The microlayer also avoids toxicity of compounds such as hydrogen sulfide that otherwise accumulate under such conditions.

Despite the harsh conditions under which mangrove forests develop, they can form highly diverse and productive communities. Riverine mangrove forests are recognized among the most productive ecosystems in the world, due in large part to low salinities, high nutrient supply, and regular flooding (Day et al. 1987). Less ideal conditions, such as hypersalinity or permanent flooding, severely limit mangrove growth and productivity; extreme conditions, such as restricted hydrology due to impounding, can kill many mangroves. Growth and productivity of mangroves thus ranges widely depending on the conditions under which they grow.

Mangrove Mortality

Mangrove mortality from biological sources includes competition, disease, herbivory, predation, and natural tree senescence. All developmental stages are affected, including propagules, seedlings, saplings, and trees. However, mangroves in early stages of development experience higher mortality rates and mortality is generally density-dependent. At the tree stage, smaller trees are at higher risk due to competition with larger trees for light and/or nutrients.

Mangrove diseases include impacts from fungi that **defoliate** and kill black and red mangroves in Australia and Florida. Insects such as scales and caterpillars cause defoliation and, in Puerto Rico, beetles and other boring insects are known to kill mangroves. *Rhizophora* seedlings are especially vulnerable to mortality caused by the boring beetle. Crabs are important predators of propagules and are a major source of mortality at this stage. Differences in predation rates on seedlings of different mangrove species may eventually alter species dominance in the adult trees (Smith 1987). Overall, these various biotic disturbances have a relatively minor impact on the mangrove forest when compared with larger-scale environmental impacts.

In contrast with purely biological causes, severe environmental disturbances can inflict larger-scale mortality on mangrove forests. These disturbances include periodic frosts, hurricanes, and other storms that can cause physical damage to mangroves, and heavy sedimentation (Jiménez and Lugo 1984). In spite of the drastic consequences of massive tree mortality, mangrove forests are generally able to recover.

Habitat Function

Shoreline Stabilization and Protection

Located along the coastline, mangroves play a very important role in soil formation, shoreline protection, and stabilization. The mangrove forest's extensive, above-ground root structures (prop roots, drop roots, and pneumatophores) act as a sieve, reducing current velocities and shear, and enhancing sedimentation and sediment retention (Carlton 1974; Augustinus 1995). The intricate matrix of fine roots within the soil also binds sediments together. Not only do mangroves trap sediments—they also produce sediment through accumulated, mangrove-derived organic matter. Mangrove leaves and roots help maintain soil elevation, which is especially important in areas of low sediment delivery, such as the southern coast of Florida. By enhancing sedimentation, sediment retention, and soil formation, mangroves stabilize soils, which reduces the risk of erosion, especially under high-energy conditions such as tropical storms.

Coastal protection is also related to the location of mangroves in the intertidal zone. Mangroves are able to absorb and reduce the impacts of the strong winds, tidal waves, and floods that accompany tropical storms, thereby protecting uplands from more severe damage (Tomlinson 1986; Mazda et al. 1997). Even though some of these forces can devastate the mangrove forest, mangroves in general have a great capacity to recover after major disturbances. Mangroves produce abundant propagules, their seedlings grow quickly, and they reach sexual maturity early—characteristics that accelerate their natural ability to regenerate. The speed of recovery, however, depends on the type of forest affected, the nature, persistence, and recurrence of the disturbance, and the availability of propagules.

Animal Habitat and Food Source

Mangroves provide both habitat and a source of food for a diverse animal community that inhabits both the forest interior and the adjacent coastal waters. Some animals depend on the mangrove environment during their entire lives while others utilize mangroves only during specific life stages, usually reproductive and juvenile stages (Yañez-Arancibia et al. 1988).

Detritus – Non-living organic matter that is so decomposed that it is impossible to identify the original parent material.

Mangroves' intricate aerial root system, which is most highly developed within the lower intertidal zone, provides a substrate for colonization by algae, wood borers, and fouling organisms such as barnacles, oysters, mollusks, and sponges. From the diverse group of invertebrates found in mangroves, arthropods, crustaceans, and mollusks are among the most abundant and have a significant role in mangrove ecosystems. As mentioned earlier, some species of crabs, recognized as propagule or seedling predators, can influence mangrove forest structure (Smith 1987), as may seedling predation by beetles or other insects. Crabs and snails, important components of the detritus food chain, help break down leaf litter through grazing.

Shrimp, an important fisheries resource, find food and shelter in mangrove forests. Likewise, commercially important bivalves such as oysters, mussels, and clams are commonly found in and around mangrove roots. Mangroves are also recognized as essential nursery habitat for a diverse community of fish, such as groupers, snappers, and snook, which find protection and abundant food in these environments, especially during juvenile stages.

Many animals found within mangroves are semi-aquatic or derived from terrestrial environments. Numerous insect species are found in mangrove forests; some play critical roles as mangrove pollinators, herbivores, predators, and as a food source for other animals (Hogarth 2007). Amphibians and reptiles such as frogs, snakes, lizards, and crocodiles also inhabit mangrove forests. Birds use mangroves for refuge, nesting, and feeding. In Florida and Australia, up to 200 species of birds have been reported around mangrove communities (Ewel et al. 1998). Most of these birds do not depend completely on mangroves, and use these habitats only during part of their seasonal cycles, or during particular stages of the tide. Mammals living in or using mangrove forests include raccoons, mink, river otter, wild pigs, rodents, deer, black bear, monkeys, and bats. Finally, sea turtles, manatees, and dolphins live in mangrove-dominated estuaries.

Water Quality Improvement

Mangrove habitats maintain water quality. By trapping sediments in the mangrove root system, these and other solids are kept from offshore waters, thereby protecting other coastal ecosystems such as oyster beds, seagrasses, and coral reefs from excessive sedimentation. This process can also remove agrochemical and heavy-metal pollutants from the water, since these contaminants adhere to sediment particles.

Mangroves also improve water quality by removing organic and inorganic nutrients from the water column. Through denitrification and soil-nutrient burial, mangroves lower nitrate and phosphorus concentrations in contaminated water, preventing downstream and coastal eutrophication (Ewel et al. 1998). However, the potential of mangroves to “clean” water is limited and depends on the nature of the inputs, and the surface area and nutrient biochemistry of the mangrove forest. Mangroves have also been used to treat tertiary wastewater (Twilley 1998). Mangrove systems are often nutrient limited and thus have a large capacity to retain nutrients.

Mangrove Economic Value and Uses

Mangroves provide products and services, not all of which are easily quantified in economic terms. Mangrove products can be obtained directly from the forest (wood) or from a derivative, such as crabs, shrimp, and fish. The most common uses of mangrove wood are as a source of fuel, either charcoal or firewood, and as the primary material for the construction of boats, houses, furniture, etc. Given these uses, commercial mangrove production (especially of *Rhizophora* spp.) is common around the world, primarily in Asia (Bandaranayake 1998).

Besides wood, other mangrove products have been exploited commercially. Mangrove bark has traditionally been used as a source of tannins, which are used as a dye and to preserve leather. The pneumatophores of different mangrove species are used in making corks and fishing floats; some are also used in perfumes and condiments. The ash of *Avicennia* and *Rhizophora* mangle is used as a soap substitute. Other mangroves extracts are used to produce synthetic fibers and cosmetics. Mangroves are also used as a source of food (mangrove-derived honey, vinegar, salt, and cooking oil) and drink (alcohol, wine). For example, the tender leaves, fruits, seeds, and seedlings of *Avicennia* marina and vegetative parts of other species are traded and consumed as vegetables (Bandaranayake 1998).

Mangroves have great potential for medicinal uses. Materials from different species can treat toothache, sore throat, constipation, fungal infections, bleeding, fever, kidney stone, rheumatism, dysentery, and malaria. Mangroves also contain toxic substances that have been used for their antifungal, antibacterial, and pesticidal properties (Bandaranayake 1998).

Mangrove forests have been widely recognized for their role in maintaining commercial fisheries by providing nursery habitat, refuge from predators, and food to important species of fish and shrimp.

Demonstrating a statistical relationship between mangroves and fishery yields has proven difficult, however, because mangroves, seagrasses, and other nearshore habitats are closely linked, and all provide nursery habitat and food for fish (Pauly and Ingles 1999).
Mangrove ecotourism is not yet a widely developed practice, but seems to be gaining popularity as a non-destructive alternative to other coastal economic activities. Mangroves are attractive to tourists mostly because of the fauna that inhabit these forests, especially birds and reptiles such as crocodiles.

Mangrove forests are among the most carbon-rich forests in the tropics, and there has been a growing interest in their potential value for carbon sequestration. Hutchison et al. (2013) estimated a total global mangrove above-ground biomass of 2,829,387,000 tonnes, with an average of 184.8 tonnes per hectare. McLeod et al. (2001) estimated that mangrove forests bury 31,000,000–34,000,000 tons of carbon per year. These data provide a tangible reason to conserve and restore mangroves–they can be valued directly in monetary terms for their carbon storage functions.

Anthropogenic and Naturally Occurring Impacts

Storms and Hurricanes

Mangroves are particularly sensitive to storms and hurricanes because of their exposed location within the intertidal zone, their shallow root systems, and the non-cohesive nature of the forest soils. The effect of storms and hurricanes varies, depending on factors such as wind fields and water levels. Small storms generally kill trees by lightning or wind-induced tree falling, creating forest gaps—an important mechanism for natural forest regeneration. Coastal sedimentation resulting from storms can also lead to mangrove forest expansion.

In contrast, high-energy storms (hurricanes and typhoons) can devastate mangrove forests. Entire mangrove populations can be destroyed, with significant long-term effects to the ecosystem (Figure 1.7; Jiménez and Lugo 1985). Mangrove forests that are frequently impacted by hurricanes show uniform tree height, reduced structural development and, sometimes, changes in species composition. However, mangrove forests can recover despite such impacts. How fast a forest recovers depends on the severity of mangrove damage and mortality, mangrove species composition, the degree of sediment disturbance and propagule availability.

Sea Level Rise

In response to global climate change, a gradual increase in sea level rise has been documented since the late Holocene (7000 YBP) and continues to the present. Estimated global rates of sea level rise (**eustatic**) since 1992 have been estimated to be 3.2 mm/yr^{-1} (IPCC 2013). Local subsidence, uplift, or other geomorphological changes can cause relative sea level rise (RSLR) to be greater or less than eustatic rise. Along the Atlantic Coast of the United States, for example, an estimated RSLR of 2-4 mm/yr has been calculated for a period spanning the last 50 years. In contrast, some areas along the Louisiana coast are experiencing a RSLR of 10 mm/yr (NOAA 2014)

Eustatic sea level rise – The worldwide rise in sea level elevation due mostly to the thermal expansion of seawater and the melting of glaciers.

RSLR – relative sea level rise - The net effect of eustatic sea level rise and local geomorphological changes in elevation. Local subsidence can make RSLR much greater than eustatic rise.

Microtidal – A tidal range of less than one meter.

Changes in sea level affect all coastal ecosystems. Changes in hydrology will result as the duration and extent of flooding increases. How well mangrove ecosystems will adapt to this hydrological change will depend on the magnitude of the change and the ability of mangroves to either 1) increase mangrove sediment elevation through vertical accretion, or 2) migrate in a landward direction. The mangrove sediment surface itself is in dynamic equilibrium with sea level, since a local loss of elevation will result in faster sediment accumulation. The problem with accelerated sea level rise is that the rate of rise might be faster than the ability of mangrove forests to accumulate and stabilize sediments. Mangroves can migrate back into previous uplands, but only if there is enough space to accommodate the mangroves at the new intertidal level. Local elevation gradients may make this regression impossible.

Mangroves colonizing macrotidal environments and receiving land-based and/ or marine sediments (i.e., riverine mangroves) are generally less vulnerable to changes in sea level rise than are mangroves in **microtidal** environments, such as in Florida and the Yucatan, or mangroves with restricted hydrology. Land-based and marine sediments increase vertical accretion through direct deposition on mangrove soils. Nutrient and freshwater supply tend to enhance mangrove productivity, which contributes to vertical accretion through the production and deposition of organic matter and root growth (Krauss et al. 2014). Mangroves under restricted hydrology depend mostly on *in situ* organic matter production to attain vertical accretion. Different mangrove ecotypes will therefore have differing sensitivities to increases in RSLR.

Chlorosis/chlorotic – abnormal condition characterized by the absence of green pigments in plants, causing yellowing of normally green leaves.

Sedimentation

Even though mangroves colonize sedimentary environments, excessive sediment deposits can damage them. Moderate sedimentation is beneficial to mangroves as a source of nutrients and to keep pace with predicted increases in eustatic sea level rise. When excessive, sudden sedimentation can reduce growth or even kill mangroves. Complete burial of mangrove root structures (aerial roots, pneumatophores) interrupts gas exchange, killing root tissue and trees. For example, *Avicennia* trees will die after 10 cm of root burial (Ellison 1998). Seedlings are especially sensitive to excessive sedimentation. Under experimental conditions, *Rhizophora apiculata* seedlings had reduced growth and increased mortality after 8 cm of sediment burial (Terrados et al. 1997). Excessive sedimentation can result from natural phenomena such as river floods and hurricanes, but also from human alterations to the ecosystem. Road and dam construction, mining, and dredge spoil have buried and killed mangroves.

Mangrove Pollution

Human-caused pollution in mangrove ecosystems includes thermal pollution (hot-water outflows), heavy metals, pesticides, PCBs, and other industrial pollutants, nutrient pollution (including fertilizers and sewage), and oil spills. Oil spill impacts are discussed in detail in Chapter 2. Thermal pollution from hot-water outfalls is not common in the tropics but, when present, reduces leaf area and causes **chlorotic** leaves, partial defoliation, and dwarfed seedlings. Seedlings are more sensitive than trees, showing 100% mortality with a water temperature rise of 7-9°C above ambient temperatures (Hogarth 2007).

Mining and industrial wastes are the main sources for heavy metal pollution (especially mercury, lead, cadmium, zinc, and copper). When heavy metals reach a mangrove environment, most are already bound onto suspended particulates (sediments) and in general do not represent an ecological threat. Although the accumulation of heavy metals in mangrove soils has not been studied in detail, they may decrease growth and respiration rates of mangroves, and will also negatively impact associated animals. Concentrations of mercury, cadmium, and zinc are toxic to invertebrate and fish larvae, and heavy metals cause physiological stress and affect crab reproduction.

Runoff from agricultural fields represents the main source of organic chemical contamination in mangrove ecosystems, including fertilizers and pesticides. Little is known about the effects of pesticides in mangroves and associated fauna, although chronic effects are likely. As with heavy metals, many of these compounds are absorbed onto sediment particles and degrade very slowly under **anoxic** conditions. Despite the possibility of burial, heavy metals and pesticides may **bioaccumulate** in animals that use mangroves (especially those closely associated with mangrove sediments), such as fish, shrimp, and mollusks.

Anoxic – Without free oxygen.

Bioaccumulate – Uptake of dissolved chemicals from water and uptake from ingested food and sediment residues.

Nutrient pollution in mangroves can have various effects. Sewage disposal under carefully managed conditions can enhance tree growth and productivity as a result of added nutrients, especially nitrogen and phosphorus (Twilley 1998). However, if the rate of disposal is greater than the uptake rate (a function of forest size and mangrove ecotype), excessively high nutrient concentrations will result. This causes excessive algal growth, which can obstruct mangrove pneumatophores and reduce oxygen exchange. Algal mats can also hinder growth of mangrove seedlings (Hogarth 2007).

Excessive microbial activity accompanies high levels of nutrients, and depletes oxygen in the water, which is harmful for mangrove-associated aquatic fauna.

Development and Forest Clearing

Despite the ecological and economic importance of mangroves, deforestation has been widespread. Deforestation has mostly been related to firewood and timber harvesting, land reclamation for human establishment, agriculture, pasture, salt production, and mariculture. Tropical countries have sustainably harvested mangrove wood for generations, but increasing populations have led to unsustainable practices.

Despite laws established for mangrove protection in many different countries, unregulated exploitation and deforestation continues. Worldwide, 20-35% of mangrove area has been lost since about 1980, and mangrove areas are disappearing at the rate of approximately 1% per year (FAO 2007). In the Philippines, approximately 60% of the original mangrove area has disappeared. In Thailand, 55% of the mangrove cover has been lost over about 25 years. Eventually, the overexploitation of mangrove forests will degrade habitat, increase shoreline erosion, damage fisheries and, ultimately, the services derived from these ecosystems will be lost.

Anchialine ponds – A rare Hawaiian ecosystem, consisting of pools with no surface connection to the ocean, but affected by tides. These pools support an assemblage of animals and plants, many of which are endangered.

Invasive Species

Mangroves have been introduced in several tropical islands where they did not occur naturally, and may thus be considered an invasive species. Hawaii is an example of such a case, where the proliferation of *Rhizophora mangle* has deteriorated habitat for some endemic waterbirds and has damaged sensitive archaeological sites.

The proliferation of mangroves has also been linked to the premature infilling of a unique Hawaiian aquatic ecosystem called **anchialine ponds**. Despite providing useful environmental services (e.g., shoreline protection, organic matter production, and water quality), the mangroves may proliferate in these foreign environments and seriously impact the native flora and fauna. The cost of mechanical removal has been reported to vary from $108,000 to $377,000 per hectare (Allen 1998).

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Weathering – Changes in the physical and chemical properties of oil due to natural processes, including evaporation, emulsification, dissolution, photo-oxidation, and biodegradation.

Canopy – topmost layer of leaves, twigs, and branches of forest trees or other woody plants.

CHAPTER 2. OIL TOXICITY AND EFFECTS ON MANGROVES

Key Points

- Mangroves are highly susceptible to oil exposure; oiling may kill them within a few weeks to several months.
- Lighter oils are more acutely toxic to mangroves than are heavier oils. Increased **weathering** generally lowers oil toxicity. However, heavier oils can result in substantial physical smothering and coating impacts.
- Oil-impacted mangroves may suffer yellowed leaves, defoliation, and tree death.
- More subtle responses include branching of pneumatophores, germination failure, decreased **canopy** cover, increased rate of mutation, and increased sensitivity to other stresses.
- Response techniques that reduce oil contact with mangroves, such as offshore use of chemical dispersants, reduce the resultant effects as well. Tradeoffs include potential increased toxicity to adjacent communities, and increased penetration of dispersed oil to mangrove sediments.
- The amount of oil reaching the mangroves and the length of time spilled oil remains near the mangroves are key variables in determining the severity of effect.
- Mangrove-associated invertebrates and plants recover more quickly from oiling than do the mangroves themselves, because of the longer time for mangroves to reach maturity.
- Under severe oiling conditions, mangrove impacts may continue for years to decades, resulting in permanent habitat loss.

In this chapter we discuss the toxicity of oil to the broad class of trees called mangroves. In contrast to other habitats, tropical or otherwise, there is a fairly robust literature on the effects of oil to mangroves. This work includes monitoring of mangrove areas oiled during actual spills, field studies of oil impacts on mangroves, and laboratory studies that attempt to control some of the variables that may otherwise complicate the interpretation of research results. Predictably, the body of results is not unanimous in type of impact or the severity of those documented, but there are some consistencies that can serve as the starting point for spill response guidance.

Oil Groups

Sublethal effect – An effect that does not directly cause death but does adversely affect behavior, biochemical, physiological, or reproductive functions, or tissue integrity.

One of the universal challenges faced by resource managers and spill responders when dealing with oil impacts is the fact that "oil" is a complex mixture of many kinds of chemicals. The oil spilled in one incident is almost certainly different from that spilled in another. In addition, oils within broad categories like "crude oil" or "diesel" can be vastly different, depending on the geological source of the original material, refining processes, and additives incorporated for transportation in barges, tankers, or pipelines. Even if we could somehow stipulate that all spilled oil was to be of a single fixed chemical formulation, petroleum products released into the environment are subjected to differential processes of weathering that immediately begin altering its original physical and chemical characteristics. As a result, samples of oil from exactly the same source can be very different in composition after being subjected to a differing mix of environmental influences.

Oils can be divided into five groups as shown in Table 2.1 based on their general behavior, persistence, and properties. Each group is defined by a range in specific gravity, defined as the ratio of the mass of the oil to the mass of freshwater, for the same volume and at the same temperature. If the specific gravity of the oil is less than the specific gravity for the receiving water (freshwater = 1.00 at 4°C; seawater = 1.03 at 4°C), it will float on the water surface. API gravity[1] is another property that is often reported and can be used to characterize an oil's behavior.

Mechanisms of Oil Toxicity to Mangroves

Observations from many spill events around the world have shown that mangroves suffer both lethal and **sublethal effects** from oil exposure. Past experience has also taught us that such forests are particularly difficult to protect and clean up once a spill has occurred because they are physically intricate, relatively hard to access, and inhospitable to humans. In the rankings of coastal areas in NOAA's Environmental Sensitivity Indices, commonly used as a tool for spill contingency planning around the world, mangrove forests are ranked as the most sensitive of tropical habitats.

[1] API = (141.5/specific gravity) - 131.5. An API of 10 is equal to a specific gravity of 1.00; an API of 45 is equal to a specific gravity of 0.80. Note that API gravity has an inverse relationship with specific gravity.

Table 2.1. Oil groups and their characteristics.

Group 1: Gasoline products

- Specific gravity is less than 0.80; API gravity >45
- Very volatile and highly flammable
- Evaporate and dissolve rapidly (in a matter of hours)
- Narrow cut fraction that will evaporate with no residues
- Low viscosity; spread rapidly into thin sheens
- Will penetrate substrates but are not sticky
- High acute toxicity to animals and plants

Group 2: Diesel-like Products and Light Crude Oils

- Specific gravity is 0.80-0.85; API gravity 35-45
- Moderately volatile and soluble
- Refined products can evaporate to no residue
- Crude oils can have residue after evaporation is complete
- Low to moderate viscosity; spreads rapidly into thin slicks; not likely to form stable emulsions
- Are more bioavailable than lighter oils (in part because they persist longer), so are more likely to affect animals in water and sediments

Group 3: Medium Crude Oils and Intermediate Products

- Specific gravity of 0.85-0.95; API gravity 17.5-35
- Moderately volatile
- For crude oils, up to one-third will evaporate in the first 24 hours
- Moderate to high viscosity; will spread into thick slicks
- Are more bioavailable than lighter oils (because they persist longer), so are more likely to affect animals and plants in water and sediments
- Can form stable emulsions and cause long-term effects via smothering or coating

Group 4: Heavy Crude Oils and Residual Products

- Specific gravity of 0.95-1.00; API gravity of 10-17.5
- Very little product loss by evaporation or dissolution
- Very viscous to semi-solid; may be heated during transport
- Can form stable emulsions and become even more viscous
- Tend to break into tarballs quickly
- Low acute toxicity to biota
- Penetration into substrates will be limited at first, but can increase over time
- Can cause long-term effects via smothering or coating, or as residues on or in sediments

Group 5: Sinking Oils

- Specific gravity of >1.00; API gravity <10
- Very little product loss by evaporation or dissolution
- Very viscous to semi-solid; may be heated during transport or blended with a diluent that can evaporate once spilled
- Low acute toxicity to biota (though may have some toxicity if blended with a lighter, more - toxic diluent)
- Penetration into substrates will be limited at first, but can increase over time
- Can cause long-term effects via smothering or coating, and as residues on or in sediments

It is clear from spills, and field and laboratory studies, that oil can harm or kill mangroves. What is less obvious is how that harm occurs and the mechanism of toxicity. Although there is some consensus that oil causes physical suffocation and toxicological/physiological impacts, researchers disagree as to the relative contributions of each mechanism, which may vary with type of oil and time since the spill (Proffitt et al. 1997).

Similar to the oil toxicity situation for many other intertidal environments, the mangrove-related biological resources at risk in a spill situation can be affected in at least two principal ways: first, from physical effects; second, the true toxicological effects of the petroleum.

Many oil products are highly viscous. In particular, crude oils and heavy fuel oils can be deposited on shorelines and shoreline resources in thick, sticky layers that may either disrupt or completely prevent normal biological processes of exchange with the environment. Even if a petroleum product is not especially toxic in its own right, when oil physically covers plants and animals, they may die from suffocation, starvation, or other physical interference with normal physiological function.

Mangroves have developed a complex series of physiological mechanisms to enable them to survive in a low-oxygen, high-salinity world. A major point to remember in terms of physical effects of oil spills on mangroves is that many, if not most, of these adaptations depend on unimpeded exchange with either water or air. Pneumatophores and their lenticels tend to be located in the same portions of the intertidal most heavily impacted by stranded oil. While coatings of oil can also interfere with salt exchange, the leaves and submerged roots of the mangrove responsible for mediation of salts are often located away from the tidally influenced (and most likely to be oiled) portions of the plant. Thus, salt mediation is less susceptible to impacts from oil than are respiratory functions occurring at the air-water interface.

These physical impacts of oil are linked to adaptive physiology of the mangrove plants, but are independent of any inherent chemical toxicity in the oil itself. The additional impact from acute or chronic toxicity of the oil would exacerbate the influence of physical smothering. Although many studies and reviews of mangroves and oil indicate that physical mechanisms are the primary means by which oil adversely affects mangroves, other reviewers and mangrove experts discount this weighting. See, for example, Snedaker et al. (1997). They suggest that at least some species can tolerate or accommodate exposure to moderate amounts of oil on breathing roots.

The lighter, or lower molecular weight, aromatic hydrocarbons that often are major components of oil mixtures are also known to damage the cellular membranes in subsurface roots; this, in turn, could

PAH – polynuclear aromatic hydrocarbon; also called polycyclic aromatic hydrocarbon, a component of oil. PAHs are associated with demonstrated toxic effects.

Genotype – Genetic makeup of an individual organism.

impair salt exclusion in those mangroves that have the root filters described in Chapter 1- adaptations to salinity. Disruption of ion transport mechanisms in mangrove roots, as indicated by sodium to potassium ion ratios in leaves, was identified as the cause of oil-induced stress to mangroves in the 1973 *Zoe Colocotronis* spill in Puerto Rico (Page et al. 1985). Mangroves oiled by the 1991 Gulf War spill in Saudi Arabia showed tissue death on pneumatophores and a response by the plants in which new, branched pneumatophores grew from lenticels—an apparently compensatory mechanism to provide gaseous exchange (Böer 1993).

Genetic damage is a more subtle effect of oil exposure, but can cause significant impact at the population level. For example, researchers have linked the presence of polynuclear aromatic hydrocarbons (**PAH**) in soil to an increased incidence of a mangrove mutation in which chlorophyll is deficient or absent (mangroves such as *Rhizophora* mangle are viviparous and can self-fertilize, so they are well-suited for genetic screening studies such as those examining the frequency of mutations under different conditions; Klekowski et al. 1994a, 1994b). The presence or absence of pigmentation allows for easy visual recognition of **genotype** in the trees. The correlation between sediment PAH concentration and frequency of mutation was a strong one, raising the possibility that a spill can impact the genetic mix of exposed mangroves.

Acute Effects

The acute toxicity of oil to mangroves has been clearly shown in laboratory and field experiments, as well as observed after actual spills. Seedlings and saplings, in particular, are susceptible to oil exposure: in field studies with *Avicennia marina*, greater than 96% of seedlings exposed to a weathered crude oil died, compared to no deaths among the unoiled controls (Grant et al. 1993). Other studies found that mangrove seedlings could survive in oiled sediments up to the point where food reserves stored in propagules were exhausted, whereupon the plants died.

The *Avicennia* study cited above also found that fresh crude oil was more toxic than weathered crude. Based on laboratory and field oiling experiments in Australia, the authors cautioned against readily extrapolating results from the laboratory to what could be expected during an actual spill. Container size and adherence of oil to container walls were thought to be important factors that may have skewed laboratory toxicity results by lowering actual exposure concentrations (Grant et al. 1993).

Infrared photography – Photography using films sensitive to both visible light and infrared radiation. Live vegetation is particularly highlighted with infrared films and so is a useful tool for aerial surveys of live and dead plants.

Another set of Australian studies investigated the toxicity of two oil types, a light crude and a Bunker C, to mature mangroves (*Rhizophora stylosa*) over a period of two years (Duke et al. 2000). A number of interesting results were obtained from this study, including:

- Unoiled control mortality was low over the two-year study period;
- Plots oiled with Bunker C showed no difference in mangrove mortality relative to unoiled controls;
- Mangroves treated with the light crude oil showed a significantly higher mortality than controls and the Bunker C treatment;
- Addition of chemical dispersant to the crude significantly reduced the toxicity but not to control levels;
- Most tree deaths occurred in the first six months after treatment.

The last observation is consistent with conditions observed at several oil spills in mangrove areas. In fact, obvious signs of mangrove stress often begin occurring within the first two weeks of a spill event, and these can range from chlorosis (Figure 2.1A) to defoliation to tree death. In the 1999 Roosevelt Roads Naval Air Station (Puerto Rico) spill of JP-5 jet fuel, an initial damage assessment survey conducted in the first month post-spill determined that 46% of mangrove trees, saplings, and seedlings along a transect in the most impacted basin area were stressed (defined as showing yellowed, or chlorotic, leaf color). This compared to 0% along the unoiled reference transect (Geo-Marine, Inc. 2000). Figure 2.2B shows the most heavily impacted area about nine months after the initial release with many of the initially stressed trees dead. Color **infrared**, aerial photography taken at regular intervals through 19 months post-spill confirmed the visual observations. Analysis of the infrared photographs of the affected mangrove area shown in Figure 2.2B indicated that two weeks after the release, 82% of the total mangrove area was classified as "impacted" relative to pre-spill conditions. Under more controlled conditions, studies using fresh crude oils have suggested that defoliation, when it occurs, should reach a maximum between 4-12 weeks post-spill.

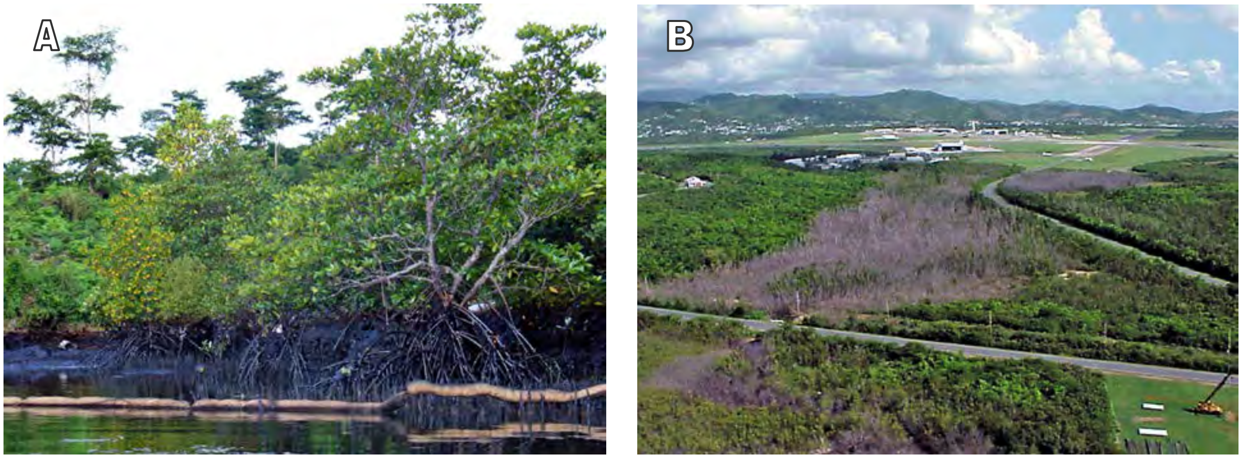

Figure 2.1. Acute oil toxicity effects. A) Chlorosis of red mangroves three weeks after a spill of an intermediate fuel oil spill from the M/T *Solar I* in the Philippines (Ruth Yender, NOAA). B) Aerial view of Roosevelt Roads, Puerto Rico jet fuel spill in 1999 showing dead mangroves (Dan L. Wilkinson, Geo-Marine, Inc).

A monitoring study conducted in Australia after the *Era* spill in 1992 found a consistent set of mangrove responses including leaf staining, chlorosis, leaf death, and complete defoliation. Within three months after the oil washed ashore, extensive defoliation of mangrove trees had begun and many appeared to be dead. The degree to which mangroves were damaged and the extent to which they recovered from spill damage were correlated to oiling levels (Wardrop et al. 1996).

In the 1986 Bahía las Minas (Panama) spill, scientists monitoring the effects of the oil on mangroves recorded a band of dead and dying trees where oil had washed ashore five months previously. A year and a half after the spill, dead mangroves were found along 27 km of the coast. Photographs taken just before the spill showed no evidence of tree mortality (Jackson et al. 1989).

Chronic Effects

The line between acute and chronic impacts can be a little blurry at times. In the case of mangroves, visible response to oiling may be almost immediate, with leaves curling or yellowing, as at the Era and Bahía las Minas spills. The tree, however, may survive for a time only to succumb weeks or months later. Alternatively, depending on the nature of exposure, it may recover to produce new leaf growth.

At least one researcher has summarized acute and chronic effects of oil to mangroves in tabular form (Table 2.1) (Lewis 1983). In this case, the line between acute and chronic effect was defined at 30 days; others may shift the border one way or the other.

Table 2.2. Generalized responses of mangrove forests to oil spills. From Lewis (1983).

STAGE	OBSERVED IMPACT
Acute	
0 - 15 days	Deaths of birds, fish, invertebrates
15 - 30 days	Defoliation and death of small (<1 m) mangroves Loss of aerial root community
Chronic	
30 days - 1 year	Defoliation and death of medium (<3 m) mangroves Tissue damage to aerial roots
1 year – 5 years	Death of larger (>3 m) mangroves Loss of aerial roots Regrowth of roots (sometimes deformed) Recolonization of oiled areas by new seedlings
1 year – 10 years?	Reduction in litter fall Reduced reproduction Reduced seedling survival Death or reduced growth of recolonizing trees? Increased insect damage?
10 – 50 years?	Complete recovery

Mangroves can be chronically impacted by oil in several ways. Stressed mangroves could show differences in growth rates or altered reproductive timing or strategy. They may also develop morphological adaptations to help them survive either the physical or chemical consequences of residual oil contamination. Such modifications may require expending additional energy, which in turn, could reduce the mangroves' ability to withstand other non-spill-related stresses they may encounter. One consequence of the complex physical structure and habitat created by mangrove trees is that oil spilled into the environment is very difficult to clean up. The challenge and cost of doing so, and the remote locations of many mangrove forests, often results in unrecovered oil in mangrove areas affected by spills. This, in turn, may expose the trees and other components of the mangrove community to chronic releases of petroleum as the oil slowly leaches from the substrate, particularly where organic-rich soils are heavily oiled.

Researchers who have compared oil spill impacts at several different spill sites have found similar types of impacts that differ primarily in the magnitude of effect. The degree of impact appears to be related to the physical factors that control oil persistence on the shoreline and exposure to waves and currents. Interestingly, the presence and density of burrowing animals like crabs also affects the persistence of oil in mangrove areas and can determine whether an exposure is short- or long-term, because of oil penetration via burrows into an otherwise impermeable sediment.

In many parts of the world, mangrove stands co-occur with industrial facilities and thus may be subjected to chronic contamination from petroleum compounds, other organic chemicals, and heavy metals. As a result, it can be difficult to determine the additional stress imposed by a spill event vs. existing stress. Newer assessment tools, such as molecular biomarkers, can isolate sources of stress more readily than non-specific but commonly used methodologies, and show promise for distinguishing spill impacts from other pollution sources.

Root abnormalities have been reported as a response to chronic oil exposures. Adventitious roots and deformed red mangrove propagules were observed on *Avicennia* trees after the 1978 *Howard Star* spill in Tampa Bay (Figure 2.2) and at many spills since then. *Avicennia* mangroves oiled during the 1991 Gulf War spill had surviving pneumatophores that tended to develop branched secondary pneumatophores. These were observed two years after the spill in areas that were known to have been oiled, and were interpreted to be a response to impairment of normal respiration (Böer 1993).

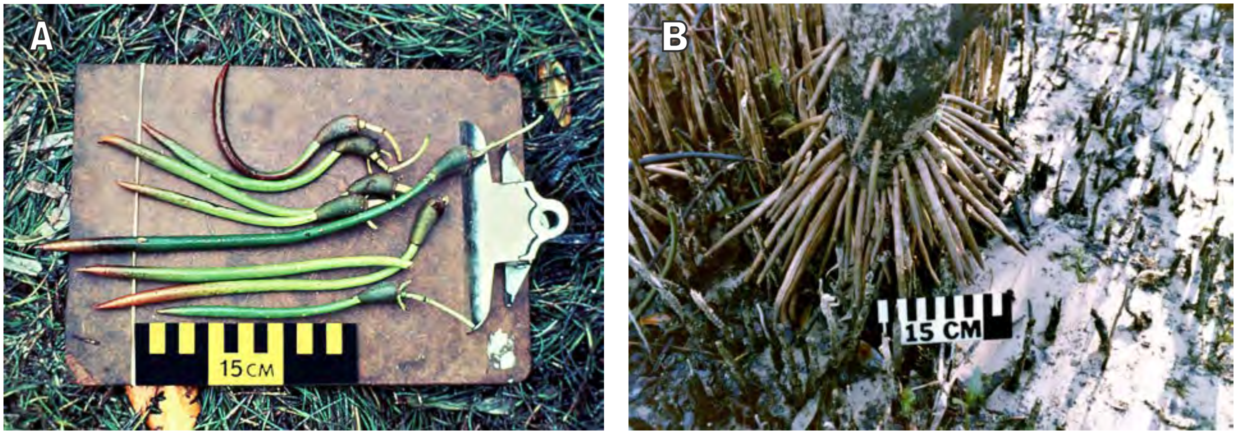

Figure 2.2. Propagule and root deformities observed in January 1980 as response to the chronic effects of oil exposure after the 1978 *Howard Star* oil spill in Tampa Bay, Florida. A) Deformed red mangrove propagules collected from oil sediments (upper) contrasted with normally developed propagules from adjacent unoiled sediments (lower). B) Abnormal adventitious roots at the base of a black mangrove tree (Research Planning, Inc.).

Studies of the 1986 Bahía las Minas (Galeta) oil spill in Panama concluded that its impact was "catastrophic." Five years after the incident, researchers suggested that oil remaining in mangrove sediments adversely affected root survival, canopy condition, and growth rates of mangrove seedlings in oil-deforested gaps. Six years after the spill, surviving forests fringing deforested areas showed continued deterioration of canopy leaf biomass (Burns et al. 1993).

The follow-up study of the 1992 *Era* spill in Australia also noted a lack of recovery four years after the initial release–although effects themselves had appeared to have peaked, no strong signs of recovery were recorded in the affected mangrove areas (Wardrop et al. 1996).

The experimental (i.e., intentional and controlled) 1984 TROPICS spill in Panama confirmed long-term impacts to oiled mangroves, termed "devastating" by the original researchers who returned to the study sites ten years later. They found a total mortality of nearly half of the affected trees and a significant subsidence of the underlying sediment. This was compared to a 17-percent mortality at seven months post-oiling, a level that appeared to be stable after 20 months (Dodge et al. 1995). Over the decades, the dead trees at the oiled site were slowly replaced by "waves" of seedlings because early ones did not survive to produce trees (Baca et al. 2014). In 2009, 25 years after oiling, the oiled site exhibited a decline of the mangroves (there were 1,085 small trees), whereas the dispersed and reference sites remained at baseline levels (with 124 and 392 small trees, respectively) (DiMicco et al. 2011). In 2013, 29 years later, the counts of adult trees had recovered though there were still an abundance of small trees at the oiled site, and curling and distortions of prop roots in small trees and seedlings were noted at the oiled site, but not at the other sites (Baca et al. 2014).

The results from the more intensively studied spills that have occurred in the last fifteen years suggest that chronic effects can be measured over long time periods, potentially a decade or decades. They also indicate the difficulties in measuring longer-term impacts due to the time frames involved–and, hence, the value of longer-term monitoring of mangrove status following an oil spill.

Mangrove Community Impacts

With the realization that mangrove stands provide key habitat and nursery areas for many plants and animals in the tropical coastal environment, many researchers have included the associated biological communities in their assessments of oil impacts. Of course, this considerably broadens the scope of spill-related studies, but realistically, it would be arbitrary and artificial to consider only the impacts of oil on the mangroves themselves.

Endpoint – A measured response of a natural resource to exposure to a contaminant, such as oil, in the field or laboratory.

Studies of the Bahía las Minas spill in Panama concluded that significant long-term impacts occurred to mangrove communities. Both the habitat itself and the epibiotic community changed in oiled areas. After five years, the length of shoreline fringed by mangroves had decreased in oiled areas relative to unoiled areas, and this translated to a decrease in available surface area ranging from 33 to 74 percent, depending on habitat type. In addition, defoliation increased the amount of light reaching the lower portions of the mangrove forest (Burns et al. 1993).

In the Bahía las Minas spill, a massive die-off of plants and animals attached to the mangrove roots followed the initial release. Five years after the spill, the cover of epibiotic bivalves was reduced in oiled areas relative to unoiled reference areas. Open-coast study sites recovered more quickly, although differences in cover of sessile invertebrates remained significant through four years.

More controlled experimental oiling experiments have been less conclusive. One such study in New South Wales, Australia found that invertebrate populations were highly variable with differences attributable to oiling treatment difficult to discern. Though snails were less dense shortly after oiling treatments, they recovered by the end of the study period several months later (McGuinness 1990).

Another experiment in Australia focused on the effect of one toxic component of oil, naphthalene, on a gastropod snail common in the mangroves of eastern Australia. The sublethal **endpoint** used for impact assessment was the crawling rate of the snails. Two responses were elicited in short- and long-term exposures to naphthalene. An increased level of activity in the short-term exposure was interpreted as an avoidance response, while the decreased crawling rate induced by the longer-term exposure suggested a physiological consequence of the toxicant. The measurable differences in response attributed to the hydrocarbon implied that normal behavior patterns of the snails would be significantly disrupted by oil exposure (Mackey and Hodgkinson 1996).

The TROPICS experimental spill found no short- or long-term effects to three species of mangrove oysters studied in the experiment. In fact, populations at oiled sites showed the most substantial increases over time that was speculatively attributed to breakdown and mobilization of petroleum hydrocarbons as additional food sources (Dodge et al. 1995). However, by 2013, 29 years later, oysters and snails in the oiled site declined, whereas the dispersed oil and reference sites maintained gradual increases (Baca 2014)

Some studies have looked at the toxicity of undispersed and dispersed oil to both mangroves and the associated invertebrate community. The limited findings are somewhat equivocal: one study found that dispersing oil appears to reduce the inherent toxicity of the oil to mangroves, but increases the impacts to exposed invertebrates (Lai 1986). Another assessment concluded no difference in toxicity to crustaceans from dispersed and undispersed crude oil (Duke et al. 2000). However, the same study also evaluated toxicity of Bunker C fuel oil and found that crude oil was more acutely toxic than the Bunker. The authors attributed this to the physical and chemical differences between the oil types.

Australian researchers studying the effects of the 1992 *Era* spill on fish populations around oiled mangroves found no measurable assemblage differences between groups inside and outside oiled zones, although juveniles of several species were significantly smaller in oiled creeks than in unoiled creeks (Connolly and Jones 1996).

Indirect Impacts

As is the case with most, if not all, spill-affected resources, some indirect impacts on mangroves have been identified. For example, residual oil remaining on the surface of mangrove sediments oiled during the Gulf War spill in Saudi Arabia increased the ambient soil temperatures to the point where germination and growth of intertidal plants was adversely affected (Böer 1993).

In Panama, the breakdown of protective structure provided by roots of dead mangroves caused a secondary impact from the oil spill at Bahía las Minas. For five years post-spill, the tree remnants had protected young seedlings, but when the roots finally gave way, drift logs crushed the recovering mangrove stand and essentially destroyed that part of the mangrove fringe (Duke et al. 1993).

Decomposition of the mangrove root mass following large-scale mortality causes significant erosion and even subsidence of the land where the forest was located. In the TROPICS experiment, approximately 8 cm of surface elevation loss was noted by researchers who returned to the study site 10 years after the oiling (Dodge et al. 1995).

Prolonged flooding of diked mangrove areas due to cleanup operations is a possible indirect spill impact that would be limited to those areas where hydrologic conditions are easily controlled. This was suggested as a factor in the 1999 jet fuel spill at Naval Station Roosevelt Roads in Puerto Rico. In that spill, culverts providing water exchange with coastal waters were closed both to facilitate oil recovery and to prevent the spread of oil to other areas. However, in doing so, the water levels in some basin mangrove forests were held at much higher levels (>1 m) for periods of more than a week. It has been suggested that this action either contributed to or was a major source of mortality to mangroves in the weeks that followed (Wilkinson et al. 2001).

Even if oiling does not result in tree death, the surviving trees can become weakened and vulnerable to other natural stressors, which can eventually lead to death (Figure 2.3). Examples of these stresses include cold weather and hypersalinity (Snedaker et al. 1997), drought, flooding, storms, disease, and herbivory.

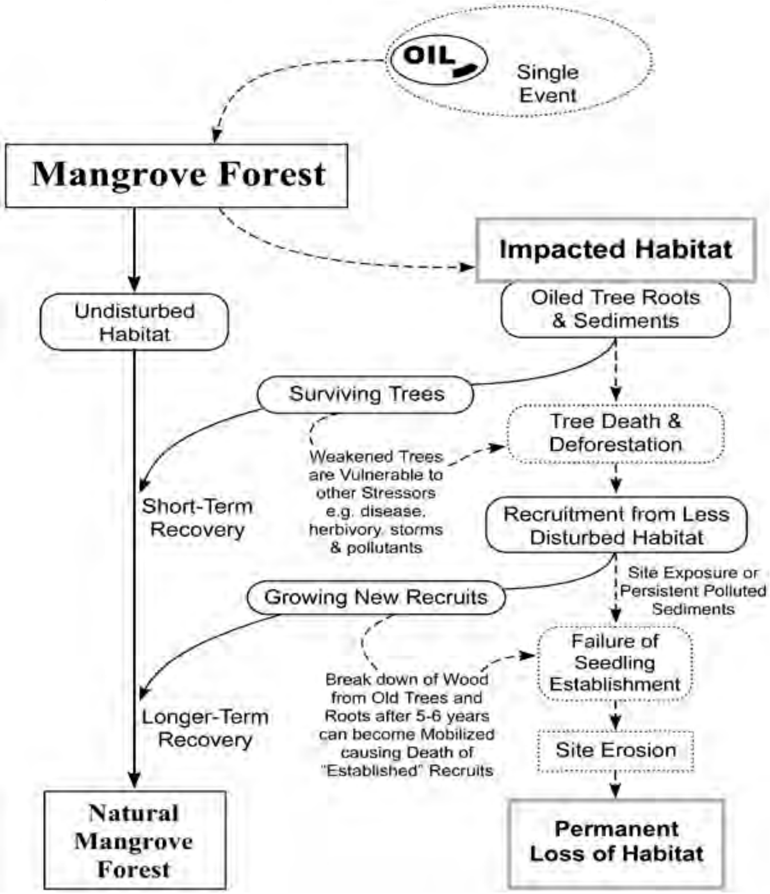

Figure 2.3. Schematic diagram depicting the effects of a large oil spill on mangrove forests. Major pathways are shown as either recovery (on the left) or permanent loss (on the right). From Duke et al. (1999).

Summary and Response Implications

The body of literature available for the toxicity of oil to mangroves presents a range of results from which we can extract some points for spill response guidance.

- Mangroves are highly susceptible to oil exposure. Acute effects of oil (mortality) occur within six months of exposure and usually within a much shorter time frame (a few weeks). Commonly observed mangrove responses to oil include yellowing of leaves, defoliation, and tree death. More subtle responses include branching of pneumatophores, germination failure, decreased canopy cover, increased rate of mutation, and increased sensitivity to other stresses.
- Different oil types confer different toxicity effects. While this is a universal truth in spill response, for mangroves the lighter oils are more acutely toxic than heavier oils (for example, light crude oil is more toxic than a Bunker-type fuel oil). Similarly, less-weathered oil is more toxic to mangroves than the same oil that has been subjected to more intense weathering.
- The physical effects of oiling (e.g., covering or blocking of specialized tissues for respiration or salt management) can be as damaging to mangroves as the inherent toxicity of the oil. Although some studies indicate that mangroves can tolerate some coating without apparent damage, many others identify physical effects of oiling as the most serious.
- Response techniques that reduce oil contact with mangroves reduce the resultant toxicity as well. For example, chemical dispersants seem to reduce oil toxicity to mangroves. In this case, the tradeoff is the possibility of increased toxicity to adjacent and associated communities, such as offshore coral reefs, and increased penetration of dispersed oil that may reach mangrove sediments.
- Comparing spill impacts at several mangrove sites indicates that variable effects are related to geomorphology and hydrologic kinetics of the mangrove ecosystem that, in turn, control whether oil persists in the mangrove habitat. Oiled mangrove forests that are sheltered from wave and current exposure are likely to be more severely affected than well-exposed, "outer fringe" mangrove areas. Another consideration that also can be significant is the density of burrows from associated organisms such as crabs, which can increase the penetration and persistence of oil with depth into sediments. Berms can protect inner areas or concentrate oil in front of them.
- Mangrove communities are complex and, as might be expected, the impacts of oil to the associated plants and animals vary. The available information suggests that while oil spills undoubtedly affect such communities, they appear to recover more quickly than the mangroves themselves. Because of this, longer-term effects are likely to be related to death of the mangroves and loss of the habitat that supports and protects the community.

As we have noted, the toxicity implications from an oil spill in a mangrove area depend on a wide variety of different factors. Generally, the amount of oil reaching the mangroves and the length of time spilled oil remains near the mangroves are key variables in determining the severity of effect. Although it is stating the obvious to a spill responder that prevention is the best tool for minimizing the environmental impacts of an incident, for mangroves this is especially true. Reducing the amount of oil reaching the mangroves not only reduces the short- and long-term toxicological effects but also reduces cleanup impacts and the potential for chronic contamination. In a response, these considerations may translate into increased protection for mangroves and possible use of response measures that reduce mangrove exposure to oil (e.g., offshore countermeasures such as burning or dispersants, shoreline countermeasures such as chemical cleaners or flushing). The long-term character of many of the mangrove impacts that have been observed argues for serious consideration of such strategies.

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CHAPTER 3. RESPONSE

Biogenic – In mangroves, the trees themselves create the habitat. Biogenic also means "resulting from the actions of living organisms."

Key Points

- Mangroves are highly sensitive to oil and are priority areas for protection.
- Winds and tides carry spilled oil into mangrove forests, where oil coats the soil surface, aerial roots, and propagules.
- Dispersing or burning oil offshore can prevent or lessen impacts to mangroves.
- Spill containment and cleanup techniques should minimize any additional impacts to mangroves and other natural resources at risk.

As detailed in the previous chapter, mangroves are particularly sensitive to oil and, where they are native, often are priority areas for protection. The objective of spill response in mangroves, as in any habitat, is to minimize the damage caused by the accident and released oil. Spill containment and cleanup techniques should minimize any additional impacts to mangroves. Mangrove forests are a **biogenically** structured habitat–the trees themselves create the habitat. Death of the trees, the structuring organism, causes loss of habitat, with corresponding impact on the suite of associated species dependent upon them, including offshore and nearshore resources such as coral reefs and seagrass beds. Potential response strategies should be evaluated to determine whether the ultimate benefits from the response action outweigh any environmental costs to the mangrove forests and associated sensitive habitats at risk.

Variables such as oil type, weather, location, and availability of response equipment will determine initial spill response options. In the best-case scenario, oil is prevented from moving into and contaminating mangrove areas. Promising, on-water response techniques that can help prevent or reduce the amount of oil reaching mangrove forests in some cases include offshore chemical dispersion and *in situ* burning.

On-Water Response Options to Prevent or Reduce Mangrove Oiling

Mechanical Recovery Offshore

Mechanical containment and collection of spilled oil on water using equipment such as booms and skimmers are primary initial cleanup methods used at many spills. Experience has shown, though, that mechanical recovery alone usually cannot adequately deal with very large spills offshore. Weather and sea conditions, the nature of the oil, and other factors may limit the effectiveness of mechanical recovery. In such cases, alternative open-water response techniques, such as dispersant application or *in situ* burning of oil on water, may significantly reduce the risk that oil will reach shore and impact mangroves and other sensitive intertidal and shoreline habitats.

Offshore Dispersant Application

Chemical dispersants are products applied to oil on the water surface to enhance formation of smaller oil droplets that are more readily mixed into the water column and dispersed by turbulence and currents. During and since the *Deepwater Horizon* oil spill, dispersants have also been considered as a response action to reduce the amount of oil reaching the surface during a subsea release. Most oils physically disperse to some degree due to agitation created by wave action and ocean turbulence. Chemical dispersants enhance and speed up this natural dispersion process. Dispersing oil soon after release minimizes impacts to wildlife at the water surface (e.g., birds and marine mammals) and reduces the amount of floating oil that may reach sensitive nearshore and shoreline habitats. If applied appropriately offshore, chemical dispersants can be an effective tool for protecting mangroves and the habitat they provide. Tradeoffs among other resources at risk, such as potential effects of temporarily higher concentrations of oil in the water column on pelagic organisms and sedimentation of oil in sensitive benthic habitats such as coral reefs and seagrass beds, should be considered before dispersant use. When applied appropriately in sufficiently deep water, impacts to coral reefs and seagrass beds are expected to be minimal.

Offshore *in situ* Burning

In situ burning is a response technique in which spilled oil is burned in-place. When used appropriately, *in situ* burning can remove large quantities of oil quickly and efficiently with minimal logistical support. Like dispersants, *in situ* burning can help minimize impacts to wildlife at the water surface and reduce the amount of oil that reaches sensitive nearshore and shoreline habitats, including mangroves. A potential disadvantage of open-water *in situ* burning is that a small percentage of the original oil volume may remain as a taffy-like residue after the burn. Floating residue can be collected but residues that sink or escape collection and move inshore could potentially contaminate mangroves or other habitats. It is important to note that, in contrast to open-water burning, *in situ* burning should not be conducted within mangrove forests, as explained below under "Response Techniques Inappropriate for Mangroves."

Booms

Wrack – Organic material, usually from dead seagrass or algae that wash up on shorelines.

Booms are floating barriers that deflect or contain oil, and they can be used along mangrove shorelines and inlets to prevent oil entry. Booms are usually used in two modes: 1) to deflect oil to containment and recovery areas, and 2) to exclude oil from coming ashore. To be effective, booms must be deployed immediately after a spill before oil moves into mangrove areas. This means that appropriate types and sufficient amounts of booming materials must be stockpiled and available at the time of the spill, and that strategies for boom placement and deployment have already been established and tested. Booms generally cannot be deployed successfully along mangrove shorelines with strong currents, breaking or choppy wave action, or along sections of mangrove shorelines behind shallow flats where the boom fouls on the flat at low tide. Booms must be deployed and anchored carefully, and maintained vigilantly to prevent physical damage during installation and removal.

Stranded Oil Behavior in Mangroves

Mangroves grow in low-energy depositional areas, which also tend to be the sites where oil accumulates. Spilled oil is carried into mangrove forests by winds and tidal currents. Oil slicks generally move into mangrove forests when the tide is high, depositing on the soil surface and on aerial roots and propagules when the tide recedes. The resulting distribution of deposited oil is typically patchy due to the variability in tidal heights within the forest. If there is a berm or shoreline present, oil tends to concentrate and penetrate into the berm or accumulated detrital **wrack**–organic material, usually from dead seagrass or algae, that washes up on shorelines. The oil can penetrate into the soil, particularly through burrows and other voids like those formed by dead mangrove roots. Lighter oils tend to penetrate more deeply into mangrove forests than heavier and more weathered oils, but will not persist unless they mix into the soil. However, crude oils and heavier refined products can pool onto sediment surfaces and can be highly persistent. These heavy oils and emulsified oil can be trapped in thickets of red mangrove prop roots and black mangrove pneumatophores and are likely to adhere to and coat these surfaces, as well as other organic materials, such as seagrass wrack. Re-oiling from resuspended oil, particularly as tides rise and fall, may further injure plants over time. Where oil persists, sheens may be generated for months or years.

Getter et al. (1981) identified four patterns of oil stranding that result in extensive tree mortality in mangroves (Figure 3.1). The main factor causing the highest tree mortality is where there is a rise in elevation, called a berm, where the oil tends to accumulate in highest concentrations. If the berm is located in the interior of the forest, usually created by the accumulation of sediments and wrack built

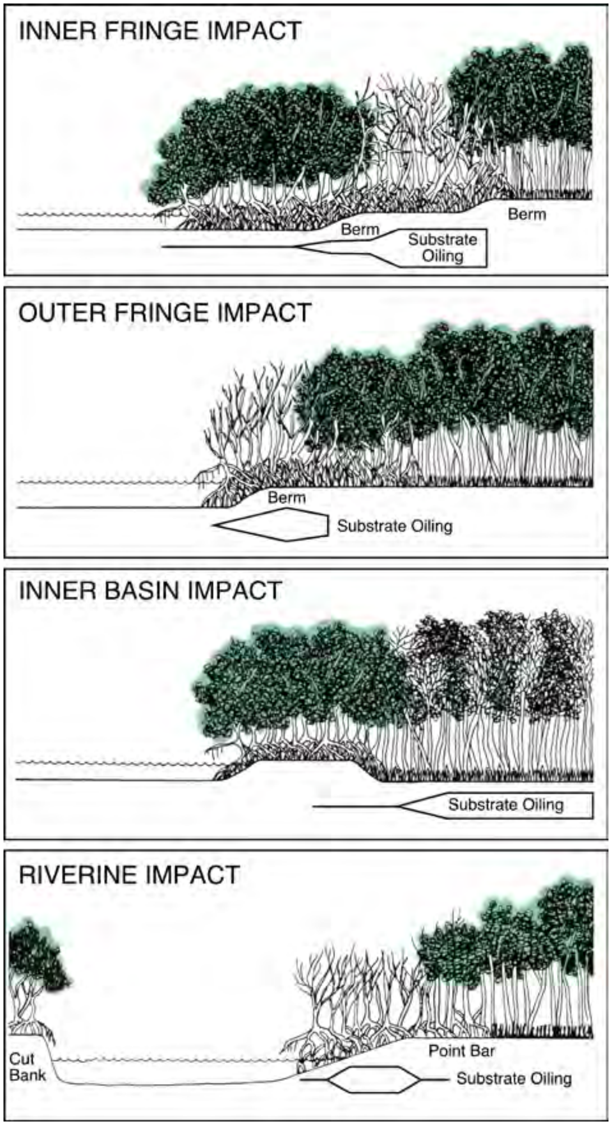

Figure 3.1. Schematic showing the different patterns of oil spill impacts to mangrove forests (modified from Getter et al. 1981).

Figure 3.2. Infrared aerial photograph of a band of dead mangroves where oiling was heaviest on the prop roots and penetrated into the soils. Note the lighter color of the outer fringe mangroves indicating stress. This is a classic example of inner fringe impact (Research Planning, Inc.).

Figure 3.3. Extensive riverine impacts to mangroves three years after the Funiwa 5 spill of 400,000 barrels of crude oil in Nigeria in 1980 (Research Planning, Inc.).

Anaerobic – Occurring with little or no oxygen.

by storm waves, oil accumulation there causes "inner fringe" impact, as shown in Figure 3.2 at the *Peck Slip* spill in Puerto Rico. If the berm is at the seaward edge of the forest, the result is "outer fringe" impact. If oil is washed through a fringing mangrove into a shallow interior basin, the result is 'inner basin" impact. Along rivers, the oil tends to strand most heavily on the point bar, causing "riverine" type impacts, as shown in Figure 3.3 at the Funiwa-5 oil spill in Nigeria. Note that the trees on each point bar up the river are dead.

Assessing the extent and distribution of stranded oil can be difficult, particularly in dense forests, because the forest interior sometimes can be oiled even if the mangrove fringe is not, due to its lower tidal height. Access to interior areas of forests usually must be limited in order to minimize damage. Also, the tree canopy may hide oil on the ground during oil-observation overflights. Affected areas may become more apparent from the air as trees die or defoliate. Oiled trees may start to show evidence of effects, such as leaf yellowing, within weeks after oiling. Trees may take months (or longer) to die, especially with heavy oils.

Cleanup of oiled interior mangroves can be particularly difficult because some mangrove forests are nearly impenetrable. Intrusive cleanup operations may significantly damage roots and seedlings, and also trample oil deeper into sediments, where it is slower to break down.

Consequently, access to interior areas of mangrove forests should be limited and highly supervised. During later, less-supervised stages of mangrove cleanup on Eleanor Island at the 1993 *Bouchard B-155* Bunker oil spill in Tampa, Florida, cleanup workers reportedly spread oil from the mangrove fringe to the roots of previously unoiled mangrove plants in the mangrove interior as they moved back and forth removing surface sediment contamination. In spills of relatively fresh, lighter oil, such as diesel or crude, sediment penetration and toxic damage can occur very rapidly and the oil can break down relatively quickly. In such cases, cleanup operations are not expected to save many mangrove trees or effectively remove much oil, and any benefits are probably outweighed by the potential additional damage from access for cleanup.

Natural processes will eventually remove remaining oil. Tidal action and precipitation can help physically flush stranded oil out of contaminated mangrove areas. Weathering processes degrade the oil, gradually reducing quantity and toxicity. Oiled substrate may not be able to support mangrove growth while toxicity levels remain high. Oil can degrade quickly in warm tropical environments, but more slowly if degradation is inhibited by **anaerobic** soil conditions. Oil may persist for very long periods in the peaty or muddy sediment where mangroves are most often found. Heavier oils can persist in mangrove sediment for decades after a spill.

Cleanup Options for Oiled Mangroves

If mangrove shorelines are oiled, extreme caution must be exercised in selecting cleanup activities. Potential benefits of oil removal must be weighed against the risks of potential additional harmful impacts from the cleanup technique. Table 3.1 lists possible cleanup methods and their potential impacts.

Natural Recovery

There are several circumstances under which it is appropriate to do nothing. The foremost of these situations is when cleanup would cause more harm than benefit to mangroves or other associated habitats, or when shorelines are inaccessible. When no cleanup is conducted, oil will slowly degrade and be removed naturally, assisted by natural and storm-generated flushing. (See *Era* spill case study, Chapter 5).

Table 3.1. Recommendations for response options in oiled mangroves by oil group (modified from NOAA 2010).

Oil Group Descriptions
- I – Gasoline products
- II – Diesel-like products and light crudes
- III – Medium grade crudes and intermediate products
- IV – Heavy crudes and residual products

The following categories are used to compare the relative environmental impact of each response method in the specific environment and habitat for each oil type. The codes in each table mean:
- A = The least adverse habitat impact.
- B = Some adverse habitat impact.
- C = Significant adverse habitat impact.
- D = The most adverse habitat impact.
- I = Insufficient information – impact or effectiveness of the method could not be evaluated.
- – = Not applicable.

Response Method	Oil Group			
	I	II	III	IV/V
Natural Recovery	A	A	A	A
Barriers/Berms	C	B	B	B
Manual Oil Removal/Cleaning	–	D	C	C
Mechanical Oil Removal	–	–	–	–
Sorbents	–	A	A	A
Vacuum	–	B	B	B
Debris Removal	–	A	A	A
Sediment Reworking/Tilling	–	–	–	–
Vegetation Cutting/Removal	–	–	–	–
Flooding (deluge)	–	B	B	B
Low-pressure, Ambient-water Flushing	–	B	C	C
Shoreline Cleaning Agents	–	–	I	I
Nutrient Enrichment	–	C	C	C
Natural Microbe Seeding	–	I	I	I
in situ Burning	–	–	–	–

Spills of light oils, which will naturally evaporate and break down very rapidly, do not require cleanup. Such light oils are usually gone within days. Furthermore, light fuel oils such as gasoline and jet fuels typically impart their toxic impacts immediately, and cleanup can do little to reduce the damage. The only light refined products that might warrant some cleanup are diesel and No. 2 fuel oil where the sediments are heavily contaminated. It is important to recognize, though, that even where natural recovery is advisable, light oils can cause significant injury and contaminated mangrove habitats may require many years to recover.

Cleanup also is not recommended for small accumulations of oil, regardless of product type. Impacts caused by light accumulations generally do not warrant the tradeoffs associated with cleanup activity. Even for major spills, there may be cases for which it is best to rely on natural recovery, depending on the nature of the oiling and the characteristics of the mangrove forest affected. Generally, cleanup should not be conducted in interior areas of mangrove forests because of the risk of damaging mangrove roots and seedlings, trampling oil into the sediment where it will degrade much more slowly, and spreading oil into previously unoiled areas. Exceptions may be made if access is possible from upland areas or if vegetation is sparse enough to permit access without injury to pneumatophores and prop roots. If cleanup is attempted in interior mangroves, experienced personnel must constantly oversee cleanup crews to prevent further injury.

In any case, attempts should be made to control the movement and spread of any mobile oil within the mangroves to prevent contamination of adjacent areas. Several response techniques described below, including barriers, passive collection, and flushing, can be used to help control and contain mobile oil.

Barriers/Berms

Sediment berms and dams can be used to temporarily close off the mouths of small inlets where currents and waves are low enough not to wash the sediments away. This method would be most appropriate to protect a small pond that was of high sensitivity. If water quality is of concern, an underflow dam can be installed to allow water flow in/out of the area. A nearby source of sediment to build the berm is needed. Because of the risk of altering the hydrology of the site, special care will be needed to make sure that all sediments are removed and the site restored to its original configuration.

Filter fences can be installed along the mangrove fringe; however, numerous stakes are necessary to keep them in place, and they often fail under wave action. Furthermore, they are very difficult to remove because the stakes get buried in mud, the cloth can get weighted down with mud, and debris tends to accumulate around them. Complete removal is important because the stakes and other materials can pose hazards to people, boats, and wildlife. Recording accurate GPS coordinates when such barriers are installed will aid in their location during removal. Most of the time, filter fences will have low effectiveness and a high risk of additional impacts.

Manual Oil Removal

Manual removal, using hand tools and manual labor, is often conducted to remove bulk oiling by heavier oils, such as crude oil or intermediate fuel oils, stranded in mangroves. Manual removal can help prevent other areas from becoming contaminated as the oil moves around, and helps limit long-term sediment contamination. Consideration should be given, however, to the trade-off between these benefits of manual removal and the damage to the mangroves that often accompanies manual cleanup. It is nearly impossible to reach the tangle of prop roots and pneumatophores of most mangroves without causing physical damage. Trampling of oil deeper into the sediment from foot traffic can be another harmful consequence of manual cleanup. Garrity and Levings (1996) observed that black mangrove pneumatophores along paths used by cleanup workers were significantly more likely to be killed than those in areas accessed by one or a few workers. Where pneumatophores had been dense at the time of the spill, paths often were bare substrate by 15 months post-spill as broken pneumatophores died and rotted away. (See Bahía las Minas case study.)

If manual removal is conducted in mangroves, and particularly in interior areas, consideration should be given to ways to minimize foot traffic and other impacts. Conducting activities from boats, when possible, is advisable. Close supervision of cleanup crews is essential.

Passive Collection with Sorbents

Even when natural recovery is the selected option, sorbents are often deployed to recover any oil released from the area. Sorbents are composed of materials that either adsorb oil on the surface or absorb oil into the pores of the material. There are many types: natural organic substance (e.g., peat, wood, cotton, straw, shredded sugarcane process residue called “bagasse”), synthetic organic substance (e.g., polypropylene, polyurethane), inorganic mineral substance (e.g., clay, vermiculite, diatomite), or a mixture of the three. The material may also be treated with oleophilic (oil-loving) or hydrophobic (water-hating) compounds to improve performance. They come in various forms: round sausage “boom,” snare, sweeps, pads, rolls, loose particulates, pillows, and socks.

Sorbents vary in their effectiveness depending upon oil type, degree of oil weathering, and sorbent absorption or adsorption capacity. Sorbent materials must be placed and removed carefully to minimize disturbance of sediments and injury to the mangroves. Likewise, sorbent materials must be closely monitored and maintained to ensure they do not move, become stranded on the shoreline, tangled in the vegetation, or buried in sediments, causing damage to the mangroves or associated resources. Sorbents must be removed when they become saturated or are no longer effective or needed.

Sorbents have been used to wipe heavy oil coating from mangrove surfaces. Before using sorbents in this way, consideration should be given to associated physical damage. This activity is best conducted under close supervision and only in areas where substrate is firm enough to support foot traffic and prevent mixing of oil into the sediments.

Vacuuming

Vacuuming can be used to remove pooled oil or thick oil accumulations from the sediment surface, depressions, and channels. Vacuum equipment ranges from small units to large suction devices mounted on barges, usually used outside vegetated areas. Generally, vacuuming should be conducted only at the outer fringe of mangrove forests; it is most feasible and least damaging where vegetation is not very dense, enabling easy access. Vacuuming can be used effectively on heavier and medium oils, providing they are still reasonably fluid. Lighter, more flammable petroleum products such as jet fuel and diesel generally should not be vacuumed.

As shown in Figure 3.4A, vacuuming was used effectively to remove pooled Bunker C oil that stranded in mangroves during the 1993 Tampa Bay oil spill response (see Case Studies for more details). Vacuuming worked particularly well where oil stranded on sand substrate at the mangrove fringe. The technique was less effective over fine sediment and oyster beds. To minimize cleanup damage, care was taken to place the vacuum barge over firm sand substrate, where there were no seagrass beds. Removing or disturbing fine sediments during vacuuming in mangrove areas should be minimized.

Vacuuming free-floating oil on the water surface is much more difficult. Vacuuming of a heavy fuel oil floating in the mangroves on the south coast of Puerto Rico generated mostly water, requiring extensive oil:water separation systems (Figure 3.4B). Overall, it was not very effective.

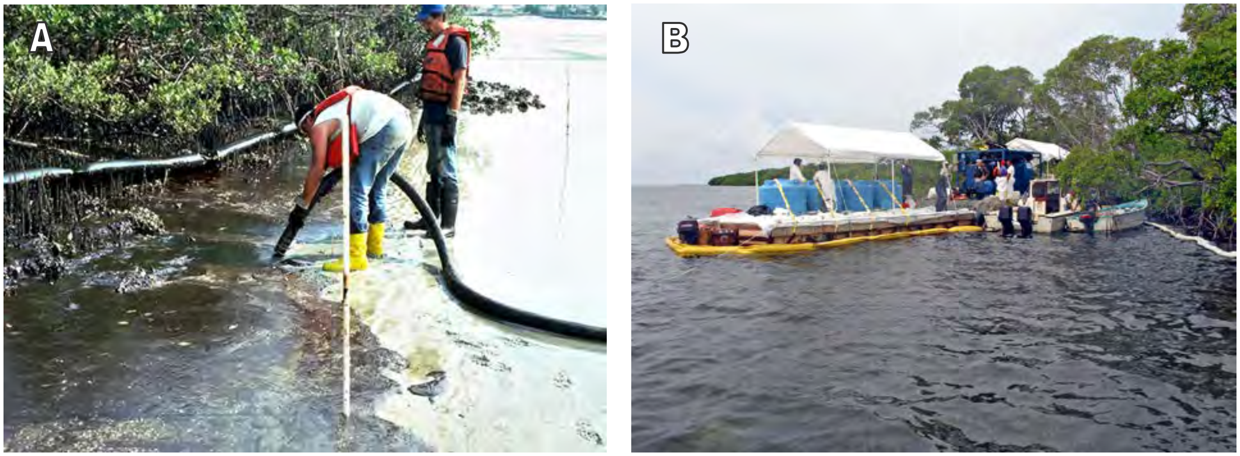

Figure 3.4. Vacuuming techniques in mangroves. A) Successful removal of thick oil from mangroves working on a firm sand flat during the 1993 Tampa Bay, Florida spill (Jacqueline Michel, Research Planning, Inc.) B) Unsuccessful attempt to remove floating oil trapped in the mangrove fringe during the 2007 Guánica, Puerto Rico spill of heavy fuel oil. Note the multiple tanks to separate the large volume of water recovered (Brad Benggio, NOAA).

Ambient Water Flooding (Deluge) and Low-Pressure Ambient Water Flushing

Low-pressure flushing with ambient seawater can wash fluid, loosely adhered oil from the sediment surface and mangrove vegetation into areas where it can be collected, as long as it can be done without resulting in significant physical disturbance of the sediment. Generally, flushing is most feasible at the outer fringe, but can sometimes be used to remove oil trapped within the mangrove forest. Ibáñez (1995) successfully used low-pressure flushing of the soils and mangrove roots in a 2.5-3 hectare mangrove affected by 28,000 gallons of slop oil in Cartagena, Colombia over a 54-day period; three years later, the forest had grown to cover 7 hectares. Flushing at water levels high enough to submerge sediments may help minimize impact to the substrate. If substrate mixing is likely or unavoidable, responders should allow the oil to weather naturally. Flushing is not effective with heavy oils or highly weathered oils. One of the biggest challenges is to get “behind” the oil that is trapped in the vegetation so it can be flushed to open water where the oil can be contained with boom and recovered using vacuums, skimmers, or sorbents. Flushing operations have to consider tidal currents (flush on a falling tide) and wind (an onshore wind will push any released oil back onto the shoreline).

Chemical Shoreline Cleaners

Chemical shoreline cleaners are products sprayed on oil-coated surfaces to "loosen" the oil so that it can be flushed off with ambient water. Tidal flushing or water sprays alone cannot effectively wash away heavy oil. Shoreline cleaning products vary in their toxicity and recoverability of the treated, mobilized oil. Chemical shoreline cleaners loosen or dissolve heavy oil deposited over the lenticels on coated prop roots or pneumatophores so the residue can be washed away and lenticel functioning restored. Functioning of the lenticels, which enable delivery of oxygen to the subsurface roots, is critical to survival of the trees. Further testing and more experience with the effectiveness and effects of using shoreline cleaners on mangroves are needed to determine whether their use is advisable, and under what conditions.

Some experimental studies (Teas et al. 1987, 1993) have reported promising results using chemical shoreline cleaners on mangrove trees coated with oil. A shoreline cleaner (Corexit 9580) applied to oiled red mangroves coated with Bunker C oil and then washed with seawater (within 7 days of oiling) reportedly effectively reduced oil adhesion and exposed the lenticels, restoring their air permeability. The study concluded that mangrove trees can be saved with shoreline cleaners if the interval between oiling and cleaning is no longer than about a week. Another study (Quilici et al. 1995) reported harmful effects on mangrove trees treated with shoreline cleaner without flushing. Results likely depend on the particular product used and application technique, as well as the unique spill and habitat conditions encountered. Again, there is currently insufficient information on the efficacy and effects of shoreline cleaning agent use in mangrove areas. In addition, RRT approval would be required prior to the use of shoreline cleaning agents in mangroves.

Enhancing Bioremediation: Nutrient Enrichment, Microbe Seeding, and Soil Oxidants

Nutrient addition (generally nitrogen and phosphorus) can enhance biodegradation of oil under nutrient-limited conditions. Because so many other cleanup techniques are either ineffective or can cause physical damage to mangroves, there have been several field studies to determine if adding nutrients, microbes, and/or oxygen to speed degradation of the oil in mangrove habitats (there are many studies showing oil degradation in laboratory and greenhouse studies under optimum conditions). Teas et al. (1991) found that adding fertilizer to the soil when planting *Rhizophora* propagules in oiled sediments 28 months after the Panama spill enhanced their growth in the dense peaty soils in only one of three sites, so further use of fertilizers was not recommended. Quilici et al. (1995) found that photosynthetic capacity, litter disappearance rate, and soil respiration were no different in oiled *Rhizophora* plots with or without added nutrients. Scherrer and Mille (1989) reported that oleophilic fertilizer enhanced the oil biodegradation process in peaty mangrove sediment, though the fertilizer in this experiment was added to the oil before the mangrove vegetation was contaminated.

Field studies in Australia using a light, waxy crude oil and a heavy fuel oil with nutrient addition and forced air injection compared to oil-only plots showed that, after 13 months, although there had been an increase by up to five orders of magnitude in the number of oil-degrading microbes, there were no differences in oil removal or weathering rates and no difference in tree mortality (Burns et al. 2000, Duke et al. 2000, Ramsey et al. 2000). However, leaf densities of surviving trees and Sipunculan worm densities in the soils were higher in bioremediation plots. Field studies in Brazil showed that natural microbe seeding did not stimulate oil degradation after 3 months (Brito et al. 2009). It appears that most mangrove soils have large amounts of readily degradable carbon, thus nutrient addition can stimulate the microbial population without increasing the oil degradation rates.

Some researchers are looking to phytoremediation as a treatment method for oiled mangroves, though the results are mixed. Tam and Wong (2008) showed that, in greenhouse microcosms, natural attenuation was more effective than microbe seeding and phytoremediation. A group in Brazil found that *Avicennia* seedlings planted in oiled mangrove soils did speed degradation of the oil compared to nutrients and controls (Moreira et al. 2013). They also reported that the seedlings in the oiled plots grew taller and had a larger root, compared to seedlings in unoiled soils. Nutrient addition could provide some value to the surviving plants, but keeping the nutrients in place during tidal flushing is difficult. Therefore, in the matrix in Table 3.1, nutrient enrichment methods are ranked as "C" because of the lack of proven effectiveness in speeding oil removal or weathering rates under realistic, field conditions.

Removal of Oiled Wrack and Debris

Heavily oiled wrack and debris should be removed if it can be done without significantly damaging prop roots, pneumatophores, and seedlings or trampling oil into the sediment. However, oiled wrack should not be removed until the threat of oiling has passed, since wrack and leaf litter can act as a sort of natural barrier sorbent and actually protect the trees from direct oil contact. Unoiled and lightly oiled wrack and leaf litter should not be removed because they provide habitat and contribute to the ecosystem.

Inappropriate Response Techniques for Mangroves

Under no circumstances should live mangrove vegetation be cut or burned. Both techniques will destroy trees and mangrove habitat. Mangrove trees are slow-growing and take decades to reach a mature stage. The loss of a large number of trees may compromise the forest structure, making it unlikely to recover naturally. Other cleanup techniques used at some oil spills but inappropriate in mangroves include mechanical oil removal, high-pressure or hot-water flushing, steam-cleaning, slurry sand blasting, trenching, and sediment reworking, tilling, or removal. All these methods would severely damage or destroy mangrove forests and associated organisms and habitats. All of these techniques may also cause or contribute to severe erosion.

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CHAPTER 4. MANGROVE RECOVERY AND RESTORATION

Key Points

- Mangroves can take more than 30 years to recover from severe oil spill impacts.
- Adequate tidal exchange is critical to restoration success.
- Mangrove seedling and tree density and health are the only widely measured recovery indicators at many spills.
- Restoration that works with natural recovery processes to reestablish mangrove habitat is the best course of action over the long term.

Mangrove ecosystems around the world suffer degradation from logging, coastal development, spraying of herbicides, conversion to fish ponds, and from oil spills and other pollutants. The continued loss of mangrove forests worldwide underscores the importance of projects focusing on restoration of forest structure and functions.

Because mangroves take 20–30+ years to recover from severe oil spill impacts, restoration projects attempt to speed up this recovery process. Adequate tidal exchange is most critical to restoration success. Mangrove restoration projects in Florida and the Caribbean often involve re-establishing natural hydrologic and tidal regimes, planting mangrove propagules, and/or planting marsh plants to provide a habitat that can be colonized more easily by mangrove trees.

An oil spill alone rarely changes the basic geophysical appearance and shape of the mangrove ecosystem. For this reason, restoration after an oil spill may be easier than after an event that substantially changes tidal elevation or hydrology or results in the complete removal of mangrove trees. However, an oil spill may come as an additional impact on a mangrove ecosystem already degraded by human and industrial development, such as near refineries (Bahía las Minas), ports, or airfields (Roosevelt Roads) or stressed by other natural or man-made causes such as hurricanes, cold weather, sea level rise, changes in hydrology or salinity regime. Cumulative or chronic impacts may decrease the resiliency of the mangrove ecosystem and increase the time it takes the system to recover, or make it more difficult for the system to recover at all.

As with other wetland ecosystems adversely impacted by oil spills, we have learned valuable lessons from past mangrove restoration projects, including those that failed. Restoration projects need a clear goal from the outset that is based on understanding the mangrove ecosystem’s natural ability to recover. The most effective role for restoration projects is to correct hydrology and elevation, or assist when natural recruitment mechanisms are impeded or no longer functioning.

Recovery

Recovery of any impacted ecosystem following a perturbation such as an oil spill is interpreted by many to mean a return to the system in place at the time of the spill. Mangroves' specialized niche is in a unique, changeable zone, subject to sediment flow that accretes and erodes, varying amounts of fresh water, impacts from storms and hurricanes, invasion by foreign species, and predation. Thus, even if we had a precise description of ecosystem conditions just before the spill, we still might not be able to return it to its pre-spill state.

A more practical way to measure recovery is to compare the impacted system with an unimpacted one (hopefully, nearby), using metrics such as tree height, density, canopy cover, above-ground biomass, and abundance and diversity of associated invertebrates, fish, and plants. Since compromised ecosystems can be more vulnerable to stresses such as disease or predation, the recovering habitat must also show the resilience of a functioning ecosystem.

It is rare to find long-term, follow-up studies on mangroves beyond 1-2 years post-spill. It is even rarer to find studies that measure associated communities of invertebrates or other components of the mangal (mangrove forest habitat) besides the mangrove trees themselves. Even when mangrove trees appear to have recovered, restored mangrove ecosystem may differ from unimpacted mangal in its functioning and ecosystem complexity. Even with its limitations, mangrove tree density and health are the only widely measured recovery indicators at many spills, so we are using mangrove tree recovery to compare between spills shown in Table 4.1. Keep in mind that the recovery times indicated would probably be even longer if more comprehensive and ecological recovery measures were used.

Table 4.1 summarizes impacts and recovery times for mangrove trees at eight oil spills impacting five regions. Mangroves in the Bahía las Minas region of Panama were oiled by the *Witwater* spill in 1968 and again in 1986 by a refinery spill. Mangroves at Roosevelt Roads Naval Air Station in southeastern Puerto Rico were impacted by spills in 1986 and again in 1999, though different sections of mangroves were oiled at each spill. Because of the short duration of the follow-up studies, no cases were able to document recovery, except for fringe mangroves at the *Witwater* spill. In most of these studies, mangroves were regrowing in the oil-impacted areas but tree height, percent area of open canopy, and other parameters remained different from controls.

Table 4.1. Impacts and recovery times for mangrove trees at eight oil spills impacting five regions.

Location	Oil Type	Mangrove Impacts	Mangrove Recovery	Published Reports
Era, Australia, August 1992	Bunker fuel	*Avicennia marina* 75-100 ha impacted	>4 yr.	Wardrop et al. 1997
Santa Augusta, U.S. Virgin Islands 1971	Crude	*Rhizophora mangle*	>7 yr. (little to no recolonization)	Lewis 1979
Zoe Colocotronis, Puerto Rico March 1973	Venezuela crude	*Rhizophora mangle* *Avicennia nitita*	>6 yr. (mangrove fringe)	Nadeau and Bergquist 1977, Gilfillan et al. 1981
Witwater, Panama, 1968		49 ha deforested	23 yr. (fringe) >23 yr. (sheltered)	Duke et al. 1997
Bahía las Minas, Panama, April 1986	Crude	*Rhizophora mangle* *Laguncularia racemosa* *Avicennia germinans* *Pelliciera rhizophorae*	>5 yr. (fringing mangroves) >6 yr. (recovery underway)	Garrity et al. 1994, Duke et al. 1997
Roosevelt Roads NAS, Puerto Rico,	Jet fuel (JP-5)	*Laguncularia racemosa*		
Nov 1986 October 1999		6 ha killed (1986) 31 acres impacted (1999)	>1 yr. >1.5 yr.	Ballou and Lewis 1989 Wilkinson et al. 2001
Tampa Bay, August 1993	No. 6 & No. 2 fuel	*Avicennia germinans* *Rhizophora mangle* *Laguncularia racemosa* 5.5 acres oiled	>2 yr.	Levings et al. 1995, 1997

Da Silva et al. (1997) diagrammed generalized mangrove impact and recovery from an oil spill in four stages. These timeframes are approximate and will likely vary in different systems. See also Table 2.1 in Chapter 2 for additional details on timeframes for oil impacts to mangroves.

- Initial impact ~ 1 year: propagules and young plants are most likely to die during this time
- Structural damage ~ 2 1/2 years: trees begin to die
- Stabilization ~ 5+years: deterioration of mangroves ceases, but no improvement noticeable
- Recovery ~ timeframe unknown: system improves via colonization, increased density, etc.

Additional impacts such as from hurricanes or other natural or human-caused disturbances could significantly delay these recovery processes.

Mangrove Restoration

Restoration success has rarely been studied quantitatively, but we know restored mangrove ecosystems often do not equate with natural ones. Shirley (1992) found that plant diversity was similar in restored and natural forests one year after restoration, but that environmental conditions were different and a number of fish and invertebrate species were absent from the restored site. McKee and Faulkner (2000) found that development of structure and biogeochemical functions differed in two restored mangrove stands because of different hydrological and soil conditions. Tree production and stand development were less where tidal exchange was restricted, and some waterlogging occurred due to uneven topography. Other assessments of restoration success, in terms of initial survival and percent cover after one or several years, have been mixed.

These experiences emphasize the need for developing clear restoration goals that incorporate the mangrove ecosystem and its functions, as well as the growth and health of the trees themselves. Once the goal is defined, the project is designed and implemented, followed by monitoring to ensure that restoration is proceeding as anticipated. Projects should be monitored for 10 or more years to adequately assess long-term survival, resiliency, and complexity of the restored system (Field 1998). Depending on the type of impact and the state of the impacted mangal, restoration may take several approaches:

- Replant mangroves
- Remediate soils
- Encourage natural regeneration through improved site conditions
- Restore an alternate site to provide similar habitat (in-kind restoration)

Replant Mangroves

There is an extensive body of technical information on replanting mangroves. Specific details on elevation, use of fertilizer, planting density, species selection, etc. can be found in Snedaker and Biber (1996) and Field (1996, 1998). Today, restoration projects have moved away from broad use of planting except in those cases where natural processes are inadequate to naturally repopulate the area with recruits from surviving trees or more distant sources. Examples include mangrove forests where hydrology has been substantially altered, or where physical barriers such as dead trees, debris, or berms restrict circulation such that propagules have no access to denuded areas. Getter and Lewis (2003) stated: "It is a waste of time and money just to attempt to replant mangroves without understanding why they died or why they have not recolonized on their own."

If planting is chosen as the best course, seedlings will survive best when they are planted in a sheltered location and at appropriate tidal elevation levels for each species. Planted seedlings are lost primarily because of erosion, predation, death from natural causes, planting at incorrect elevations, and residual oil toxicity (Getter et al. 1984). Planting one- to three-year old trees (usually supplied from nurseries) costs more but results in much better survival rates, especially in locations exposed to higher wave energy. Seedlings and propagules can survive even when planted in soils with residual oil contamination, though generally only after oil has weathered for 9-12 months.

Red mangrove seedlings (*R. mangle*) survived when planted in areas with one-year old residual oil at Bahía las Minas. A restoration planting project at St. Croix in the U.S. Virgin Islands planted seedlings 8 years after heavy oiling from the Santa Augusta spill, with 40% survival after two years (Lewis 1989).

Planting is still used to establish new mangrove forests in areas where they have not previously existed (such as in newly accreted shorelines or along human-built structures), or to replant in forests that have been logged. Survival of planted mangroves ranges from 0% to as high as 80% after one year. Lowest rates are often in areas with high wave energy where propagules are simply washed away. A planting technique that successfully increases survival rates of planted mangroves in exposed areas is called the Riley encasement method. Seedlings are planted inside PVC tubes (bamboo can also be used) to anchor and protect the seedlings until they become established (Rothenberger 1999).

Survival rates drop as the time after planting increases (e.g., one to two years or more). Even when plantings survive and grow, densities of planted trees may be lower than those naturally recruited, as found at the Bahía las Minas spill. Five years post-spill, replanted *R. mangle* survived well (especially in sheltered areas), but trees were less dense than in areas that recolonized naturally (Duke 1996). Restoration that enhances natural recovery processes to reestablish mangrove habitat has proven to be the best course of action over the long term.

Remediate Soils

Residual oil that has contaminated soils in mangrove forests degrades very slowly, since these soils are anaerobic below the top 1-2 mm (Burns et al. 2000). Experiments and field studies examining the possibility of accelerating oil degradation through addition of nutrients or increased aeration have shown little advantage to these methods. During the first year after a spill, biodegradation occurs at very low levels, and the main routes of oil removal are dissolution and evaporation. Thus, it is critical during spill response to attempt to keep oil from penetrating into sediments. Some restoration-planting projects surround seedlings with clean, fertilizer-augmented soil so the new trees can establish themselves and develop root structures in uncontaminated soils, before having to contend with possible toxic effects from residual oil.

Erosion of soils in mangrove forests following a disturbance can impede future re-establishment of new trees, since mangroves thrive only at specific tidal elevations. Since mangrove root mass comprises 40-60% of the total forest biomass, any substantial die-off of adult trees could cause subsidence of soils and erosion as a secondary impact. In such cases, augmenting soils, or assisting processes of sediment accretion may be a necessary part of restoration activities.

Encourage Natural Regeneration

Restore hydrology

Adequate hydrology has been identified as the most important parameter for mangrove recruitment (Lewis and Streever 2000). When tidal connections have been cut off or altered, as is common along developed coasts, re-establishing these connections can promote natural recruitment and improve the overall health and functioning of the mangrove ecosystem. Roosevelt Roads NAS is an example where impounded mangroves were impacted by a jet fuel spill in 1999. These mangroves suffered both from toxic fuel impacts and from extended submersion of roots when tidal conduits were closed to contain the spill during response. Facilitating or increasing tidal exchange to these impounded mangrove forests could be a promising restoration activity. A component of in-kind restoration conducted after the Tampa Bay spill involved restoring tidal circulation at a previous dredge disposal site where mangroves had been impounded by dikes. Figure 4.1 shows an example of a restoration project where dredged materials were excavated to the appropriate elevations and natural recruitment was very successful.

Figure 4.1. Mangrove restoration project at West Lake Park, Ft. Lauderdale, Florida. Dredged materials were excavated to the appropriate tidal elevation. No planting was conducted, mangroves re-established solely by natural recruitment once hydrology was restored (Robin Lewis, Lewis Environmental Services, Inc.).

Plant "nurse" habitat

Since mangrove propagules and seedlings grow best in sheltered conditions, one strategy for more exposed areas is to plant salt marsh plants such as *Spartina alterniflora* to create nurse habitat. These plants grow quickly (one to two years), trap and hold sediments (which decreases erosion), and create a more sheltered habitat where young mangroves can establish. This staged approach is modeled after natural successional patterns and boosts natural recruitment of mangroves (Mauseth et al. 2001).

Propagules may be available only during certain times of the year or may not distribute far from the parent tree due to poor circulation or blocking by debris. Removing floating debris that may block channels enables propagules to reach and recolonize denuded areas naturally.

Restore in-kind resources

Increasingly, in-kind restoration is used for projects in the United States, especially for resource damage settlements after oil spills. In-kind restoration restores habitat in a different location in the same ecosystem and is meant to contribute to the overall habitat function of the region.
A recent example of in-kind restoration is Tampa Bay, Florida, where several mangrove islets were heavily oiled during a spill in 1993. Restoration efforts purchased a former dredge disposal site within Tampa Bay that included degraded mangrove forest. Tidal connections were restored, marsh grasses were planted along the shoreline, and the land was deeded to the County to function as wildlife habitat and provide water-filtering functions (see Case Studies for more detail).

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CHAPTER 5. MANGROVE CASE STUDIES

Introduction

Mangroves around the world have been exposed to oil both from individual spills and from chronic pollution from refinery and storage tank discharges. Well-documented oil spills in mangrove areas provide a good idea of some of the complexities and variability of the impacts and response options. This chapter highlights techniques (learned from field trials, toxicology, and laboratory studies) to measure the health of mangroves. With help from NOAA's IncidentNews.gov database and from colleagues around the world, case studies of oil spills impacting–or potentially impacting–mangroves are presented in this chapter. The focus is on individual incidents and does not include cases involving long-term pollution. However, some spills occurred at sites that had been impacted by previous spills (Bahía las Minas, Panama and Roosevelt Roads, Puerto Rico). The selected case studies also focus more on the direct and indirect effects of oiling and cleanup on the mangroves themselves, less on associated fauna and flora. The response data from the case studies investigated included a wide range of documentation such as: incident description, response actions, cleanup methods, oil type, environmental impacts, and recovery and restoration efforts. These are briefly reviewed below in chronological order.

One lesson that is quite clear from even a few of the cases is that the full extent of damage to mangroves is not apparent for many months or years after an incident, regardless of the fuel type and extent of response (other than full protection). Many questions remain about most studies. The most important is, how long does recovery actually take? Although a number of post-spill studies were conducted for as long as 10 to 20 years, only a few reports discussed monitoring that continued long enough to confirm full recovery.

Zoe Colocotronis, La Parguera, Puerto Rico, 1973

On March 18, 1973, the *Zoe Colocotronis* ran aground on a reef 3.5 miles off the La Parguera tourist area on the southwest coast of Puerto Rico. The master intentionally released 37,579 barrels (1.58 million gallons) of Venezuelan (Tijuana) crude oil. An estimated 24,000 barrels (1.01 million gallons) stranded on the beaches of Cabo Rojo. Three separate pools of black oil 6-8 inches thick oiled the shore of Cabo Rojo on the Bahía Sucia side. On March 21, a large number of sea cucumbers, conchs, prawns, sea urchins, and polychaete annelids washed ashore. Organisms died in the *Thalassia* seagrass beds and oil moved into mangrove forests composed of white, red, and black mangroves.

Response

Cleanup efforts were conducted outside the mangrove areas and involved booming, digging sumps, and pumping the collected oil into tank trucks. On March 23, before the oil in the mangroves could be recovered, an unexpected wind shift drove patches of oil out of the mangroves and into other areas and onto the beaches. By March 24, 604,000 gallons of nearly pure oil had been removed from other areas using sumps, skimmers, and vacuum trucks. Steam cleaning was not used because there was no accessible source of fresh water. No cleanup was conducted in the mangroves.

Impacts

U.S. Environmental Protection Agency (EPA) scientists surveyed the mangrove areas for a week beginning 24 hours after the spill. Detailed surveys were conducted of all oiled areas during the second week after the spill and again during the thirteenth week. Additional EPA site visits were made in January 1974 (10 months later) and January 1976 (34 months later) providing some idea of long-term effects. In one well-studied area, one hectare of red and black mangrove trees was defoliated and died during the three years following the spill. However, the EPA scientists also noted that much of the associated invertebrate life had recovered (Nadeau and Bergquist 1977).

In November 1973, eight months following the spill, oil chemists from Bowdoin College in Maine visited several oiled sites and noted a re-emergence of young trees. Although sediment oil concentrations remained high, the oil was heavily weathered and degraded. These observations suggested that the toxic components were gone in about half a year. This team had also visited oiled black mangrove sites four times between April 1979 and April 1981, 6 to 8 years after the spill. The scientists measured ratios of sodium and potassium in some plants, supporting the idea that oil injured the trees by disrupting salt and water balance and that such disruption might have been alleviated by directed cleanup. However, they made no comment on the visible health of the mangroves at that time (Page et al. 1979; Gilfillan et al. 1981).

Eleven years after the spill other chemists took sediment cores from several previously oiled mangrove sites and found concentrations ranging from 10,000 to 100,000 ppm (dry weight, total unresolved hydrocarbons) in a layer 6 cm below the relatively clean surface sediments. In addition, they found oil, possibly from the 1962 *Argea Prima* spill, 14-16 cm below the surface. These researchers did not report the status of the mangrove trees themselves (Corredor et al. 1990).

In 2002, 29 years after the spill, Getter and Lewis (2003) re-occupied the twelve original EPA transects and compared tree measurements and photographs with those from the 1970s. They reported that the outer fringe forests had fully recovered in terms of vegetation structure (?), with mature red mangroves that were 10-15 cm in diameter. Vegetation structure in the inner basin forest of black mangroves was also fully recovered.

Restoration

No restoration activities were undertaken at this spill.

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Peck Slip, Eastern Puerto Rico, 1978

On December 19, 1978 the barge *Peck Slip* released between 440,000 and 450,000 gallons of Bunker C oil into open waters offshore of eastern Puerto Rico. Within two days oil had stranded in segments along 26 km of eastern Puerto Rico shorelines, mostly sand beach. However, some oil entered outer and inner fringing mangroves in three areas, and inner basin mangroves in one of these areas.

Response

No cleanup actions were undertaken although observers noted floating absorbent pads at one site. Surveys of mangroves were conducted shortly after the spill (December-early January 1979; Robinson 1979), 3 months later (Gundlach et al. 1979), 10 months later, and 18 months later (Getter et al. 1981).

Impacts

Mangroves on a small island (Isla de Ramos) were lightly impacted (prop roots had a 15-cm band of oil 50 to 60 cm above the substrate) and apparently did not suffer long-term injury. Near Punta Medio Mundo, about 1.05 hectares of inner fringe and inner basin mangrove roots were heavily oiled (prop roots with up to a 1-m band of oil) and 1 hectare was moderately oiled (0.3 to 0.45-m band of oil; Robinson, 1979). An estimated 3.5 tons of oil coated the mangrove roots. Algae growing on the prop roots absorbed the oil. Another two acres of mangroves at Pasaje Medio Mundo were moderately oiled with an estimated 1.3 tons of oil (prop roots oiled by a 0.2-m band on oil).

Within two to three months the heavily oiled inner fringing and basin mangroves at the Punta Medio Mundo forest were defoliated. Prop-root oiling had widened to a band of over 2 m high, possibly from climbing crabs that were oiled (Figure 5.1). Later site visits confirmed that mangroves with the most heavily oiled prop roots remained defoliated 10 and 18 months later (Getter et al. 1981). This was one of five sites studied by Getter et al. (1981). From these studies the authors urged that inner fringing and inner basin mangroves receive highest priority for protection from oil spills.

Figure 5.1. Heavy oiling of red mangrove prop roots from the *Peck Slip* spill in Puerto Rico in 1978. Note that the oil has spread 2 m above high tide by climbing crabs. The rod to the right is 1.5 m high (Research Planning, Inc.).

Getter and Lewis (2003) visited the site in 2002 but noted that the entire forest had been destroyed (by Hurricane Hugo in 1989), and a new forest had been reestablished.

Restoration

No restoration activities were undertaken at this spill.

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JP-5 Jet Fuel Spills, Roosevelt Roads, Puerto Rico (1986 and 1999)

In 1986 and again in 1999, Roosevelt Roads Naval Air Station storage tanks released JP5 jet fuel into a cove in eastern Puerto Rico. Before the 1986 and 1999 JP-5 spills, the area had been contaminated by oils from several past spills: a Bunker C spill in 1958 and a diesel spill in 1978, both from onshore storage tanks, and a 210,000-gallon diesel spill in 1981 from a tanker. All of these spills contaminated mangrove areas but effects of the earlier spills are unknown. In both cases, mangrove forests were contaminated, though response strategies differed markedly. Effects on mangroves were monitored at both spills.

On November 27, 1986, 59,000 gallons of JP-5 fuel washed down a catchment stream (tidal creek) and into Ensenada Honda. Two mangrove forest areas were contaminated, one in the tidal creek and the other at the head of the saltwater bay.

On October 20, 1999, 112,000 gallons of JP-5 fuel spilled from a day-tank at the Navy Base. The oil flowed into an underground drainage pipe, which runs under a runway and several roads for several hundred yards. The pipe empties into an open drainage ditch, which drains to a 12-hectare mangrove forest. This forest drains through a culvert into Ensenada Honda Bay.

Response

No cleanup actions were mentioned in reports dealing with the 1986 incident, presumably because of the high evaporation rate of JP-5 jet fuel in open conditions.

In the 1999 incident the Navy's primary environmental concern was the bay. In the face of an approaching hurricane, USN Construction Battalion (Sea Bees) personnel constructed a dam to plug the culvert between the first impacted mangrove (later named "mangrove A") and the mangrove adjacent to the bay (later named "mangrove C"). This dam trapped the water in mangrove area A, raising the levels by nearly 1 m above normal for 1.5 months. The final reports should be consulted for specifics as there were many details to the flow diversion response. Fuel was recovered, where practical, using underflow dams, skimmers, vacuum trucks, and sorbent materials. Attempts to manually remove oil with sorbents proved both ineffective and a human health risk for responders from inhalation of jet fuel fumes. It was estimated that 15-20% of the product was recovered, over 70 percent evaporated, and some 10-15% (approximately 11,200-16,800 gallons) remains unaccounted for; presumably stranded in the mangroves or in the sediments near the spill site.

The fuel flowed through the mangroves and some portion of the oil changed color from almost clear with a slight yellow tint to brown/black, similar to a light crude oil. It is unknown as to whether this was as a result of tannins from the mangroves dissolving into the oil or the JP-5, liberating heavier product remaining from previous spills.

Impacts

1986 Spill.

In the 1986 incident two mangrove areas were contaminated by JP-5 fuel: (1) the northernmost red mangroves drained by the tidal creek, and (2) the mixed species mangroves adjacent to the Coast Guard pier in Ensenada Honda. Local responders noted visible effects on adult trees within 10 days of oiling. Follow-on surveys were conducted in the second area 17 months later and again 23 months later. During these surveys 10 x 10-m grids along transects documented tree height, canopy, tree death, percent open canopy, seedling counts, and invertebrate biota. There were three transects in oiled areas plus two in unoiled areas. In June 1987, false-color aerial photos were taken of the impacted forest.

Detailed surveys five months later found most adult trees in the oiled areas dead and/or defoliated. However, there were live seedlings with highest densities along the forest front. Furthermore, sediment oil concentrations were extremely low (less than 1 ppm) and similar to concentrations in unoiled areas. Because of the low impact on seedlings and the near-absence of fuel oil six months later, researchers concluded that there was no smothering effect from the jet fuel. Adult tree defoliation and mortality was likely caused by initial direct toxicity of the fuel to root structures.

Apparently these mangroves recovered sufficiently from the 1986 JP-5 spill to merit no comment from personnel responding to the 1999 spill, other than that they were protected by the response itself.

1999 Spill.

Tidal creek mangroves were clearly damaged from the 1999 incident, due either to fuel toxicity or extended flooding, or both. Follow-up studies through October 2001 indicated that there was some recovery in the flooded area A two years after the incident, with new propagules and new shoots on injured trees. However, there were no signs of recovery in area B. Of a total of 50 acres of injured mangrove forest, about 30 acres showed no signs of recovery two years later (Lehman et al. 2001, Wilkinson et al. 2001). However, the series of water diversion activities resulted in preventing oiling of the mangrove (C) area bordering the shoreline of Ensendada Honda.

Restoration

The restoration plan consisted of hydraulic improvements to the Los Machos mangrove area. The Navy had a poorly designed culvert bridge across the mangrove channel, and the restoration consisted of removing the culverts, widening the channel, and replacing the bridge with an open span bridge. This increased tidal flushing throughout the section of mangroves.

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T/V **Era***, Spencer Gulf, South Australia, 1992*

On August 30, 1992, the tanker *Era* released an estimated 296 tonnes (974,000 gallons) of heavy Bunker oil (a blend of diesel and heavy residual) at a jetty near the head of Spencer Gulf, South Australia. On the night of September 1-2, an estimated 20 tonnes (5,500 gallons) stranded along 10-15 km of mangrove (*Avicennia*) forest south of Port Pirie, S.A. However, subsequent surveys estimated that the actual quantity stranded in the mangroves was 57 tonnes (15,600 gallons).

Response

Within two to three hours of the release, the oil slick was treated from vessels spraying dispersants Corexit 9527 and 7667; the following day, aircraft also sprayed slicks with Ardrox dispersant. Responders were advised that cleanup within the mangrove forest was not feasible and would likely increase damage to adjacent, unimpacted areas. Thus, all subsequent activity in the mangrove forest was restricted to detailed and long-term monitoring.

Impacts

Oiled mangroves were monitored for four years after the spill. This is perhaps one of the most well documented accounts available of the fate and effects of oil in a mangrove forest. Only a brief, highly simplified account can be given here, and the reader is advised to consult the report for important details and qualifications (Wardrop et al. 1997).

Due to an extremely high tide, oil penetrated far into the mangrove forest (50 m) coating leaves as well as stems, trunks, and sediment. Oil concentrations and visible damage to mangrove trees were recorded over four years. About 75-100 hectares were oiled: of these, 4.2 hectares were heavily oiled, 7.3 hectares were moderately oiled, and 38.0 hectares were lightly oiled. In 1992 heavy oiling of canopy and extensive mats of oiled seagrass debris characterized heavily oiled areas. By November

1992 mangroves over a total area of 2.3 hectares suffered extensive defoliation; the defoliated area expanded slightly to 3.2 hectares by 1995 and then stopped increasing. Trees that were totally defoliated did not recover during the four-year period. Defoliation and degree of sediment oiling were correlated: heavily oiled areas were completely defoliated and moderately oiled areas were "severely" defoliated. In lightly oiled areas, trees had less leaf damage and recovered rapidly. "Overall the extent of damage in each of the studied locations, and the speed with which it occurred, has correlated to the oiling classification assigned in the first survey" (Wardrop et al. 1997). Finally, the veracity of the original recommendation of "no cleanup" was supported: injury to mangrove trees was restricted to those initially impacted by moderate to heavy oiling.

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Witwater and Texaco Storage Tank Spills, Bahía Las Minas, Panama, 1968 and 1986

Two large oil spills, 18 years apart, resulted in long-term injury to a portion of the 1,200 hectares of mangroves of the Bahía Las Minas area of Panama.

Witwater. On December 13, 1968, the oil tanker *Witwater* broke up in heavy seas off the Atlantic coast of Panama, spilling 14,000 barrels (588,000 gallons) of Bunker C and diesel oil into the water 5 miles from Galeta Island. Strong seasonal winds pushed the slick towards the island, oiling sand beaches, rocky coasts, and mangroves.

Texaco Storage Tank. On April 27, 1986, a Texaco storage tank at a refinery on Isla Payardi, Panama, ruptured, releasing approximately 240,000 barrels (10.1 million gallons) of medium-weight crude oil. Approximately 140,000 barrels (5.9 million gallons) of oil flooded through a dike and overflowed separators and a retaining lagoon and flowed into Bahía Cativá, an arm of Bahía las Minas.

Response

Witwater. Several thousand barrels of an oil and water mix were pumped from the waters surrounding Galeta Island, and approximately 5,000 barrels (210,000 gallons) of oil were ignited and burned along shorelines in the bay. By December 17, pumping and shoreline burning cleaned up approximately half of the spilled oil.

Texaco Storage Tank. Refinery personnel reported that 60,000 barrels (2.52 million gallons) of oil were recovered. It is not known how much of this recovered oil was from the sea. Dispersants were applied in Bahía Cativá, Islas Naranjos, offshore of Bahía Las Minas, near Portobelo, and along the northern breakwater at the mouth of the Panama Canal, although the dispersants appeared to be ineffective due to the weathered state of the oil and the calm seas. Skimmers were also used and recovered some floating oil. Vacuum trucks were used as part of the shore-based cleanup effort, recovering oil floating on the nearshore water. Several channels were dug through the mangroves to drain the oil. These channels appeared, instead, to have helped move the oil inshore. Increased disturbance due to the construction of the channels may have also contributed to subsequent erosion. Oiled sediment and debris were manually removed along the more accessible shorelines. Seawater was sprayed on some sandy areas to aid oil removal. Pumping to recover floating oil appeared to be the most effective oil recovery method. The shallow waters and mangroves rendered many oil spill cleanup techniques impractical.

Impacts

Archived aerial photographs (1966, 1973, 1979, and 1990) and ground surveys were keys to understanding the effects of these two spills on mangrove forests.

Witwater. Despite the cleanup, both red and black mangrove trees were severely oiled, and the majority of the red mangrove seedlings were killed. Oil also damaged much of the mangrove forest biota. Initial reports did not indicate that adult trees had suffered. Aerial survey photos from 1966 and 1973 were used to assess deforestation and open canopy. About 49 hectares of mangrove forest (representing 4 percent of the total mangrove area) had been completely deforested in 1973 (five years after the spill). Most deforested areas had new recruits by 1979 (eleven years after the spill) but 3 hectares were lost to sea-margin encroachment. Observable differences (crescent-shaped bands of open canopy that were 5-100 m wide, and canopy height and structure) and oiled sediment persisted into 1992, 23 years after the *Witwater* spill.

Texaco Storage Tank Spill. The distribution of oil was surveyed from aircraft for two months following the release. A total of 51 miles of shoreline was heavily oiled, including some mangroves recovering from the *Witwater* spill. In a central embayment (Bahía Cativá), approximately half the surrounding forested area (and halfway up the intertidal zone) was killed. Oiled habitats within this distance included extensive mangroves, intertidal reef flats, seagrass beds, and subtidal coral reefs. Re-oiling of the shoreline and mangroves was a continuing problem. Oil slicks were regularly observed within Bahía las Minas for at least four years following the spill with oil coming predominantly from areas of fringing mangroves. As the oiled red mangrove trees decayed, it was believed that eroding, underlying sediments released trapped oil.

An affected reef flat habitat was the site of an ongoing study at the Smithsonian Tropical Research Institute's field station at Punta Galeta. A detailed study of mangrove trees revealed that one- to two-year-old seedlings appeared to survive whereas the surrounding adults died. It was believed that, somehow, young seedling structure (perhaps lack of prop roots) enabled the young trees to tolerate periods of oil immersion. It was suggested that the disruption of the substrate before replanting may remove such survivors, hampering forest recovery. Oil persisted in the mangroves through May 1989. Initial oiling of the trees produced measurable amounts of oil on 100% of all the roots that were sampled. Through May 1989, the mangrove roots in the open coast and channel areas showed 70% oiling, while the oiled proportion in the stream mangroves remained 100% oiled. The decrease in oil coverage resulted from weathering, microbial degradation, and loss of oiled bark or encrusting organisms. Root mortality was greater in oiled areas.

Subsequent aerial and ground surveys indicated "recovery of the 1986 spill was well-advanced by 1992" (Duke et al. 1997) due, in part, to extensive restoration. However, about 5 hectares of fringing forest were lost to sea-margin encroachment and important differences remained between sheltered and exposed areas.

Although ten times more oil was spilled in 1986 than in 1968, this did not result in ten times more damage to mangroves. Calm winds, lower tides, different oil type, and longer weathering time before impact may have resulted in less toxicity.

Restoration

Because of extensive mangrove mortality, several replanting projects were conducted at Bahía las Minas, in hopes of speeding mangrove forest recovery, which was at the time estimated to take 20 years or longer (Teas et al. 1989).

Experiments to determine whether propagules could survive if planted directly in oiled sediment found 100% mortality up until six months post spill. By nine months post-spill, propagules survived at rates similar to those at unoiled sites. Beginning 12 months after oiling, red mangrove seedlings that had been raised in a separate nursery area were planted (with added fertilizer) in areas of the damaged mangrove forest. A total of 42,000 nursery plants and 44,000 propagules were planted.

Studies conducted in 1989 (33 months post-spill) looked at the effectiveness of the plantings conducted in 1987, by comparing mangrove densities in areas that had recruited naturally with those that were replanted. Though planted seedlings had survived in all areas studied, naturally recruited plants were most dense. Thus, natural recruitment was more effective at recolonizing oil-damaged areas and, over time, natural recruits out-competed planted seedlings. Researchers also noted detrimental collateral impacts from planting, including cutting and removing dead timber for boat access (which removed shelter for seedlings), trampling sediments, digging holes (which accelerated erosion), and damaging existing seedlings (Duke 1996). Overall, planting did not result in a net benefit to the mangrove forest. However, since recolonization of mangroves was lowest in exposed areas, Duke (1996) suggested that an effective restoration activity could be to protect very exposed areas until mangrove trees are well established.

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Bouchard *Barge B-155, Tampa Bay, August 1993*

On August 10, 1993, the freighter Balsa 37, the barge *Ocean 255*, and the barge *Bouchard 155* collided in the shipping channel west of the Sunshine Skyway Bridge and south of Mullet Key in Tampa Bay, Florida. The collision caused three separate emergencies: (1) the *Balsa 37* was listing, threatening to spill phosphate rock; (2) jet fuel, gasoline, and diesel caught fire on the Ocean 255; and (3) the *Bouchard 155* was holed at the port bow, spilling approximately 8,000 barrels (338,000 gallons) of No. 6 fuel oil into Tampa Bay. By August 15 most of the floating fuel oil had come ashore and heavily coated sand beaches, several mangrove islands, and seawalls within Boca Ciega Bay.

By August 16 very little floating oil was seen offshore. In the shallow, low-energy areas along the mangrove islands inside Johns Pass and at a few locations in the surf zone, oil had mixed with beach sand and shallow sediments to form underwater tarmats, some of which came ashore on the mangrove keys (Figure 5.2)

Figure 5.2. Heavy oil stranding on the mangrove substrate and coating of the prop roots and pneumatophores (Research Planning, Inc.).

Response

The No. 6 fuel from the barge is the only material known to have been released from this incident. Countermeasures used during this spill were mechanical or manual removal. Skimming operations were used to collect free-floating oil. Efficiency and effectiveness of skimming operations were extremely high. Oil in and around mangrove islands was removed by vacuuming. Areas were left oiled when it was felt that cleanup methods would cause greater impact than leaving the oil in place. Some of the submerged oil in very shallow areas was removed using buckets and shovels. Oiled seagrass beds were cleaned by gently lifting oil out of them by hand.

Impacts

Tarmats had formed when the viscous oil mixed with sand in the surf zone along the Gulf beaches and when slicks passed over shoals at the entrance to Johns Pass. The mats that entered Johns Pass were almost neutrally buoyant and stranded on the tidal flat and in the mangrove fringe on one of the small islands just inside the pass (Eleanor Island). There, mats up to 10 cm thick accumulated around the mangrove roots and oyster clusters. Much of this oil was vacuumed out using a vacuum transfer unit on a grounded barge staged on the firm, sandy tidal flat. On all, 2.2 hectares of mangroves were moderately to heavily oiled.

Scientists visited oiled and unoiled mangrove keys quarterly between November 1994 and April 1996. Individual trees, pneumatophores, and prop roots were tagged to enumerate trends in defoliation, leaf health, shoot number and length, and mortality of juvenile and adult plants or their structures. Visual oiling trends were documented through late 1995 and sediment samples for wet chemistry were collected in 1996. Adult red mangrove trees at the most heavily oiled site (outer Eleanor Island) deteriorated over this time period, with moderate to heavy defoliation and soft, rotting prop roots. "Of marked trees, 20% were totally defoliated and appeared dead by June 1994" (Levings and Garrity 1995). Nine-month mortality of juvenile red and black mangrove plants was 5% at unoiled reference sites, 35% in heavily oiled areas on the protected side of the island, and 50% in heavily oiled areas on the exposed side of Eleanor Island. It was predicted additional mortality would continue to occur.

The researchers also measured for signs of sublethal stress in adult trees: one to two years after the spill and cleanup, surviving red mangroves experienced graded negative responses in four measures of shoot growth and production, suggesting that sublethal long-term effects may be common in oiled mangroves. Sediments around trees experiencing these responses contained greater than 500 ppm total hydrocarbons (dry weight).

More follow-up observations are needed at these sites, but we are not aware of any extending beyond three years after the spill and cleanup.

Restoration

Trustees from state and Federal agencies and the responsible party developed a restoration plan for mangroves and associated habitats damaged in the spill. A compensatory plan provided mangrove and associated wetland habitat for fish, birds, and epibenthic communities at a site in the same watershed but not necessarily impacted by the spill.

The responsible party purchased a former dredge disposal site in Boca Ciega Bay and deeded it into public ownership. This site contained degraded mangrove forest that was restored through excavation of the upland fill to appropriate tidal elevations to increase tidal exchange and removal of exotic plants and debris. On the bayward edge of the mangrove forest, smooth cordgrass (*Spartina alterniflora*) was planted to create a fringing salt marsh buffer that could eventually provide habitat for mangrove seedlings. A monitoring program was established with specific success criteria, including vegetative cover and height of mangroves, absence of exotic species, and functional tidal exchanges. At 60 months post-restoration, the site met five of the six performance criteria. The rapid recolonization of the site by mangroves precluded smooth cordgrass, which was planted initially after the site was re-constructed, from expanding to form a significant cover. The restoration project was considered a success because the ultimate objective was re-establishment of mangrove habitat (Lewis 2004).

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Guanabara Bay, Brazil, 2000

On January 18, 2000, 340,000 gallons of marine fuel oil (a blend of diesel and a residual fuel oil) were released from a pipeline at the Petrobras refinery inside Guanabara Bay, north of Rio de Janeiro, Brazil. Two areas of mangroves were heavily impacted: 1) near the pipeline break which resulted in extensive contamination of interior mangrove habitats; and 2) near the Suruí River where the heaviest oiling was along the outer fringe.

Response

Initial efforts included mechanical oil recovery from the water surface, mangrove areas protection with booms, beach cleanup, and rocky shore cold water flushing. No cleanup efforts were attempted in mangroves.

Impacts

In the heavily oiled areas one year after the spill, impacts were as follows: 24-96% tree mortality versus 11-22% in unoiled areas; adventitious roots in juveniles and seedlings of *Avicennia* at 20-50% whereas unoiled sites had ~0%; increased litter production; adult crab density reductions of 70% and juvenile crab density reductions of 40%; and no differences or a large increase in ovid female crabs. Total PAHs in soils were patchy, ranging from 11-355 ppm.

By 5-7 years post-spill, vegetative recovery was similar to mangrove growth following a natural disturbance, with no persisting chronic effects of oiling. The abundance of adult and juveniles crabs at three oiled sites showed no difference compared to an unoiled site, whereas one oiled site had a 65% reduction in juvenile crabs. The total PAHs in soils decreased, ranging from 3-18 ppm and soil bioassays showed no toxicity; however, large numbers of oligochaetes indicated continued stress in the oiled sediments.

In lightly oiled mangrove areas, impacts were as follows: 34-49% tree mortality versus 11-22% in unoiled areas; increased litter production; adult crab density reductions of 30-50% and juvenile crab density reductions of 20-50%; and ovid females crab abundances that were 1.5-3x greater than in unoiled areas. Total PAHs in soils at were at background levels (0.1-0.2 ppm) in one oiled area, and were 0.9-3.4 ppm in other oiled areas. By 5-7 years post-spill, there were no differences in any of these measures in the lightly oiled areas compared to unoiled reference sites.

M/T Solar I*, Guimaras Island, The Philippines, 2006*

On August 11, 2006, the tanker M/T *Solar I* sank in 700 m of water offshore of Guimaras Island, near Iliolo, in the central Philippines. The vessel was carrying an estimated 2 million liters (528,000 gallons) of bunker fuel for a local power plant. Over 200 km of shoreline were oiled, including sand beaches, cobble beaches, rocky shores, and mangroves.

Response

Cleanup was conducted on sand and cobble beaches, using mostly manual methods and local workers. Oiled seawalls around villages were scrubbed. The mangroves were heavily oiled, in many areas oiling extended throughout the mangrove stands, from the seaward edge to the landward extent of mangroves (Figure 5.3). There were some initial attempts to cut the oiled mangroves, which were stopped. Cleanup activities were completed in about one month, although some areas were not accessible and were left uncleaned.

Figure 5.3. Heavy fuel oil from the M/T *Solar I* that penetrated completely through the mangrove forest to the landward zone, coating the prop roots and trunks of the trees (Ruth Yender, NOAA).

Impacts

A long-term monitoring plan was implemented to assess the impacts of the spill. Studies of mangrove forests found that 0.93 hectares died in patches throughout the impacted area within three months. The largest patch was 0.49 ha. Though the oil swept through and oiled the entire mangrove forest in many areas, the dead patches occurred only at the inner part of the forest, adjacent to the terrestrial uplands. This pattern is likely a result of higher oil concentration at the landward extent of tides (up to the uplands) reduced tidal flushing, and no wave action.

The oil apparently did not penetrate into the mangrove soils, and one year later, total PAHs (16 parent PAHs) in soils were <0.16 - 0.8 ppm. PAHs in shellfish (bivalves, crabs, and gastropods) were 0.04-3.1 ppm one month after the spill, 9.7 to 18.7 ppm one year after the oil spill, and 1 ppm to 2.4 ppm two years after. It was noted that several storms hit the area in 2007 and 2008.

One year later, the mangrove forest community structure showed a drastic reduction in density and stand basal area. *Rhizophora* trees adjacent to the deforested area showed reductions in leaf size and canopy cover that reached up to a maximum of 48-58%. Propagules adjacent to the deforested area showed deformities and necrosis. In the deforested areas, saplings and seedlings were highly grazed and necrotic. No information was provided on the degree of sediment oiling in the deforested areas; however, the researchers attributed the continued stress responses to residual oil exposure. Three years after the spill, the deforested areas showed two patterns of response: 1) in areas where the dead trees were not being harvested for firewood, the logs trapped propagules and facilitated mangrove colonization; and 2) where the dead trees were harvested, an open gap was formed that exposed the area to surging waves, preventing recolonization. PAHs in the mangrove soils were reported to be below sediment toxicity levels.

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MANGROVE GLOSSARY

Aerial roots – Roots that are formed in and exposed to air. In mangrove species (e.g., *Rhizophora* spp.), aerial roots develop into stilt roots (prop roots and drop roots) that anchor into the sediment, offering mechanical support, nutrient absorption, and gas exchange.

Anaerobic – Occurring with little or no oxygen.

Anchialine ponds – A rare Hawaiian ecosystem, consisting of pools with no surface connection to the ocean, but affected by tides. These pools have a characteristic water quality and assemblage of animals and plants, many of which are endangered.

Anoxic – Without free oxygen. Aerobic metabolism (e.g., bacterial respiration) can consume dissolved free oxygen in water and soils, resulting in anoxic conditions that are detrimental to oxygen-breathing organisms.

Bioaccumulate – Uptake of dissolved chemicals from water and uptake from ingested food and sediment residues.

Biogenic – In mangroves, the trees themselves create the habitat. Biogenic also means "resulting from the actions of living organisms."

Canopy – topmost layer of leaves, twigs, and branches of forest trees or other woody plants.

Chlorosis – abnormal condition characterized by the absence of green pigments in plants, causing yellowing of normally green leaves.

Defoliation – The removal of the foliar tissues of a plant, resulting from mechanical (e.g., hurricanes), biological (herbivore), or chemical agents (e.g., plant hormones).

Deposition – The accumulation of material on a substrate. In mangrove systems this term is typically used in relation to accumulation of surface sediment.

Detritus – Non-living organic matter that is so decomposed that it is impossible to identify the original parent material.

Drop roots – Roots that develop on a branch and begin as aerial roots but eventually grow into a substrate; these roots can provide mechanical support (e.g., *Rhizophora* spp.).

Endpoint – A measured response of a natural resource to exposure to a contaminant, such as oil, in the field or laboratory.

Eustatic sea level rise – The worldwide rise in sea level elevation due mostly to the thermal expansion of seawater and the melting of glaciers.

Evapotranspiration – The transfer of water from the soil, through a plant, and to the atmosphere through the combined processes of evaporation and transpiration. Evaporation is a function of surface area, temperature, and wind. Transpiration is a process of water loss through leaf stomatal openings, and is related to gas exchange and water transport within a plant. When the stomates open, a large pressure differential in water vapor across the leaf surfaces causes the loss of water from the leaves.

Genotype – Genetic makeup of an individual organism.

Hermaphroditic – Both sexes present in an individual organism.

Infrared photography – Photography using films sensitive to both visible light and infrared radiation. Live vegetation is particularly highlighted with infrared films and so is a useful tool for aerial surveys of live and dead plants.

Lenticel – A small elliptical pore in the surface tissues of mangrove pneumatophores and prop roots, where gas exchange occurs.

Mangal – a mangrove forest and its associated microbes, fungi, plants, and animals.

Mangrove – a tree or woody shrub that has adaptations for growing in the intertidal zone (specifically, adaptations to salinity and flooded conditions).

Microtidal – A tidal range of less than one meter.

PAH – polynuclear aromatic hydrocarbon; also called polycyclic aromatic hydrocarbon, a component of oil. PAHs are associated with demonstrated toxic effects.

Pneumatophore – A vertical above ground extension of an underground root, with lenticels and aerenchyma to allow for gas exchange. Pneumatophores are characteristic of trees adapted to flooded conditions (such as *Avicennia* spp.)

Prop roots – Roots that develop on a trunk and begin as aerial roots but eventually grow into a substrate; these roots can provide mechanical support (e.g. *Rhizophora* spp.), sometimes called "stilt roots."

Propagule – Seedling growing out of a fruit; this process begins while the fruit is still attached to the tree. For some species of mangroves, propagules represent the normal, tidally dispersed means of reproduction.

RSLR – relative sea level rise - The net effect of eustatic sea level rise and local geomorphoplogical changes in elevation. Local subsidence can make RSLR much greater than eustatic rise.

Sublethal effect – An effect that does not directly cause death but does affect behavior, biochemical, physiological, or reproductive functions, or tissue integrity.

Vivipary – The condition in which the embryo (the young plant within the seed) germinates while still attached to the parent plant (synonymous with viviparity)

Weathering – Changes in the physical and chemical properties of oil due to natural processes, including evaporation, emulsification, dissolution, photo-oxidation, and biodegradation.

Wrack – Organic material, usually from dead seagrass or algae that wash up on shorelines.

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