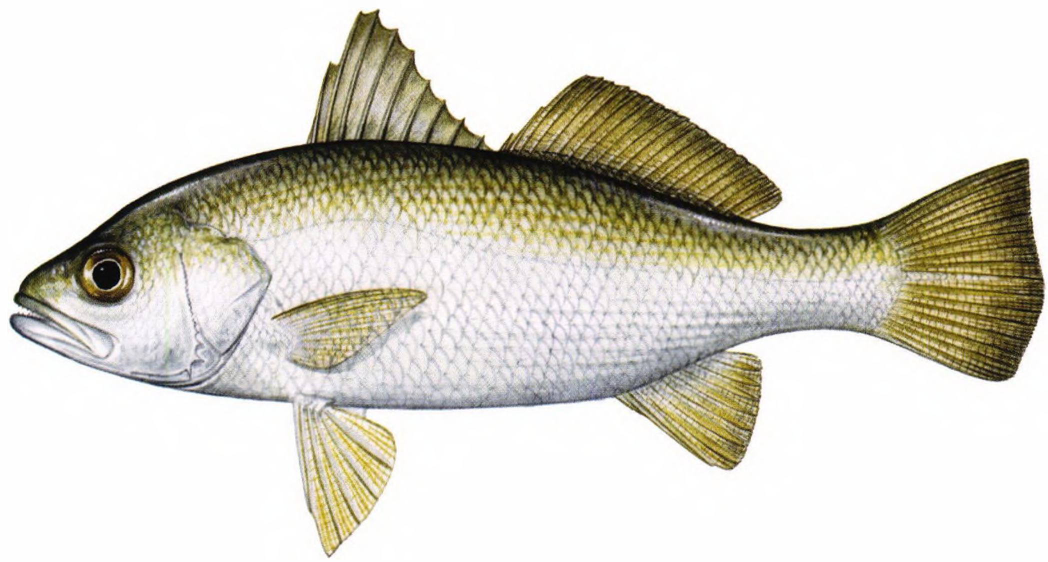
National Park Service
U.S. Department of the Interior

South Florida Natural Resources Center
Everglades National Park

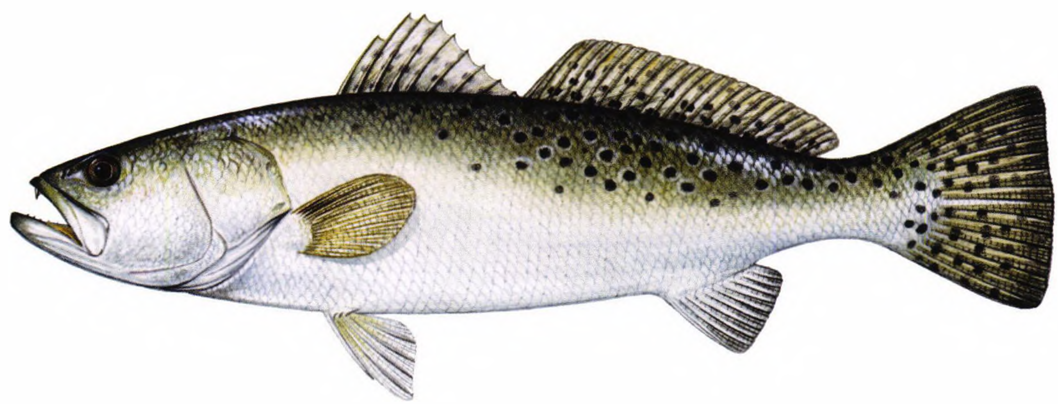
RESOURCE
EVALUATION
REPORT

SFNRC Technical Series
2006:1

ECOLOGICAL & HYDROLOGIC TARGETS for Western Biscayne National Park



silver perch (*Bairdiella crysoura*)



spotted seatrout (*Cynoscion nebulosus*)

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Biscayne National Park
Homestead, FL

South Florida Natural Resources Center
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Ecological and Hydrologic Targets for Western Biscayne National Park

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The purpose of this document is to establish a set of scientifically based ecological and hydrologic targets in the western areas of Biscayne National Park, to use these targets to estimate the current water deliveries that are required for the protection of fish and wildlife, and to give guidance about the timing and distribution of water inflows needed to sustain the ecological targets. These current water deliveries will provide a baseline for Comprehensive Everglades Restoration Plan (CERP) projects to build upon in order to achieve substantial restoration of natural areas.

EXECUTIVE SUMMARY

National Park Service staff developed descriptive ecological targets based on biological communities and quantitative targets for salinity and freshwater inflows in Biscayne National Park. We selected biological indicators that include those described by the interagency RECOVER team to set environmental targets affected by inflows, primarily as measures of seasonal salinity patterns in key areas of the park. Using target values for salinity, we estimated hydrologic targets (freshwater inflows and their interaction with precipitation and circulation). Other relevant indicators of bay health derived from previous and current studies in the entire Biscayne Bay area also are discussed in support of defining desired ecological conditions and the salinities needed to sustain them.

The productivity and richness of the estuarine communities of Biscayne National Park have significantly diminished, as have those throughout Biscayne Bay, as a result of channel creation and the diversion of water away from the natural systems in south Florida. The quantity of freshwater, the seasonal timing of inflows, and the distribution along the coast have been significantly altered, profoundly affecting the historic estuarine nature of the western half of the bay. The alteration of the hydrology of south Florida has resulted in the near complete loss of estuarine habitats from the bay, including Biscayne National Park, diminishing the ecological and economic value of this portion of the greater Everglades ecosystem.

This report describes the desired conditions of the park in terms of biology, ecology, and available historical record. The "desired condition" takes into account historical information about the ecosystem but is not necessarily equivalent to a pre-drainage state. The desired condition for the Western Bay Zone of Biscayne National Park is a range of salinities that is consistently estuarine for support of a productive and diverse benthic community based on seagrass. These conditions also support federally-listed endangered species, such as the American crocodile (*Crocodylus acutus*) and West Indian manatee (*Trichechus manatus*), and create productive nursery habitat that sustains local and regional (Florida Keys) fishery resources.

Considering the needs of many native species, including the juvenile stages of crocodiles, gray snapper, seatrout, and pink shrimp, and populations of mojarras, pinfish, eastern oyster, and wigeongrass, the following salinity characteristics are required:

- At no time should measured salinities exceed 30 ppt. This will be particularly critical to achieve in the dry season, from November to June.
- From March through August (late dry season - early wet season), average monthly salinities should range between 15-25 ppt in the Western Bay Zone.
- In the late wet season (September-October), the Coastal Mangrove Zone should be oligohaline (0-5 ppt), and the Western Bay Zone should average less than 20 ppt.
- Salinity changes should be gradual and reflect changes in coastal inflows that approximate those of an unregulated, natural system.

Flows that achieve these salinity targets will produce stable mesohaline conditions over the 10,000 acre nearshore bay area of Biscayne National Park.

We used the methods described in draft CERP Guidance Memorandum 4 to determine how much of the existing freshwater deliveries to Biscayne National Park are contributing to the desired salinity regime. In the absence of operational hydrodynamic models, several analytical and empirical methods were applied to arrive at a range of estimates of the flows necessary to reach target salinities. It was determined that approximately 1.1 million acre-feet/year of freshwater flows would be required to meet the salinity targets described above in the 10,000 acre area of seagrass habitat. Modeled stages and flows from SFWMM Alt7r for the years 1965 to 2000 were used to quantify existing freshwater deliveries to the Bay. Following draft CERP Guidance Memorandum 4 methodology we produced a time-series comparison of the target with the existing flows. While some peak-flow freshwater deliveries exceeded the targets, the total quantity of current freshwater deliveries to Biscayne National Park is about 40% of the total desired freshwater quantity. The stable estuarine conditions desired in Biscayne National Park are not achieved by current freshwater inflows because the total volume is too little and because the timing and distribution are too unnatural. Therefore, the total volume of current freshwater inflows is required for the protection of fish and wildlife in Biscayne National Park. Improved timing of managed releases and increased total volume would also benefit the estuarine ecosystem in the park.

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FOREWORD

This report, "Ecological and Hydrologic Targets for Western Biscayne National Park," represents the culmination of a process which involved the collaboration of National Park Service staff and review by the staff of other agencies including the South Florida Water Management District (SFWMD) and the U.S. Fish and Wildlife Service. The technical analyses in this paper support the National Park Service's broad responsibility for the preservation of our nation's natural and cultural resources. In the context of the ecosystem restoration efforts in south Florida, this translates into the responsibility for determining the ecological and underlying physical conditions that represent the restored natural resources of the south Florida national parks. The description and quantification of these desired restoration conditions sets the goalposts for both ecosystem restoration projects and resources management projects that affect national park natural resources.

This paper identifies an overarching goal in the form of desired conditions for the western area of Biscayne National Park, and develops ecological and physical (salinity and hydrology) performance measures and targets for this area. The ecological analyses of habitat value arise from the well-documented relationships between salinity patterns and a healthy, diverse benthic community based on seagrass. Hydrologic analyses are then based on the ways that freshwater and seawater mix in the bay to provide desired nearshore estuarine salinities.

Future work will be needed to develop further the metrics associated with the hydrologic restoration targets for Biscayne National Park, including measures of seasonal and interannual variability, and the development of a timeline of infrastructure implementation and associated salinity changes. The National Park Service looks forward to continued cooperation with our partner agencies in the establishment of restoration targets for south Florida national parks, and to working with the responsible agencies to provide the needed water for restoration of these nationally important natural areas.

Robert Johnson
Director
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March, 2006

INTRODUCTION

The purpose of this document is to establish a set of scientifically-based ecological and hydrologic targets in the western areas of Biscayne National Park and to use these targets to estimate the current water deliveries that are required for the protection of fish and wildlife and the natural resources. These current water deliveries will provide a baseline for Comprehensive Everglades Restoration Plan (CERP) projects to build upon in order to achieve substantial restoration of natural areas.

Conservation Designations

Biscayne National Park comprises the majority of the central and southern portions of Biscayne Bay. It was originally designated by Congress in 1968 as Biscayne National Monument, and later established as a national park in 1980. Biscayne Bay, its tributaries, and Card Sound are also designated by the state of Florida as aquatic preserves, and Card and Barnes Sounds are part of the Florida Keys National Marine Sanctuary. Biscayne Bay was designated under the Surface Water Management and Improvement Act of 1987 as a priority water body by the Florida Legislature. The waters of Biscayne National Park, Biscayne Bay Aquatic Preserve, and the two sounds are classified as Outstanding Florida Waters and, as such, are subject to the most stringent regulations, including Florida antidegradation policies. Card and Barnes Sounds are important for the endangered American crocodile because they contain one-third of all crocodile nesting habitat in the continental United States, and the east shore of Barnes Sound is included within the Crocodile Lakes National Wildlife Refuge.

All of these areas, including those in the Coastal Mangrove Zone, are Essential Fish Habitat as described by a federal mandate to improve fishery management plans in the United States (NOAA 1996). By definition, "essential habitat" incorporates habitat required by the full life cycle of a species, recognizing the need for protection of nursery and spawning habitats that are critical to the survival of a species.

The National Park Service mission, as defined by the Organic Act of 1916, is "to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations." The National Park Service (NPS) believes that Biscayne National Park deserves a particularly high level of consideration for resource protection and restoration.

Relationship to CERP Processes

In drafting this report, existing performance measures and targets developed through the CERP Restoration, Coordination, and Verification (RECOVER) team for Biscayne Bay were used as the basis for interim targets for desired conditions. Modifications were made based on results of studies conducted in the bay or similar habitats in south Florida to improve the performance measures. In particular, while the RECOVER SE-6 performance measure is applicable in 3,200 acres adjacent to the mainland shore, we modified the measure to apply to 10,000 acres after considering physical conditions (including the sedimentary environment and the circulation of the bay) that affect the potential spatial extent of seagrass, the basis for the diverse benthic communities in the western part of Biscayne Bay.

The hydrologic targets and flow volumes described in this report were developed using the process described in draft CERP Guidance Memorandum 4. The Guidance Memorandum method was developed jointly by staff from the Corps of Engineers, the South Florida Water Management District, the National Park Service, and the U.S. Fish and Wildlife Service and, while the GM is specifically designed to quantify water made available by a CERP project, we determined that the method could be applied for the purposes of this report with minor modifications. The quantification method requires the use of hydrologic restoration targets based on desired and/or historic ecological conditions. According to this method, water that is available for the protection of fish and wildlife includes all existing managed flows or water levels that are equal to, or less than, the restoration target as determined by comparing time series. Water in excess of the daily restoration targets may be beneficial if delivered at other times of the year, but the sum of the daily exceedences are less than the additional water required to meet annual restoration targets.

This report describes the desired conditions of the park in terms of biology, ecology, and available historical record. The "desired condition" takes into account historical information about the ecosystem, but is not necessarily equivalent to a pre-drainage state. Biological indicators, including those described by RECOVER, are used to set environmental targets affected by inflows, primarily as measures of seasonal salinity patterns in key areas of the park. By using target values for salinity, hydrologic targets (freshwater inflows and their interaction with precipitation and circulation) can be estimated. Other relevant indicators of bay health derived from previous and current studies in Biscayne Bay also are discussed in support of defining desired conditions and the salinities needed to sustain them.

This report provides a description of ecological targets and targets for salinity, but does not provide an estimate of quantitative hydrologic targets for the Coastal Mangrove Zone. The Coastal Mangrove Zone presents a challenge for the calculation of beneficial water using the methodology outlined in draft Guidance Memorandum 4 because human development has lowered the water table and eliminated surface water that historically entered the coastal wetlands via the tranverse glades. Because canals deliver freshwater all the way to the bay shore, freshwater inputs to the Coastal Mangrove Zone are dependent on canal stages and local rainfall. The task of estimating quantitative hydrologic targets for this area

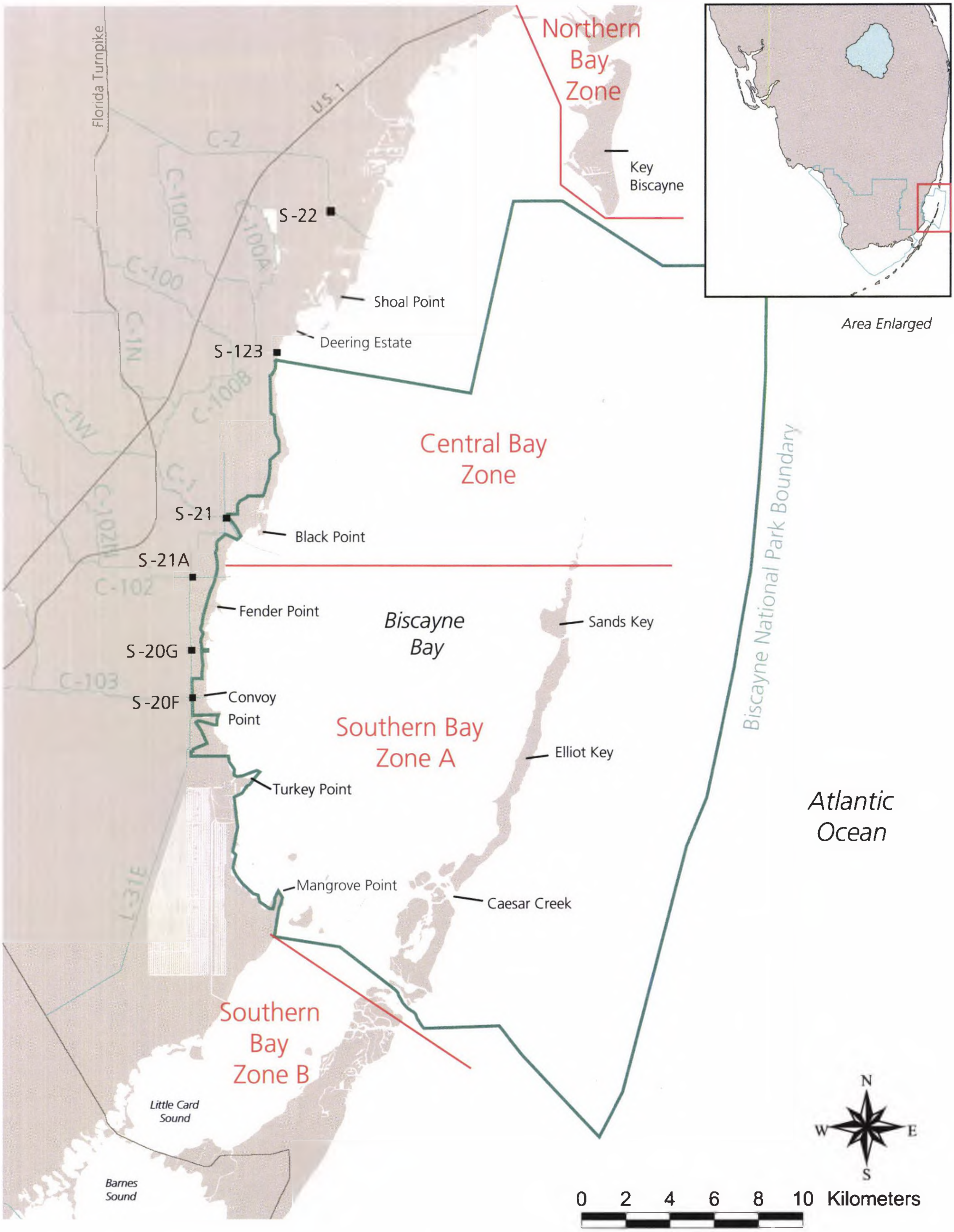

Figure 1. Biscayne National Park regional setting and Bay Zone definitions.

would be well undertaken by an interagency team. This report does provide targets related to ecology, salinity, and time series for water volume for the Western Bay Zone. To do this, we begin with two basic ecological premises: 1) healthy seagrass communities support diverse biological communities, and 2) components of the biological community are sensitive to salinity levels and salinity changes.

Area Description

Biscayne Bay is the largest estuary on the coast of southeast Florida and is continuous with the southern Everglades, separated from the Florida Bay system only by a narrow isthmus connecting Key Largo to the mainland. Naturally, freshwater flowed into Biscayne Bay from the Everglades through finger glades primarily in the wet season and through groundwater seepage year round.

This report focuses on the portion of Biscayne Bay within Biscayne National Park (Central and South Bay; Fig. 1). Though park waters are the primary concern of this report, similar methodology can be applied in northern Biscayne Bay by agencies that are more familiar with conditions there and that are responsible for its protection.

Biscayne Bay has been divided in various ways, but the most useful has been based on hydrodynamic circulation as used by the Miami-Dade County Planning Department (1986) and by the South Florida Water Management District in the Surface Water Improvement Plan for Biscayne Bay (1995). In this report, we divide Biscayne Bay into three sections (North Bay, Central Bay, and South Bay) based on dominant circulation patterns driven by proximity to oceanic inlets (Wang et al. 2003). These circulation patterns strongly influence salinity and, therefore, the ecology of the different regions of the bay. A newer and alternate delineation of the bay was created based on analysis of water quality data by Joe Boyer at Florida International University (Boyer 2004). Boyer groups areas based on similarities in water quality conditions composed primarily of nitrogen and phosphorus compounds, as well as other nutrients. Since water quality in Biscayne Bay is largely dependant on canal discharge, which was not present historically, we have chosen to use the designation based upon physical circulation patterns.

These divisions form the basis for oceanographic, geologic, and hydrologic factors that influence salinity and, therefore, ecology. Dominant circulation patterns vary based on local effects within four major hydrodynamic regions:

- North Bay (from Dumfoundling Bay south to Rickenbacker Causeway)
- Central Bay (from Rickenbacker Causeway south to Black Point)
- South Bay (from Black Point south to Jewfish Creek) (SFWMD 1995)
    a. The South Bay Section, from Black Point to Mangrove Point, the southwest corner of Biscayne National Park (Southern Bay Zone A)
    b. The Extreme Southern Bay Section from Mangrove point to Jewfish Creek, (Card and Barnes Sounds, and the associated bay, Manatee Bay), which are within the boundary of the Florida Keys National Marine Sanctuary and the Biscayne Bay Aquatic Preserve (Southern Bay Zone B).

The general circulation within Central and South Bay (Fig. 2) is driven by the large tidal flow in and out of the bay across an area known as the Safety Valve, and modified by the tidal flows through the five small creeks bisecting the island chain north of Key Largo, and by the large tidal oscillation in and out of the enclosed southern basins, Card and Barnes Sounds. Circulation and water exchange in North Bay has little to no influence on the circulation in Central Bay. This tidally-driven flow pattern is based on unpublished salinity monitoring data collected by Biscayne National Park staff. The resulting current pattern is consistent with the circulation models developed for Biscayne Bay by the U.S. Army Corps of Engineers (Dr. Rob MacAdory) and the University of Miami (Dr. John Wang). Freshwater from the mainland enters South Bay directly along the western coastline, and indirectly through Card and Barnes Sounds and Central Bay. The net effect is that the western part of the Bay (between Turkey Point and Black Point) is the area most influenced by freshwater flows. In terms of desired conditions for Biscayne National Park, and taking into account all source waters, this area of fresher water would extend along the mainland shoreline to the isthmus bounding the southern end of Barnes Sound.

When considering questions related to water management and freshwater flows from the mainland, the focus within these regions shifts westward to water and habitats nearest the coast that provide the most sensitive indicators of bay conditions. For the purposes of this report, the focus for development of targets to assist in the estimation of water for the protection of fish and wildlife is placed on two areas: the Coastal Mangrove Zone (CMZ) on the mainland of Biscayne National Park, and the Western Bay Zone (WBZ), including the seagrass bottom, which occurs in the western portion of the South Bay Section (Fig. 3).

Western Bay Zone Target Area. RECOVER has developed a performance indicator (SE-6) for CERP restoration efforts in Southern Biscayne Bay that describes indicator organisms, salinity conditions, and the "nearshore" area in which the performance measure will be applied. The area defined in SE-6 has lost historical oyster (*Crassostrea virginica*) colonies and no longer sustains red drum (*Sciaenops ocellatus*), a species that could be restored if habitat conditions were made suitable. Performance measure SE-6 defines "nearshore" as 250 m from shore during the dry season and 500 m from shore during the wet season (Fig. 3). The definition of these longitudinal bands of estuarine habitat is based on a simple consideration of a volume of water entering the bay edge as uniform flow;

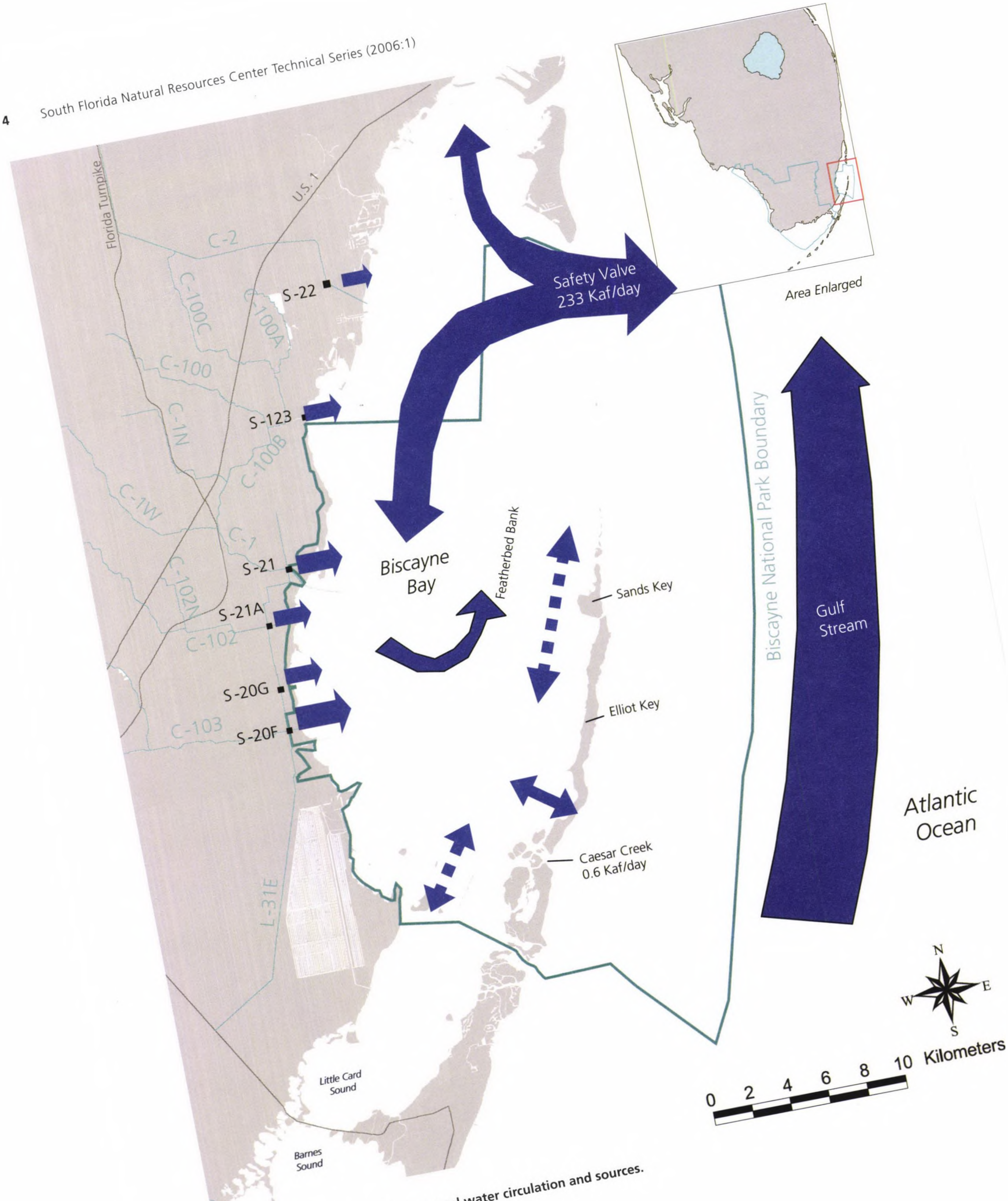

Figure 2. Biscayne National Park general water circulation and sources.

however, there is no analysis in the performance measure that explains why 250 and 500 m were chosen as target areas.

Because the characteristics of the benthic community depend on bottom type, we chose to use existing, but stable, physical characteristics of the bay bottom to assist in the definition of a target area for restoration. Based on benthic mapping and evaluation of abundance and distribution of benthic community types, the ecology of Biscayne Bay, as a whole, is dominated by the soft bottom (approximately 64% of the bottom) and hard bottom (17%) benthic communities (NOAA 1996). Soft bottom, shallow areas promote seagrass communities, whereas hard bottom areas, which occur where sediment is non-existent or very thin over a rocky substrate, are characterized by soft corals (i.e., sea fans), sponges, and isolated coral colonies.

Examination of geological maps of the bay bottom shows that areas affected by freshwater inflows along the coast of Biscayne National Park comprise a zone of soft bottom seagrass habitat that extends from Turkey Point to about 1,000 m offshore at Convoy Point to some 6,500 m offshore at the northern mainland boundary of the park (Fig. 3). The northern sector of this zone is a mix of both soft and hard bottom communities. This zone is bounded by the CMZ at the western shore of central and southern Biscayne Bay and by an area of hard bottom that occupies the Middle Bay Zone to the east. This WBZ historically received freshwater flow through coastal marshes and creeks, and groundwater recharge that correlated with the wet and dry seasons.

The bottom type and location of the WBZ, relative to historical freshwater inflows, define a target area of 10,000 acres of functional, seagrass-based estuarine habitat in Biscayne National Park. In contrast, the RECOVER dry season target of 250 m from shore covers about 1,600 acres, or only 16% of functional estuarine habitat that could be restored. The RECOVER wet season target of 500 m from shore covers about 3,200 acres, or less than 1/3 of the estuarine habitat that could be restored. It is our understanding that RECOVER may consider revising SE-6 in response to the considerations discussed here.

Our description of desired conditions and the analyses of ecological and hydrologic targets in the WBZ focus on this 10,000 acre area of submerged aquatic vegetation (SAV) habitat at the western edge of Central and South Bay, within Biscayne National Park. Currently, freshwater is delivered through canal structures along the coast. The water deliveries should be stabilized by linking volumes and timing with natural coastal marsh hydroperiods and estuarine salinities. This change would reestablish high quality nursery habitat for important fish and invertebrates in a band of soft bottom/SAV habitat from the northern boundary of Biscayne National Park south to Turkey Point (Fig. 3).

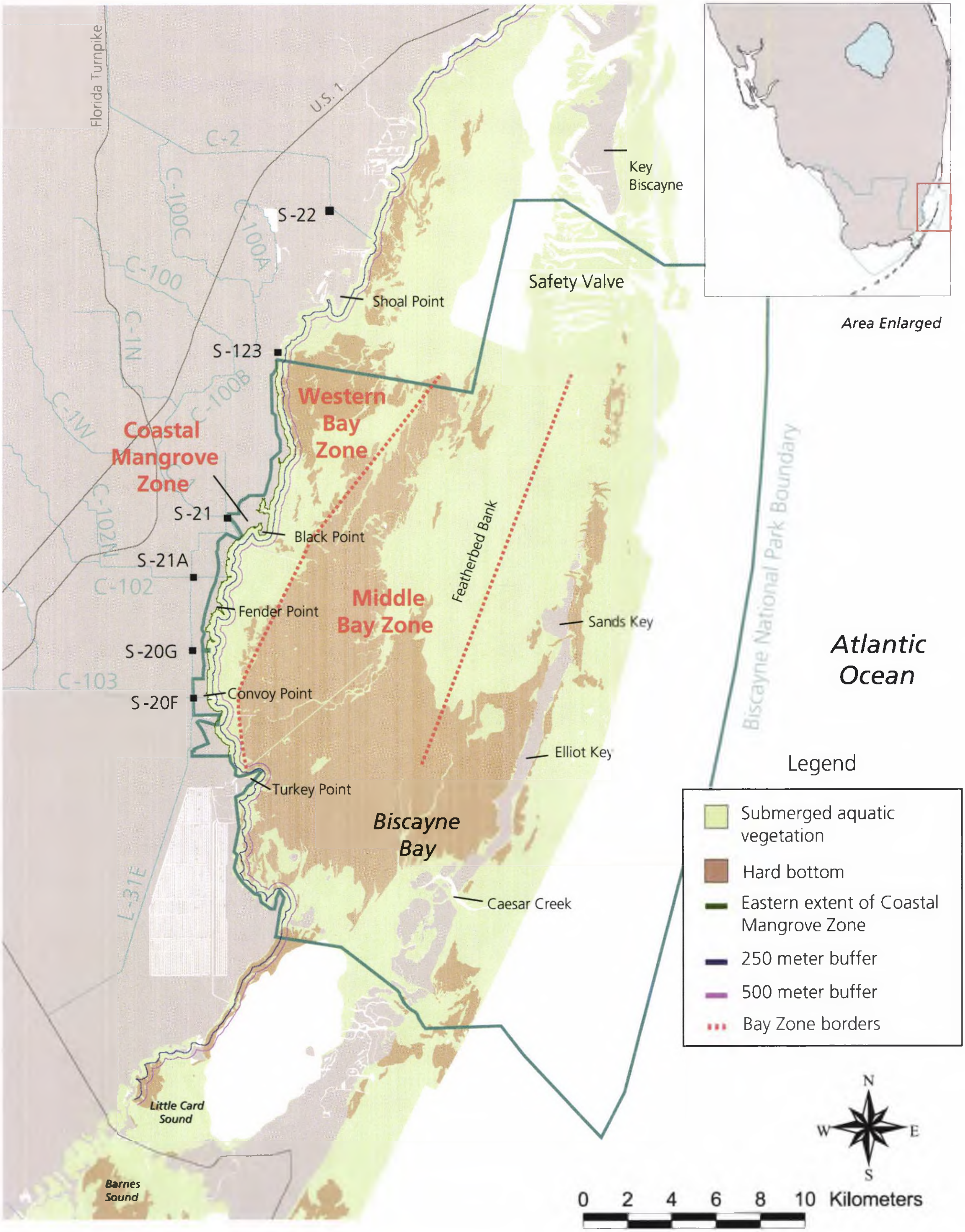

Figure 3. RECOVER performance measure focus areas and alternative Western Bay Zone focus area based on submerged aquatic vegetation on the bay bottom.

ECOLOGICAL TARGETS FOR BISCAYNE NATIONAL PARK

Historical Conditions

Coastal Mangrove Zone. What we now call the Coastal Mangrove Zone was formerly composed of freshwater marsh species. Historically, fresh surface water flowed to the bay through natural sloughs, rivers, and wetlands, and fresh groundwater flowed through the Biscayne Aquifer (Parker et al. 1955; Kohout and Kolipinski 1967; Buchanan and Klein 1976) and seeped into the bay along the coast and through the bay bottom. At the southern end of the Miami Rock Ridge, freshwater wetlands in the Biscayne Bay watershed occupied extensive coastal marl prairies that were east of the ridge where it curves westward away from the coast. Prior to drainage and land development, these marshes were dominated by sawgrass (*Cladium jamaicense*), spike rush (*Eleocharis cellulosa*), and other freshwater graminoids, including grasses and herbs (Gaiser and Ross 2004). The hydropattern depended on direct precipitation, surface flow from the Everglades through breaks in the ridge called "transverse glades," or rising groundwater when the regional water table was high (Wanless 1976). In a study of the paleoecology using soil cores along the coast, Gaiser and Ross (2004) showed a change from freshwater swamp forest to mangrove forest and a change in salinity from approximately 6.5 ppt to 12.5 ppt.

The transverse glades and freshwater forests and wetlands drained into a transition zone of coastal creeks and a mix of herbaceous freshwater-brackish wetlands, tidal marshes, and mangrove forests on the edge of the coast. These supported the bay ecosystem by spreading freshwater inflow, absorbing excess nutrients, and providing habitat - including critical nursery habitat - for fish and shellfish, as well as feeding habitat for wading birds. Local rainfall, groundwater seepage, overland sheet flow, and small coastal rivers fed water to the bay all along its mainland margins. The flow of freshwater through the forested wetlands and freshwater marshes provided dynamic storage of water and a buffer to reduce the amplitude of rainfall runoff events, and moderated the transition from freshwater inflows to estuarine and marine conditions in the bay (Wanless 1976; Browder and Wanless 2001). Egler (1952) documented the distinct vegetation bands parallel to the coast prior to construction of major drainage canals. He concluded that changes in vegetation composition were a result of increases in salinities between freshwater wetlands and saline wetlands near the coast. The area was still largely dominated by graminoid freshwater wetland, followed by dwarf mangrove scrub, and a narrow band of coastal mangroves in the 1940's and early 1950's. Kohout and Kolipinski (1967) found a distinct biological zonation of flora and fauna in nearshore Biscayne Bay based on salinity in the area around the old Cutler power plant north of the old Burger King headquarters site. Ishman et al. (1998) documented increasing salinity with distance offshore in pre-drainage Biscayne Bay. They also compared historical salinities from 1850-1900 to salinities in 1996. Gaiser and Ross (2004) also documented the historic salinity gradients in the remnant coastal wetlands. Average annual mean pre-drainage salinities were less than 2 ppt and freshwater marshes and associated forest units covered 90% of the area, with only a narrow band of mangroves along the coastline. Today that same area has a mean salinity of 13.2 ppt, and 95% of the area is covered by mangroves. Estuarine conditions, which were maintained by freshwater inflow, provided a broad band of habitats for organisms having a variety of salinity needs.

Western Bay Zone. Many different estuarine species flourished in the western part of Biscayne Bay. Miami-Dade County was at the core of the American crocodile (*Crocodylus acutus*) geographic range in the U.S. (Kushlan and Mazzotti 1989), with the coastal wetlands along the western shore of Biscayne Bay providing important habitat. Oyster reefs and associated fauna could be found in the bay (Smith 1896; Meeder et al. 2001). A large number of fish species could also be found in Biscayne Bay, with Smith (1896) listing 95 fish taxa.The presence of several species of drum (family Sciaenidae), which prefer brackish conditions, and the description of some of these species as either abundant or common, is particularly revealing of more estuarine conditions over 100 years ago (Serafy et al. 2001).

Recent paleoecological research conducted by the U.S. Geological Survey provided insight into pre-drainage conditions and general trends in bay salinities since 1900 (Ishman et al. 1998; Wingard et al. 2003, 2004). Results from sediment cores showed a long-term trend of increasing salinity at virtually all sites studied in Biscayne Bay, particularly since 1900. In the vicinity of Black Point, these data indicated that mid-level mesohaline conditions existed prior to 1900, tending toward more polyhaline conditions after that time. Sediment core data indicated that, since 1950, salinities have increased to mostly polyhaline conditions at these sites. Middle Key and Manatee Bay sites to the far south (Barnes Sound area) are farthest from the influence of Everglades transverse glades drainage, but are instead under the influence of the eastern margin of the Taylor Slough drainage system. Sediment cores from these two sites indicated conditions were predominantly freshwater (0 ppt) until about 1900. After that, oligohaline and low-end mesohaline conditions appeared, possibly in response to construction of the Flagler railroad, initial land drainage activities, and the construction of roadways (Wingard et al. 2004). The final shift occurred around the 1960's to mid-1970's when marine conditions (30-40 ppt) appeared in the sediment record, as evidenced by the remains of invertebrate species that can tolerate high salinities in areas that were once estuarine. Clearly, since 1900, a significant amount of freshwater from the historic Everglades drainage has been diverted, converting what were once fresh-to-brackish, estuarine habitats in the nearshore areas to marine conditions with the loss of estuarine productivity and function.

Current Conditions

Hydrology has been altered by regional drainage, canal construction and operation, and urban development, as well as by construction of roads, levees, and other hydrologic barriers to surface flow. The bay currently receives freshwater inflow as canal flow, with only minor overland flow, and occasional groundwater seeps (Kohout and Kolipinski 1967; Buchanan and Klein 1976; SFWMD 1995). Freshwater flow to the Card and Barnes Sounds section comes only through moderate-to-light discharges from the C-111 Canal, and from overland runoff from extensive freshwater and coastal wetlands contiguous with the mainland shoreline of these two basins.

Coastal Mangrove Zone. The L31E levee and canal run parallel to the coast about 2 km inland and intercept the local sub-basin drainages and transverse glades that used to discharge water to southern Biscayne Bay. As a result, a narrow strip of isolated coastal stream remnants and coastal fringe mangrove forest, most of which is within the park, is disconnected from the regional hydrology. The loss of freshwater inflows has resulted in the expansion of the fringing mangrove forest to the eastern side of the levee system (Ross et al. 2000; Gaiser and Ross 2004).

Currently, the hydrologic conditions within the CMZ are dependent upon canal stages and local rainfall. Although there are no current freshwater deliveries to this area, water levels in the canals determine the adjacent water table and, therefore, the water level in the CMZ. Water enters the area as groundwater seepage and as rainfall. These changes in surficial drainage have affected surface and groundwater hydrology (Parker et al. 1955; Parker 1974), reducing or eliminating coastal creek function and productivity. West of the L31E levee, the landscape is drained and compartmentalized by a network of mosquito control ditches, wetland drainage ditches, and flood control canals (e.g., Ruiz and Ross 2004). Although the wetland value of this area has decreased substantially because of increasing salinities and drainage, the ecological function of habitat created by the invasion of salinity-tolerant coastal mangroves remains particularly important to Biscayne Bay (Odum and Heald 1975; Teas 1976).

The area between Convoy Point and the northern mainland extent of the park covers some 1,500 acres of potentially high value fish and wildlife habitat that forms the longest contiguous coastal mangrove forest on the east coast of Florida. It is comprised of coastal fringe forest (primarily red mangroves), interior transitional forest (red and white mangroves), dwarf mangrove forest (red mangroves), and a mosaic of relict stream channels and coastal wetlands. This area provides food, shelter, and nursery habitat critical to sustaining the recreational and commercial fisheries in south Florida (Teas 1976; Serafy et al. 2003). Salinity fluctuations imposed by water management operations and loss of water to coastal creeks that once created brackish conditions in the prop root zone have created impaired fishery habitat with impaired nursery function.

Western Bay Zone. East of the mangroves, the WBZ is dominated by the seagrass (approximately 64% of the bottom) and hard bottom (17%) benthic communities (NOAA 1996). Submerged aquatic vegetation (SAV) in the bay is typically a mixed species community that may include shoal grass (*Halodule wrightii*), manatee grass (*Syringodium filiforme*), turtle grass (*Thalassia testudinum*), wigeon grass (*Ruppia maritime*), and three species of an uncommon SAV *Halophila*. Freshwater algae (*Chara spp.*) may also be found in low salinity coastal streams, tidal creeks, ponds, and around canal and creek outlets where fresher water predominates. The distribution of *Chara* in the WBZ is limited by its intolerance of the marine conditions now common in nearshore areas of the bay. Currently, the SAV community is dominated by turtle grass (Christian et al. 2004), an indicator of true marine conditions because of its low tolerance for brackish conditions.

The CERP Monitoring and Assessment Plan conceptual models identify salinity as the primary stressor in the WBZ, affecting biology when conditions deviate from a natural range. Salinity in this area is controlled by tidal circulation, which tends to increase salinities toward an offshore level (33-35 ppt), and by canal discharge, which is a function of canal operations and introduces freshwater (<1 ppt). To a lesser extent, salinity in this zone is affected by local rainfall (SFWMD 1995; Lirman and Cropper 2003; Faunce et al. 2003; Serafy et al. 1997). Another stressor is poor-quality water containing nutrients and contaminants (SFWMD 1995), carried by the six canals discharging into this zone (Black Creek (C-1), Princeton Canal (C-102), Military Canal, and Mowry Canal (C-103), C-111, Snapper Creek (C-2), and the Coral Gables Waterway (C-3)).

Indicator Species: Benthic Community, Endangered Species, and Important Fishery Resources

Many of the species described in this report are considered to be dependent on estuarine conditions. They require a brackish environment or they are reliant on estuarine salinities at specific stages in their life cycle. The presence of these species, both historically and at present, supports the importance of maintaining and restoring the estuarine nature of the WBZ. Many of these species are declining and some have presumably disappeared because of the lack of freshwater currently reaching the bay; therefore, the salinity range of these organisms can be used to define a beneficial salinity range for Biscayne Bay that will protect fish and wildlife. Many species including stone crab, Spanish mackerel, Crevalle jack, grey snapper, and tarpon are either recreationally or commercially important within the WBZ fishery. However, more historical information and field studies with site-specific information on preferred salinity ranges were available for the six species presented in Table 1, therefore we chose to use them as biological indicators.

Biscayne National Park's creel data (based on interviews of anglers when they return from fishing to local marinas) has been collected since about 1976. Most of the data pertain to reef fish, since a majority of the anglers fish on the reef, and are, therefore, less useful in this paper which focuses on the near-shore area. The bay species that might be affected by salinity changes near the coast (i.e., snook, spotted sea trout, red drum) are now landed infrequently in the areas we survey making it impossible to identify trends in population abundance from the creel data. The only species that are affected by salinity changes and are frequently reported are snappers and grunts, which utilize bayside seagrass beds as juvenile habitat. Also, it is impossible to distinguish the effects of salinity changes over time from fishing effects over time. For all these reasons, the Biscayne National Park creel dataset was used to provide supporting evidence of the continued presence of the biological indicator species in the bay, and was not used for more quantitative analyses of the effects of salinity changes.

The American crocodile (*Crocodylus acutus*) is primarily found in areas characterized by brackish estuarine conditions and average salinities of 14 ppt (Mazzotti 1983; Kushlan 1988; Kushlan and Mazzotti 1989). Hatchling crocodiles are particularly reliant on low salinities, generally 0 to 5 ppt (Mazzotti and Cherkiss 1998). Mazzotti and Cherkiss also determined that all size classes (hatchlings, juveniles and adults) favor water bodies with an intermediate salinity of 20 ppt. Juvenile crocodiles, in particular, seek out and seem to require a mesohaline (<20ppt with an optimum of 9 ppt) habitat for survival (Mazzotti et al. 2002).

The Eastern oyster (*Crassostrea virginica*) has long been recognized as an indicator of estuarine conditions (Dean 1892; Oemier 1894, Ritter 1896; Grave 1905; Pearse and Wharton 1938; Nelson et al. 1991; Estevez 2000; Meeder et al. 2001). The life cycle of oysters occurs entirely within estuaries. Oysters are capable of surviving salt concentrations from 5 to 40 ppt, however the optimum range for oyster reef growth is 10-20 ppt (Stenzel 1971; Meeder et al. 2000). This allows for oyster reproduction while decreasing predation rates (Grave 1905; Gunter 1950; Wells 1961).

Spotted sea trout (*Cynoscion nebulosus*) and mojarras (*Eucinostomus spp.*) are important fish species in Biscayne Bay. Serafy et al. (1997) found that populations of these two species in Biscayne Bay prefer salinities less than 20 ppt. They also found a significant decline in the abundance of these two species from 20 to 30 ppt. A re-examination of these data, with the addition of silver perch (*Bairdiella chrysoura*), was conducted to focus on evaluating the relationship between salinity and juvenile abundance (Fig. 4). A clear pattern of selection of salinities less than 20 ppt was observed in the data, with significant declines in abundance from 20 to 30 ppt. The pattern of declining fish density with increasing salinity was also observed by Campos (1985) in another study conducted in Biscayne Bay.

Pink shrimp (*Farfantepenaeus duorarum*) are a key species in the marine food chain and they are the most economically important fishery in Biscayne Bay (Bielsa et al. 1983; Berkeley and Campos 1984; Markley and Milano 1985; Browder et al. 1999; Serafy et al. 2001). Estuaries, and the seagrass communities found there, are important nursery habitats for pink shrimp, offering the most favorable food and shelter conditions for juvenile and post larval pink shrimp (Bielsa et al. 1983; Ault et al. 1999). Young shrimp find their way into the estuary by detecting lower salinity and a high amount of organic material (Lindall 1971; Odum and Heald 1975; Ault et al. 1999). These shrimp spend 2-6 months in estuarine areas before entering offshore water (Costello and Allen 1966; Bielsa et al. 1983; Ault et al. 1999). Post-larval pink shrimp are most often found in the nearshore seagrass on the western side of the central and southern portions of Biscayne Bay (Ault et al. 1999). Since this species is critically important to the bay and the regional fishery, estuarine conditions and SAV habitat must be preserved. This can only be accomplished by the stabilization and persistence of mesohaline conditions.

Table 1. Fish and wildlife indicators in Biscayne Bay.

Organism	Zone	Importance	Source
American crocodile (*Crocodylus acutus*)	Mangroves	Endangered Species	Mazzotti and Cherkiss, 1998; Kushlan and Mazzotti 1989. Kushlan 1988; Mazzotti 1983
Spotted seatrout (*Cynoscion nebulosus*)	Western Bay Zone	Commercial value, Recreational fishing	Pattillo, et al 1997; Bortone, 2003.
Mojarras (*Eucinostomus spp.*)	Western Bay Zone	Forage base species	Serafy, et al., 1997
Silver perch (*Bairdiella chrysoura*)	Western Bay Zone	Forage base species	Serafy, et al., 1997
Pink shrimp (*Farfantepenaeus duorarum*)	Western Bay Zone	Keystone species, commercial value	Bielsa et al., 1983; Serafy et al., 2001; Browder et al., 1999; Gunter et al., 1964
Eastern oyster (*Crassostrea virginica*)	Mangroves	Commercial value	Meeder et al., 2001, Wells, 1961

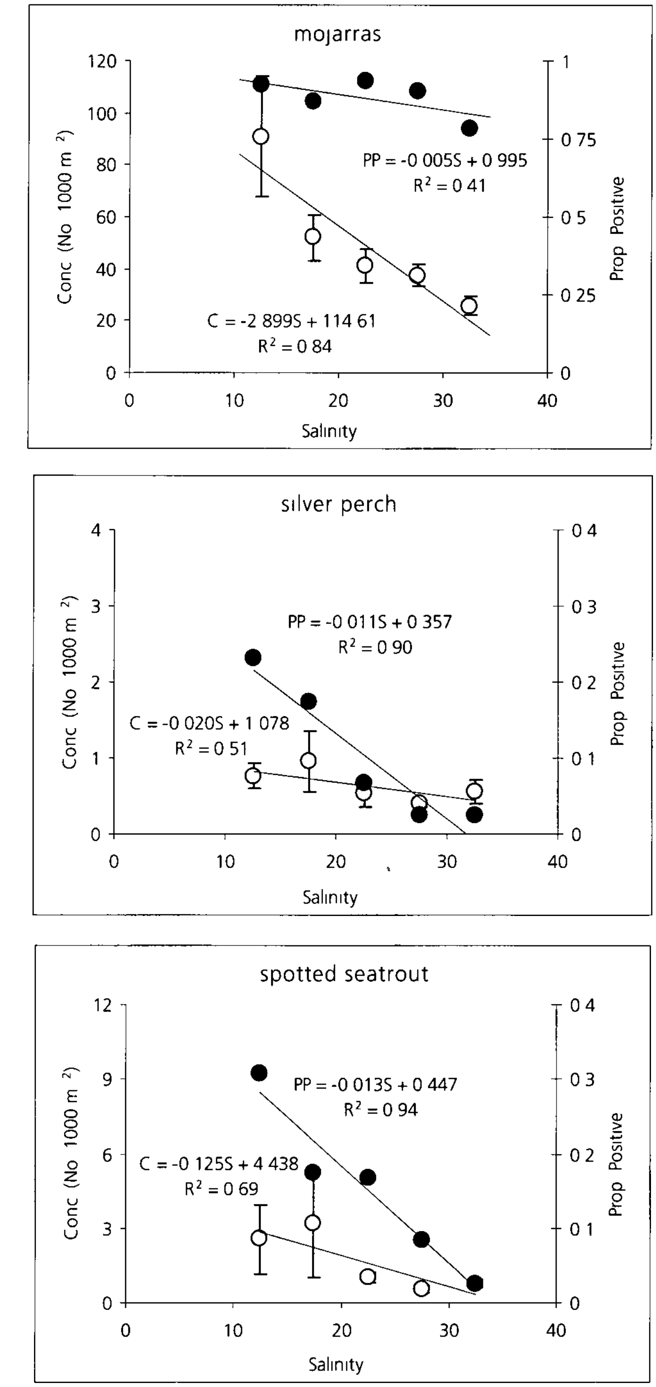

Figure 4. Abundance of key indicator fishes relative to salinity (from Serafy et al. 1997).

Desired Conditions

Coastal Mangrove Zone. In the CMZ, these low salinity values will sustain a fully-functional tidal wetland transition zone, and estuarine creeks that provide freshwater to the bay will result in stable estuarine conditions for nearshore habitats. Coastal creeks, currently intercepted by the L31E levee, should have a normal seasonal hydrograph, with flows in the wet season that are dominated by local rainfall, and declining flows in the dry season, dominated by base flows from inland drainage. The level of freshwater discharged into Biscayne National Park should support SAV dominated by wigeon grass and *Chara spp.* Emergent vegetation should consist of cord grass (*Spartina spp.*), salt grass (*Distichlis spicata*), and black rush (*Juncus roemerianus*). The existing mangrove forest should remain similar to what it is now, but should consist of a more spatially distinct buttonwood, black mangrove, and white mangrove transition zone, with red mangroves at the edges of creeks and at the bay's shoreline.

The faunal composition in the mangrove zone should be similar to that described in historical documentation of pre-drainage conditions, and where it is not detailed, composition should be similar to fauna characteristic of less impacted estuarine mangrove forests in south Florida. The desired species are those common to coastal streams and inland brackish marsh flats, such as the sailfin molly (*Poecilia latipinna*), gold-spotted killifish (*Floridichthys carpio*), sheepshead minnow (*Cyprinodon variegatus*), and eastern mosquitofish (*Gambusia holbrooki*) (Lorenz 1999; Serafy et al. 2003).

In the subtidal area of the CMZ, which is dominated by mangrove prop roots, permanent, healthy oyster communities should be common on the prop roots and as oyster reefs where the creeks enter the bay. Although oysters were once common in the bay and are characteristic of similar habitats in south Florida, they are only found in very low numbers today. Establishment of more normal volumes, timing, and distribution of water deliveries will foster the restoration of oyster colonies and the estuarine biota associated with them.

Western Bay Zone. Estuarine conditions in the WBZ will maximize SAV coverage and diversity, a key component of critical nursery and juvenile fishery habitats. Under appropriate salinity and water quality conditions, it is expected that the WBZ will sustain excellent SAV growth where sediment and water depth are appropriate. These salinities should also create a more diverse seagrass community, dominated by species that do well under estuarine conditions. Wigeon grass will be the dominant species at the mangrove/nearshore ecotone and shoal grass will be co-dominant with turtle grass throughout the WBZ. Maintaining estuarine salinity would sustain larval and juvenile red drum and provide good habitat conditions for sustaining a forage-base for red drum, including oyster, shrimp, and forage fish populations.

In general, water deliveries to Biscayne National Park should not result in damage to natural resources or extreme salinity conditions that adversely affect fishery and wildlife resources. The preferred salinity ranges for the indicator species help determine how much of the current water deliveries are beneficial for fish and wildlife and define conditions that cause impairment of natural resources. The daily mean salinity for the CMZ should fall within the 0-5 ppt in the late wet season (October and November) and average less than 20 ppt annually. A natural gradient of salinity should exist between the mangrove zone and the eastern edge of the WBZ throughout most of the year. Although the extent and character of the gradient is influenced by a variety of factors including the rate of freshwater arrival, evaporation, and tidal mixing, water management operations should not result in any unnatural extremes in salinity and should approximate natural inflows. The WBZ should have salinities between 5 and 20 ppt throughout the year, allowing for only short-term excursions (10 days or less) to higher salinities (not exceeding 30 ppt) as a result of water management. Longer hypersaline events because of intercepted coastal inflows must be avoided, and sustained periods of relatively low salinity are considered essential for sustaining key estuarine species. Unnatural pulse discharges of freshwater that cause rapid and significant decreases in salinity that damage benthic habitats must also be avoided.

Summary of Ecological Targets

The productivity and richness of the estuarine communities of Biscayne National Park have significantly diminished, as have those throughout Biscayne Bay, as a result of channel creation and the diversion of water from the natural systems in south Florida. The quantity of freshwater, the seasonal timing of inflows, and the distribution along the coast have been significantly altered, profoundly affecting the historic estuarine nature of the western portion of the bay. The alteration of the hydrology of south Florida has resulted in the near complete loss of estuarine habitats from the bay, including Biscayne National Park, diminishing the ecological and economic values of this portion of the greater Everglades ecosystem.

Additional water losses that may result from future demands for water supply and flood control will exacerbate existing impacts. Freshwater inflows during the dry season months are particularly important for protection of fish and wildlife resources, when local rainfall no longer compensates for evaporation in moderating salinity. Not only has the system become more marine in salinity, but the increased frequency and duration of hypersaline events adversely impacts even marine biota, most of which have very narrow salinity and temperature tolerances.

At present, the water that is released to Biscayne National Park provides marginal estuarine benefits, far short of those that would result from a more natural, historic hydropattern. The timing of current water releases differs dramatically from a natural pattern, with large freshwater pulses during the wet season that drive salinities too low, and minimal flows in the dry season that allow salinities to greatly exceed the pre-drainage environment. The location of current water deliveries also differs from a natural pattern, in that the CMZ no longer receives any substantial overland flow, and water inputs to the WBZ arrive as point discharge from canals. In short, the quantity, timing, and delivery of water arriving at Biscayne National Park is not adequate to provide stable estuarine conditions. Therefore, from a biological perspective, all the water that is currently provided is necessary for Biscayne National Park and the bay, and as such, is required for protection of fish and wildlife in Biscayne National Park. Furthermore, the data clearly indicate that substantially increased flows of freshwater will be required to begin the process of ecosystem recovery for the CMZ and WBZ.

HYDROLOGIC TARGETS FOR BISCAYNE NATIONAL PARK

For the purposes of monitoring and maintaining a physical environment that will support the SAV-dependent ecological targets discussed above, it is necessary to develop metrics that represent that physical environment.

Two pragmatic metrics exist for the physical conditions needed to reach the target ecological conditions for Biscayne National Park: 1) measurement of salinities in the estuarine zone and 2) quantification of the flows themselves through the coastal structures.

Though quantification of flows is easily attained, how these flows influence the salinity distributions throughout the WBZ is a complex physical question that depends on currents, winds, vertical and horizontal shear, insolation, and mixing rates, among other variables. The coastal flows to Biscayne Bay are largely managed and are a calculated parameter in current water management planning tools. We explored the link between these managed freshwater flows and the salinity in the WBZ using a variety of estimations.

Salinity

In several ways, salinity is the best metric to use as a base for the calculation of flows needed to produce the target ecological conditions. Evidence of the requirements of a number of species presented in Section 2 demonstrates that salinity is a key habitat factor for the bay ecosystem.

Figure 5 summarizes the optimal salinity ranges for Biscayne National Park ecosystem indicators, including primary producers, primary consumers, and predators. The majority of these indicator species prefer salinities between 5 and 20 ppt. Based on this observation and taking into account that other species (such as seatrout and oysters) may require periods of time with slightly higher or lower salinities, we propose the following salinity targets for the CMZ and WBZ of Biscayne National Park.

- At no time should measured salinities exceed 30 ppt. This will be particularly critical to measure in the dry season, from November to March.
  - Direct benefit to important fishery species with a life cycle stage that is well-suited to estuarine salinities, fish that serve as sport fish forage, post-larval juvenile shrimp, and oysters that rely on brackish water as a refuge from marine predators.
  - Indirect benefit to recreational and commercial fish species that rely on the forage base produced by estuarine conditions, such as adult sea trout, snapper, and grouper fish stocks.
- From March through August (late dry season - early wet season), average monthly salinities should range between 15-25 ppt in the WBZ.
  - Direct benefit to spawning habitat for sea trout, adult habitat for forage species (mojarras, silver perch), and conditions that foster a healthy and diverse seagrass community that can be sustained in a zone that is subject to freshwater runoff.
  - Indirect benefit to nursery habitat for important juvenile fish species (productive seagrass beds and an extensive brackish water refuge from marine predators).
- In the late wet season (September-October), the CMZ should be oligohaline (0-5 ppt), and the WBZ should average less than 20 ppt.
  - Direct benefit to juvenile crocodiles that have a physiological requirement for low salinity conditions.
  - Direct benefit to important forage fish species in coastal mangroves that do best at oligohaline to mesohaline conditions (such as sheepshead minnow, gold-spotted killifish).

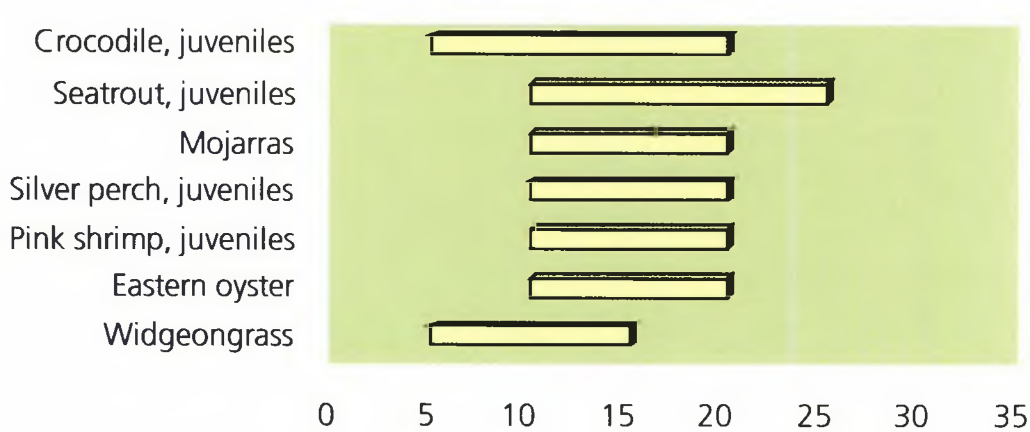

Figure 5. Optimal salinity ranges (units in ppt) for Biscayne National Park ecosystem indicators.

- Indirect benefits to all species that consume forage species that support upper trophic levels in the mangrove zone, including wading birds, mammals, and crocodiles.
- Salinity changes should be gradual and reflect changes in hydropattern that approximate a natural system. All vegetation, fish, and invertebrate species benefit from gradual changes in salinity that avoid physiological stress.
- Salinity gradients should always consist of lowest salinities near the coast and highest salinities in the ocean.

Restoration of freshwater inflows to reach the appropriate salinity should result in a highly productive SAV community that will meet the more general ecological targets outlined earlier.

From Salinity to Freshwater Flow Targets

A salinity metric is more than a sensitive link to the biological environment. Salinity also provides an excellent metric linking to the dynamic coastal environment because it is an accurate and integral measure of the net results of the total freshwater inputs, mixing rate of marine and freshwater flows, wind mixing, net evaporative losses, and amount of tidal exchange. During the dry season when there is little or no flow through the coastal structures, the salinity metric will still be applicable while a flow metric may not provide any additional useful information (it might be zero).

The freshwater inflows needed for maintenance of target salinities can be calculated in a number of ways. A factor to consider in the calculation of freshwater flows is that a water volume budget, as proposed by draft Guidance Memorandum 4, is not as well constrained in an estuary with open boundaries since it is difficult to quantify the outgoing/incoming marine flows with an accuracy near that of the incoming freshwater flows (at this time the National Park Service does not have long-term time series of inflows/outflows through the Safety Valve and the ABC Creeks).

Estimates of Target Flows

Ideally, a computer-based simulation that provides estimates of the spatial and temporal salinity distributions under various conditions would be used to arrive at target freshwater flows. A verified hydrodynamic model of Biscayne Bay that is forced by observed atmospheric and marine inputs and that is coupled with a hydrologic model to provide surface water and groundwater inputs would be such a tool. Though tools like this are under development, at this date an operational tool for salinity prediction is not available. Therefore, we used several alternative approaches, including statistical models, dynamic box models, and static volumetric estimation based on analytic estimates of water budgets and the balance of advective/diffusive processes. These methods provide a range of freshwater flow quantities within the WBZ. The limitations and advantages of each are discussed and reasonable approximations of freshwater flow quantity are provided.

Much of the available information on flow is based on current canal discharges, which do not mimic natural conditions either in spatial distribution or in timing. The desired persistent salinity gradient oriented parallel to the coastline can only be maintained by the steady flow of waters away from the coast and all along the coastline, as would be provided by a coastal freshwater/brackish marsh (this phenomenon is explained more fully in Appendix A). A constant freshwater flux is likewise desired at the historic river and creek mouths in order to maintain the estuarine salinity targets and avoid ecological damage that is similarly caused by cessation of flows or large pulses of freshwaters. Pulsed discharges of large volumes of freshwater are typical following large rain events and often result in locally low salinities near canal discharge points. The desired spatial and temporal distributions apply to all of the target flows derived in this section.

RECOVER Target Estimates. There are a number of RECOVER performance measures that apply to specific areas of Biscayne Bay for which flow or salinity targets have been developed by the Southern Estuaries Sub-team. For the purpose of estimating target flows for Central to Southern Biscayne Bay, SE-6 is applicable. SE-6 specifies a persistent salinity gradient parallel to the southern coast of Biscayne Bay at 250 m and 500 m from shore by meeting oligohaline to mesohaline nearshore targets, and it was estimated by Meeder et al. (2002) that about 470 K acre-ft/yr are required to meet these salinity requirements. Alleman (2003) arrived at a similar figure of 325 K acre-ft/yr for SE-6 targets from a historical data analysis, which lends support to the range of this estimate. In addition, SE-8 stipulates persistent flows of 15 K acre-ft/yr out of Snapper Creek and into Central Bay to maintain the ecosystem found at the creek mouth. Thus the RECOVER total for these target flows for South Bay and nearby waters is 485 K acre-ft/yr. The estimate for the 10,000 acre WBZ will be much greater because it is 5,800 acres larger.

Until the emergence of any applicable results from the desired hydrological models, which are coupled to a range of inflow conditions, some alternate performance measures and targets can be developed that test the utility of and/or supplant the RECOVER targets. Rough estimates of target flows across wet and dry seasons may be gleaned from simple calculations of the flows required to maintain a persistent salinity gradient parallel to the coastline, and no periods of hypersaline conditions. These are minimal targets but they must be achieved first in order to reach other, more voluminous, restoration target flows. The flows needed to achieve these restoration targets may be estimated analytically. It is also possible to derive a more refined, seasonally-varying volumetric estimate driven by ecosystem requirements that parameterizes the mixing and flow in the bay in order to arrive at more robust target flows.

Advection Diffusion Estimate. Due to urban coastal development, the only area in which CERP projects could restore coastal marsh conditions and natural spatial distribution of flow to the park is from Deering Estate to Mangrove Point. If water could be distributed all along the 26 km of park coastline at a steady rate, the one-dimensional advection versus diffusion example, developed in Appendix A, which maintains a persistent salinity gradient, can be applied. A sufficient net seaward flow to overcome shoreward diffusive effects along the park shoreline is over 800 K acre-ft/yr.

Other estimates of required volumes to reach target conditions have been developed independently as well. To just meet the 250 m- and 500 m-from-shoreline salinity requirements put forth by RECOVER SE-6, another advection versus diffusion estimate was developed by Downer, Klochak and Mullins (2005), and Nuttle and Downer (personal comm.). They used long-term averages of modern salinities measured at several points at different distances from the coast in Biscayne National Park and an assumed logarithmic shape of the seaward salinity gradient to arrive at an effective diffusivity of 12 m^2/s. To maintain just the 250 m/500 m salinity targets, they estimated between 0.7 – 1.4 M acre-ft/yr of freshwater needed to be provided along the coastline through the marshes between Shoal and Turkey Points. Since the area considered was confined to the near shore zone, the estimate for the full 10,000 acres would likely be much higher.

Hypersalinity Prevention Estimate. Another type of rough estimate may be developed by considering the volumes required to prevent hypersalinity in the bay. The net water budget is,

$$\frac{dV}{dt} = P - E - FW_{in} + FW_{out} + GW_{in} GW_{out} + SW_{in} + SW_{out}$$

where V is the total volume of the coastal basin, P is precipitation, E is evaporation, FW is fresh surface water, and GW is the groundwater volume. The net seawater volume, SW_{in} - SW_{out}, over several tidal periods will be small except when there are significant freshwater inputs or outputs, since any excess of freshwater will be moved to sea, and any evaporation-induced deficit of estuarine water within the bay will be replaced by seawater if no surface or groundwater is available. A deficit of water induced by any excess of evaporation over precipitation ($P-E < 0$) can be replaced by seawater which will drive the salinities even higher by adding more salt to the bay, or by freshwater flows which will maintain or lower the salinity.

The outcome of this dynamic process depends largely upon the efficiency with which the tides move seawater into the bay, mix with the bay waters, and export this mixed water back to sea. Biscayne Bay is a semi-enclosed shallow basin with an average depth of about 10 ft and an area of 141,000 acres. All exchange with ocean water is limited to certain areas (Safety Valve, Government Cut, Baker's Haulover Cut, Norris Cut, Bear Cut, and the ABC Creeks), with the 9 km opening at Safety Valve by far the largest source of ocean waters (Wang et al. 2003). The tidal mixing in Biscayne Bay is generally efficient, with a tidal prism (inter-tidal volume) of about 250 K acre-ft – this means that, in theory, the entire volume of the bay could be exchanged with only six tidal cycles (three days). In practice the less-voluminous North Bay is even more easily flushed by virtue of the many cuts opened to the Atlantic, while South Bay is not flushed as easily, with exchange restricted by the three narrow ABC Creeks to the east and at the northern end by the shallow Featherbed Banks that stretch into mid-bay perpendicular to the long axis to the bay. Consequently, North Bay has not experienced hypersalinity periods (and was an oligohaline lagoon before the opening of Baker's Haulover Cut irreparably changed it in the 1920's (Harlem 1979)), while South Bay frequently has been hypersaline in recent years.

Even with a large annual rainfall, there is a net annual loss of water to evaporation for Biscayne Bay. Considering the bay as a whole, the estimated mean evaporation rate of 1.66 m/yr (Royal Palm measurements) contrasts with 1.27 m/yr (Mowry Canal, chosen for its proximity to the bay) of precipitation, giving a net evaporative loss estimate of about 180 K acre-ft per year over the 140,000 acres, or about 1.25 ft per acre. Though these E and P estimates are highly variable and not applicable to all areas of the bay, it clearly illustrates the importance of the distribution of flows, and the different exchange rates at work in Biscayne Bay. With an evaporative loss of only 16% of the bay's total volume, a total mean freshwater input of 1.1 M acre-ft/yr from canals, about 80% of the bay's total volume, should protect against hypersalinity.

For South Bay alone on an annual basis, about 125 K acre-ft/yr would, therefore, be required to offset the loss of freshwaters to evaporation and prevent hypersalinity only. Most of this water is required during the dry season or droughts when precipitation is scarce. During these periods, net salinity increases in coastal waters have been observed in excess of 0.15 ppt per day. This estimate of freshwater flows would prevent hypersaline conditions, but would not approach target restoration salinities. Even more useful may be its demonstration of the importance of the timing and spatial distribution of this flow.

Hydrodynamic Model Estimate. The use of a hydrodynamic model for Biscayne Bay to estimate the necessary freshwater flows is advantageous since it can incorporate explicitly the impact of tidal exchange, mixing, bathymetry, and coastal currents as well as freshwater flows on the nearshore salinities at different points in the Bay. A 3-D version of the TABS-MDS (RMA10; see Brown, et al., 2003) hydrodynamic model for central and southern Biscayne Bay was recently used by Alleman and Parrish (2005) to calculate the volume of water necessary to reach the paleo-salinties estimated by Wingard, et al., (2004) from cores taken at three sites between Shoal Point and Turkey Point, two of which are within the proposed 10,000 acre target zone. The freshwater input distribution from the Natural System Model (NSM462) was increased until the modeled freshwater volumes for the years 1965-2000 produced salinities at these sites that were largely within the range of their circa-1900 salinities (Black Point, 5-18ppt; Featherbed, 25-35ppt; No Name Bank 18-30ppt). Parrish and Alleman found that the total (surface and ground) freshwater flow rate under such a 'natural' distribution necessary to maintain these salinities at these sites was approximately 1,500 cfs, or about 1090 Kaf/yr on average.

Volumetric Estimate. These rough estimates can be contrasted with a simple volumetric estimate of the freshwater flux needed to maintain a constant salinity (in the absence of wind mixing), which could be estimated by:

$$F = (Area \bullet Depth) \bullet \left[\frac{S_m - S_t}{S_m}\right] \bullet X$$

where the product of Area and Depth is the volume of the target location, S_m is the marine salinity, S_t is the target salinity, and X is the tidal exchange factor. Geometries and the desired conditions determine all parameters except for the tidal exchange factor. Though the tidal exchange factor will be variable with space (both on/offshore as a function of distance from tidal inlets, and along the bay axis due to bathymetric variations) and even time (spring/neap tides, seasonal sea level fluctuations), a conservative estimate of 15% daily water exchange for nearshore conditions may be sufficiently representative of mean conditions in Biscayne National Park. Lee and Rooth (1976) estimated the residence time in southern Biscayne Bay during the summer months to be on the order of a week; if it would take seven days for a parcel of water to be exchanged, that would mean about 1/7 of the volume there (15%) is exchanged daily, neglecting mixing efficiency. In reality, the tidal mixing factor will be a function of the distance to the openings to the ocean, the rate of wind-induced mixing, and the distance from local embayments and shoals which restrict exchange. In contrast to the weekly residence time scale in Biscayne National Park, residence times in Northern Biscayne Bay are typically a few days (about 33% exchange daily), and may be as long as many months in Card and Barnes Sound at the extreme south end of the bay (<1% of waters exchanged daily by the tides).

A first volumetric estimate is based on SE-6's seasonally-variable salinity targets within Biscayne National Park, with 1600 acres within the 250 m zone and 1600 acres within the 250-to-500 m zone, and an average depth of 1.5 ft and 3.0 ft, respectively. When applied seasonally in the equation above these figures produce a total annual target flow of 240 K acre-ft/yr (330 cfs average), given the daily mixing rate for the area of 15%. Since the volume estimate is directly proportional to the mixing rate, it is very sensitive to its value. To demonstrate the sensitivity of this estimate to the size of the mixing rate; if the estimate was increased to 20% the resulting flows would be approximately 325 K acre-ft/yr (450 cfs).

The second volumetric estimate presented here is based on the 10,000 acres of SAV habitat that are found in the WBZ, which we believe is a preferable target to the 250 m/500 m salinity targets since it is representative of the geomorphic underpinnings and the ecological potential of the Bay, not just the distance from the shoreline. The wet season/dry season salinity targets of 15 ppt/30 ppt over the 10,000 acres of grass beds included with the same 15% net tidal exchange can be added to the simple volumetric estimate to give a net total of about 1.1 M acre-ft/yr (1500 cfs).

Summary of Freshwater Flow Targets

These rough estimates of target flows have produced a range of values (Table 2) that encompass either the smaller RECOVER target area or the larger 10,000 acre target. The diffusive-process-based estimates span the range from the mid-100's K acre-ft/yr to several M acre-ft/yr, but are sensitive to the magnitude of the effective diffusivities used. As a lower bound on the problem, it was shown that approximately 100-200 K acre-

Table 2. Estimates of the average annual flow volume required to reach the salinity ranges that support the biological targets.

Method of Quantification	Estimated average annual flow volumes (K ac-ft yr-1)	Target Area	Estimated flow volume per unit area (ac-ft yr-1 / acre)	Notes
RECOVER	325	3200 acres	102	This estimate provides flows for RECOVER SE-6 250/500m region and utilizes the limited salinity observations available in the WBZ; Alleman (2003)
RECOVER	475	3200 acres	148	This estimate provides flows for RECOVER SE-6 250/500m target area; Meeder et al. (2002)
Hypersalinity prevention	125	NA	NA	This estimate prevents hypersalinity in the Bay but does not attempt to satisfy salinity targets
Advection Diffusion	800 -1400	3200 acres	250-438	This estimate is based on a range of diffusivities (A = 1 m2/s - A = 12 m2/s) applied using an advection dispersion equation and applied to the RECOVER SE-6 250/500 m target area
Hydrodynamic Model	1090	~10,000 Acres	109	Uses TABS-MDS model to calculate flows needed to achieve ca. 1900 paleo-salinity targets from Wingard, et al. (2004)
Volumetric	1100	10,000 acres	110	This estimate provides flows for the 10,000 ac SAV zone using an estimated effective tidal mixing of 15%

ft/yr are required just to offset evaporation and avoid hypersaline conditions in the bay, so the actual target flows should be well in excess of that. The volumetric estimates arrived at an estimate of 1.1 M acre-ft/yr for the full 10,000 acre target area. This is consistent with other estimates and is supported by estimates of the flows in the much smaller 3,200 acre target area (325 K acre-ft – 1.6 Maf per year) required to meet a similar salinity requirement. The fourth column of Table 2 provides the quantity of water per acre calculated to meet salinity targets, further demonstrating the consistency of the estimates. Thus the 1.1 M acre-ft/yr, seasonally varying flow target represents a reasonable estimate of the required freshwater flows and will be adopted as the standard against which beneficial waters will be measured for this report. This estimate may be supplanted or refined by subsequent analyses that more properly take into account the dynamic nature of the flows within Biscayne Bay.

Estimation of Current Flows

Hydrologic pattern has been altered by regional drainage, canal construction and operation, and urban development, as well as construction of roads, levees, and other hydrologic barriers to surface flow. The bay currently receives freshwater inflow almost entirely as surface water in the form of canal flows, with only minor overland flow and very little groundwater flow.

Groundwater. When there are no surface flows or rainfall available, groundwater is the only possible source of freshwaters and is vital to counteract the onset of hypersaline conditions. Although the contribution of groundwater to total flows may have been quite large during pre-drainage conditions as anecdotal evidence suggests (Kohout and Kolipinski 1967), studies show that the modern fresh groundwater inputs into Biscayne Bay are very small (<<10% of the surface flows; Langevin 2001). In addition, the saltwater intrusion line in south Florida has been stable or has encroached further inland over the past two decades (Sonenshein 1995) despite efforts to protect the water supply from saltwater intrusion, and hypersaline conditions are commonplace during droughts. Both of these observations support the understanding that groundwater flow to Biscayne Bay is limited under current conditions. Because of the relatively small contribution groundwater makes to the total water budget and the limited availability of observed data, groundwater flows were not accounted for in this analysis. However, because of the importance of groundwater flow during the dry season and in drought conditions, these flows could be included in the estimates of mean annual beneficial water volume if a reliable means for quantifying the groundwater flows to the bay existed. Work to estimate groundwater flows may provide additional information for estimating beneficial flow volumes in future analyses.

Surface Water. Canal flow estimates are derived from the head and tail water elevations across the coastal flow control structures maintained by the SFWMD and are stored in its DBHYDRO database. The observed flow data from the coastal control structures S197, S20, S20F, S20G, S21, S21A, S22, S25B, G93, S25B, S26, S27, S28, S29, and S29Z for the time period 1985-2005 were examined. On average, 1.14 M acre-ft/yr (accurate to about +/- 5%) of total surface freshwater flows enter any part of Biscayne Bay. For just the waters entering the boundaries of Biscayne National Park (direct flows through S20F, S20G, S21A, S21, and S123 at the northern coastal boundary are included, as are indirect flows from S22 and G93 into Central Bay and S197 into Barnes Sound that eventually pass through park waters), the average freshwater flux is much less, about 475 K acre-ft/yr or 40% of the total.

Figures 6 and 7 show the volume of flow contributed by each of the structures relative to each other. Of the annual average of 475 K acre-ft of canal flows that are discharged to southern Biscayne Bay from 1985-2004, 131 K acre-ft (27% of all flows) entered directly into Biscayne National Park through C-103 (S-20F), 107 K acre-ft (23%) through C-1 (S-21), 69 K acre-ft (15%) through C-102 (S-21A), and a minor amount through Military Canal. In addition, there were indirect flows to the park waters through C-100 (S-123) (47 K acre-ft, or 9%), C-2 (S-22) (95 K acre-ft, 20%), and some minor flow through C-3 (G-93). Additional freshwaters eventually enter the park through its southern boundary at the entrance to Card Sound. The freshwater in Card Sound and Barnes Sound section comes primarily from discharges from the C-111 Canal (S-197) (26 K acre-ft, 6%) into Manatee Bay in western Barnes Sound, with some additional unquantified contributions from overland runoff from extensive freshwater and coastal wetlands contiguous with the mainland shoreline

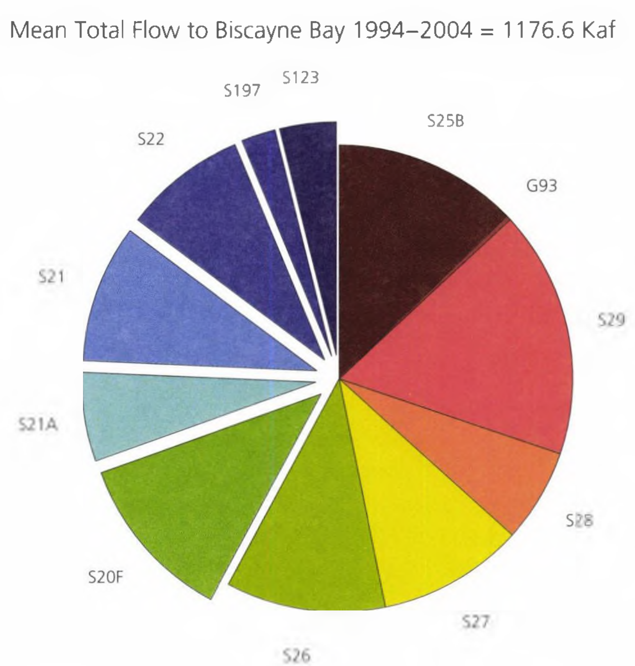

Figure 6. Distribution of total flow to Biscayne Bay by structure.

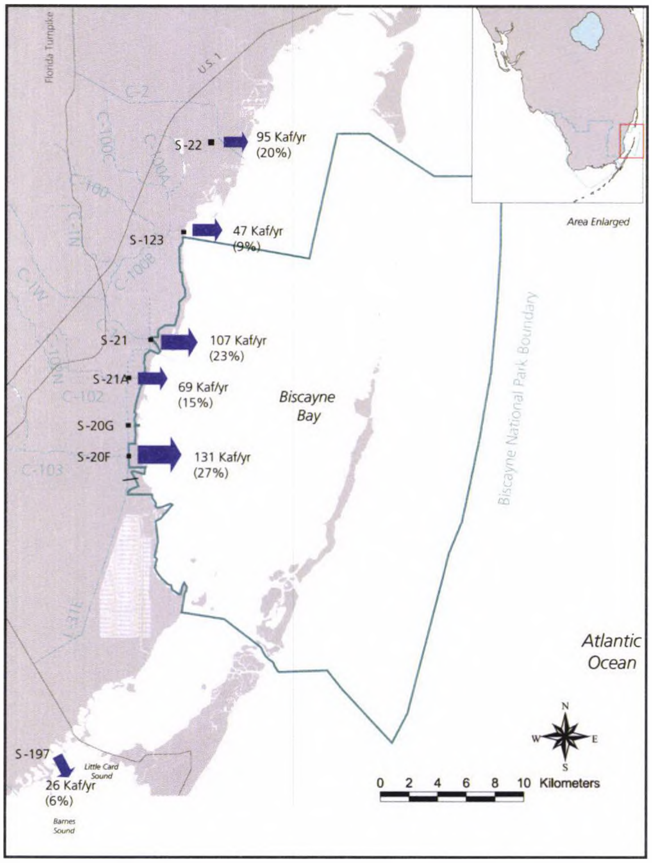

Figure 7. Annual average (percent of total) canal discharges to southern Biscayne Bay.

of these two basins. Because no other significant or quantifiable source of surface or groundwater exists, these coastal structure flows into southern Biscayne Bay are considered in this analysis to be the only freshwater inflows along the coast.

Salinity. The salinities present in Biscayne Bay are directly dependent upon these freshwater fluxes. Under the current water management scheme, large plumes of relatively freshwaters (<25ppt) extend away from the canal mouths towards the bay axis during periods of high rainfall. These fresher waters are then mixed into the other bay waters and are subject to partial exchange with marine waters (35 ppt) through tidal processes. The result in a typical year is an average bay salinity less than marine (<35ppt) during the wet season and approaching or exceeding marine during the dry season, though during years with less-than-average canal run discharges it is common to observe hypersaline (>37ppt) conditions through large portions of southern Biscayne Bay, including the western shoreline.

Time series of salinity data have been collected by Miami-Dade Department of Environmental Resources Management (DERM), Florida International University (FIU), and NPS at scattered points at different intervals within Biscayne Bay for more than the past 10 years. The salinity at a given station is largely a function of the efficiency of tidal exchange at that location (usually related to the distance from the ocean with its typical salinity of 35-37 ppt), the freshwater surface flow to the bay (mostly local but some remote influences dependent on location), the time history of evaporation and precipitation in the bay, the volume of intra-bay transports, and any wind events within the past few weeks that greatly influence mixing rates and on/offshore transports. These individual time series offer little help in assessing the synoptic distribution of spatial gradients within the bay, and very few are in the WBZ that is the region of greatest interest for salinity targets due to their ecological importance there. Taken as a whole, however, these salinity data can help elucidate the net result of all the influences on salinities in the bay.

If these observed data are integrated over 30 days, and grouped by their general location within the bay and their distance from the coastline (approximating the effect of both distance from the freshwater flows and the ocean influences), some interesting general trends emerge when correlated against the integrated observed flows from the coastal structures (Fig. 8). Nearshore (<2 km from shore, but more than 0.7 km from any canal mouth to avoid aliasing from any freshwater plume emanating from it) there is a dramatic decrease in the monthly salinity with increasing flow. However, with increasing flows there is a proportionally decreasing influence on the salinity, with a fairly well-defined $1/x^n$ shape but with a significant random error about the mean. Beyond a yearly flow rate of about 300-400 K acre-ft/yr (415-550 cfs) there is

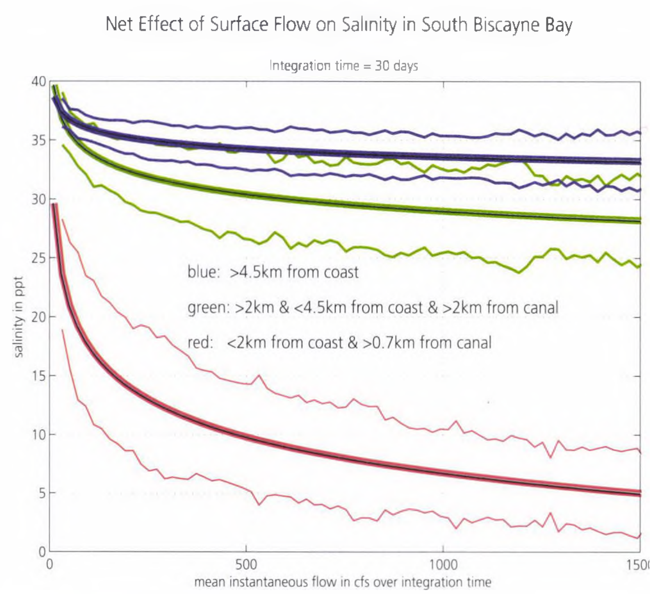

Figure 8. Observed south Biscayne Bay salinity data integrated over 30 days and grouped according to their distance from the coastline vs. flow rates expressed as K acre-ft/yr. The thick red curve denotes the area away from canal mouths but within 2km from the western shoreline (encompassing approximately 6400 acres), the green the area from 2km to 5km from shore, and the blue >5km from shore. The thin lines denote an envelope of +/- 1 standard deviation of the residuals from the fitted curve.

substantially less salinity reduction effect, so while it takes a rate of only 300 K acre-ft/yr (415 cfs) to lower mean salinities by over 20 ppt over 30 days time in the nearshore region, to reduce them a further 5 ppt appears to take about 700 K acre-ft/yr (970 cfs) more. This is mostly a reflection of conservation of volume – the increased volumes of freshwaters displace the mixed and marine waters to sea as the bay's volume stays the same – coupled with the efficiency of tidal exchange and turbulent diffusion.

The South Florida Water Management Model (SFWMM) driven by a 35-year time series of environmental inputs was chosen to represent the current flows in the quantification of beneficial waters. Choosing a model to represent the current flow conditions serves several purposes: to enable the reconstruction of flows in the past, to permit these flows to be comparable relative to some common water management operations, and to isolate local rainfall effects from the impact of the water management practices that are at the core of the estimate of beneficial waters. While a number of reasonable SFWMM model variants (Alt7r, Base2000, etc.) exist that could be utilized for this study, model run Alt7r5e was chosen. It is not expected that the use of any of the modern variants would significantly change the outcome of the analysis.

Estimation of "Beneficial" Flows

The estimate of "beneficial" flow volumes is based on the methods described in draft CERP Guidance Memorandum 4. Coastal discharges computed from the SFWMM Alt7r model runs were compared to the 10,000 acre target flow estimates to arrive at the classification of beneficial flows in accordance with Guidance Memorandum 4. The beneficial water calculation of the Guidance Memorandum provides a minimum estimate of the water volume currently available for the protection of fish and wildlife because all flows that exceed the target, even if they would be beneficial if delivered at another time, are excluded from the total beneficial quantity (Fig. 9).

Superimposed on the time series flows are the estimated target flows discussed in the previous section, both for the preferred 10,000 acre target (red wet/dry seasonal step function) and the RECOVER SE-6 3,200 acre target (yellow wet/dry seasonal step function) (Figs. 10 and 11). While most of

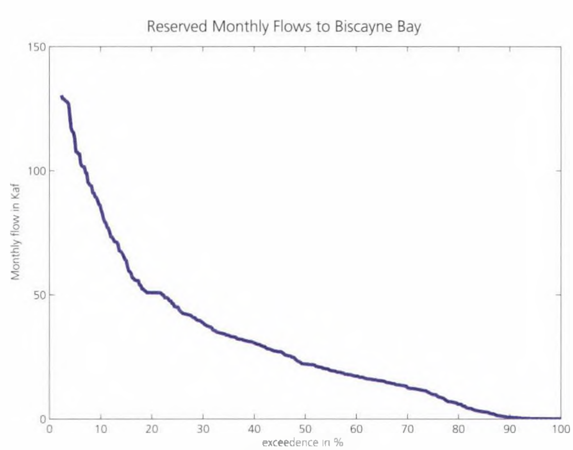

Figure 9. Exceedence curve for flows to southern Biscayne Bay based on the SFWMM Alt7r monthly time series (1965-2000) of coastal flows.

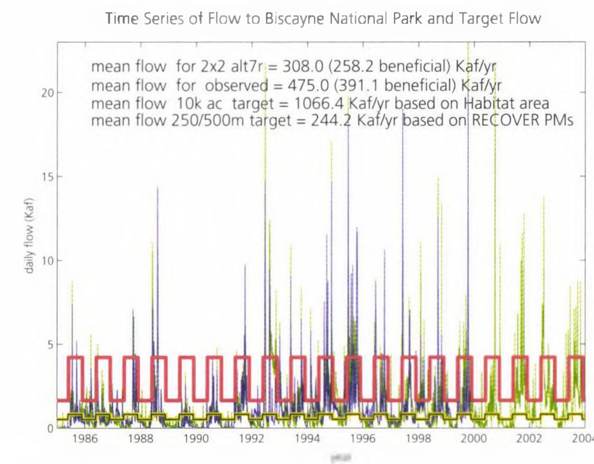

Figure 10. The daily time series of flows into southern Biscayne Bay (measured= green, modeled Alt7r5e = blue) with the 10,000 acre seasonal volumetric target (red) and 3,200 acre target (yellow).

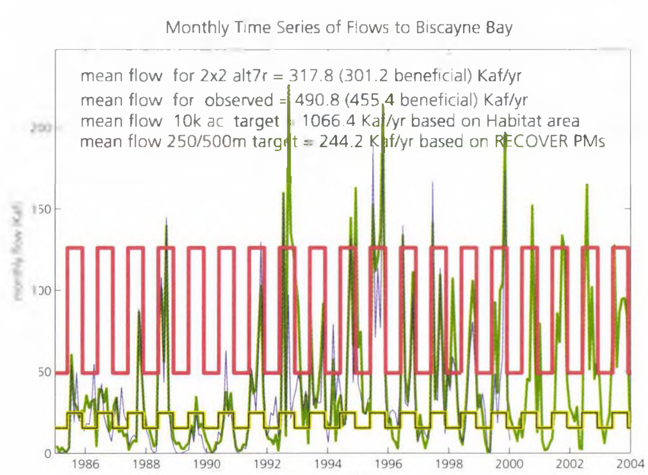

Figure 11. The monthly time series of flows into southern Biscayne Bay (measured= green, modeled Alt7r5e = blue) with the 10,000 acre seasonal volumetric target (red) and 3,200 acre target (yellow). The monthly aggregation reduces the impact of peak daily flows on the beneficial flow estimate and increases the volume by approximately 10% of the available flows.

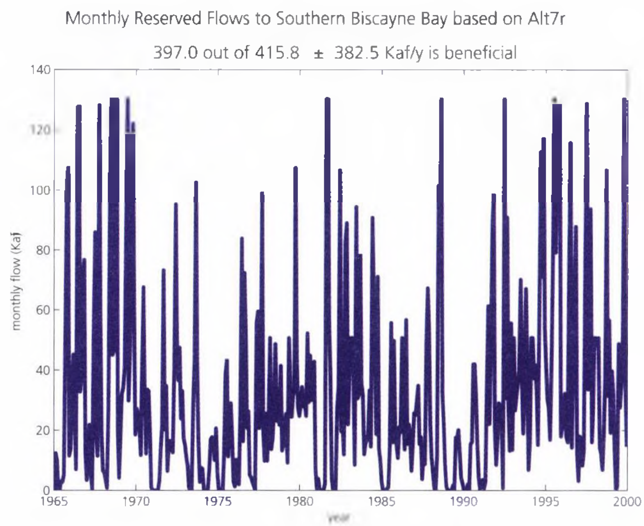

Figure 12. The monthly time series of beneficial flows to southern Biscayne Bay through S22, G93, S123, S21, S21A, S20F, S20D, and S197 as estimated from SFWMM Alt7e. Total average annual flows are 416 K acre-ft/yr using these criteria.

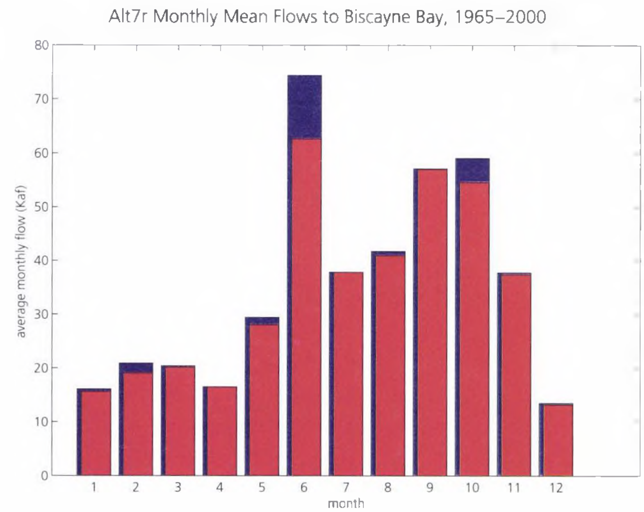

Figure 13. Average monthly flows as estimated from 2x2 Alt7r (blue). Red bars represent the average monthly flows that comprise the beneficial flow volumes for southern Biscayne Bay's 10000 acres of SAV (month 1 is January).

the flow time series is lower than the 10,000 acre target, it is clear that in the daily time series (Fig. 10) there are many peak flows which exceed the target. For the 3,200 acre target, only about 20% of flows would fit the definition of a beneficial flow. However, for the preferred 10,000 acre target, about 83% of the flows, (390 K acre-ft/yr of the 475 K acre-ft/yr total of daily observed flows,) classify as beneficial flows. The monthly aggregation (Fig. 11) reduces the cropping of the peaks by about 10%, since the pulsed flows following storm events rarely last more than a few days and do not have a great impact on the monthly mean. The monthly aggregation estimates result in 455.4 K acre-ft/yr out of 490.8 K acre-ft/yr or 92% of the observed flows being classified as beneficial for the 10,000 acre target. Figure 12 provides the time series of modeled beneficial flows. The seasonal distribution of these monthly aggregations demonstrates that the flows in the dry season (November-May) are almost always entirely classified as beneficial, and graphically demonstrates the importance of the timing of these beneficial flows (Fig. 13).

An alternate view of this same time series is made possible by using the salinity metric, where the observed and modeled flows have been transferred to salinity space via the flow volume versus salinity anomaly expression developed earlier and normalized to a 1km strip of coastal waters along the western shore to enable comparison. Though limited to 35 ppt (there is no evaporation in this example, hence hypersaline conditions are not possible), the daily flows result in salinity that is higher than the mean of the salinity targets about 75% of the time for the preferred 10,000 acre target (Fig. 14). The most significant advantage of using salinity as an ultimate flow target indicator or metric is not only ecologically critical in the estuary, but also that the salt concentration will be an integral measure of various effects with inherent time scales from days to many weeks, and length scales from meters to several kilometers. These effects, as we have already seen, are often difficult to estimate, span orders of magnitude in size, and are tricky to model at the fine scales required in Biscayne Bay.

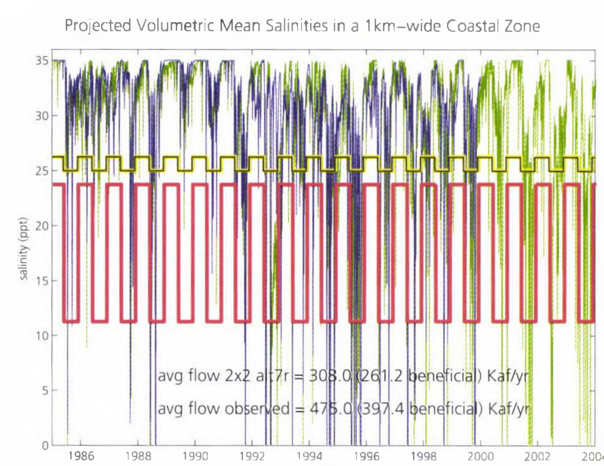

Figure 14. The daily time series of projected salinities in southern Biscayne Bay within a 1 km-wide coastal zone (driven by measured flows = green, modeled flows Alt7r5e = blue) with the 10,000 acre seasonal volumetric target (red) and 3,200 acre target (yellow).

DISCUSSION

Prior to the significant changes in the freshwater flow patterns in south Florida caused by the creation of a water control system in the early 20th century, Biscayne Bay was a true estuarine system. Large amounts of freshwater in the form of both surface and groundwater were present throughout most of the year and supported a wide range of flora and fauna. When these freshwater sources were diminished and their distribution altered by water management practices, the vegetation in the bay, as well as the juveniles of many fish and invertebrate species, were adversely affected and the ecosystem in the bay changed drastically. The ecosystem that exists today in Biscayne Bay is largely marine in nature, as the volume, timing, and distribution of freshwater flows are insufficient to maintain an estuarine environment over ecologically-significant temporal and spatial scales. In keeping both with the Everglades restoration efforts and the NPS mandate to preserve unimpaired the nation's natural resources within the parks, this document provides ecological and physical targets for desired conditions in Biscayne National Park, and attempts to quantify the existing freshwater flows that are necessary for the protection of fish and wildlife within the park.

The spatial focus of the discussion of ecologic targets includes the Coastal Mangrove Zone (CMZ) of mainland Biscayne National Park in this report and the adjacent Western Bay Zone (WBZ). Because the CMZ receives no water deliveries currently, the spatial focus for estimation of target flow deliveries is on the WBZ within Biscayne National Park – the 10,000 acre area along the western shoreline which contains the portion of the ecosystem that most benefits from freshwater flows. The shallow waters of the WBZ contain thousands of acres of seagrasses as well as a fringing mangrove forest. The desired condition, or overarching goal, for the western zone of Biscayne National Park is the existence of stable estuarine conditions that persist through the dry season, to be achieved through more natural timing and distribution of freshwater flows. These stable estuarine conditions support a productive, diverse benthic community based on seagrass. These conditions will also support endangered species and sustain productive nursery habitat for local and regional fishery resources.

The appropriate restoration area to consider was discussed in this document. The existing RECOVER performance measures focus on a narrow (500 m) strip of coastline that encompasses 3200 acres of park waters. The alternate approach used here is to focus on existing geomorphological information to define an area of soft bottom suitable for seagrasses. This habitat in the WBZ includes roughly 10,000 acres of park area. This larger region was chosen as the target area for stable estuarine conditions because it is based on bay geomorphology, a factor that is fundamental to bay ecology.

The ecological targets for the WBZ were based upon an approach that includes the benthic community, endangered species, and important fishery resources in the western bay. Because seagrass is important nursery and growth habitat for indicator species, a fundamental resource management and restoration goal is to maximize coverage by SAV beds at sustainable levels. Under appropriate salinity and water quality conditions, it is expected that this area will support excellent SAV growth where sediment and water depth are appropriate for such growth. One explicit restoration target is an increase in the vitality and diversity of the WBZ seagrass community, with wigeon grass as the dominant SAV species at the mangrove edge within the nearshore ecotone and shoal grass becoming co-dominant with turtle grass through much of the rest of the WBZ. Another explicit target is the restoration of the community of seagrass-associated fauna that have been largely extirpated from South Bay,and the enhancement of habitat for others, such as crocodiles and pink shrimp that will likewise benefit substantially from the target salinity conditions.

These ecological targets require freshwater flows that produce mesohaline conditions throughout most of the year at the bottom of the bay, with salinities ranging from 5 to 20 ppt over the soft bottom areas of the WBZ that have the substrate necessary to sustain SAV. In particular, measured dry season salinities (November through May) should not exceed 30 ppt anywhere in the zone. The ecological and salinity targets that link mesohaline conditions and associated seagrass and faunal communities for this area are not currently being met because current freshwater deliveries are insufficient in terms of quantity, timing, and distribution.

Using draft CERP Guidance Memorandum 4 methodology, freshwater flows that either contribute to reaching, or reach, the above salinity ranges in the WBZ can be considered "beneficial." To quantify these beneficial flows, the implicit flow targets, the existing flows, and the specific restoration area of concern need to be clearly defined.

Simple volumetric estimates to reach these salinity goals in the 10,000 acres of the tidally-driven system result in a target annual flow of 1.1 M acre-ft/yr, with dry and wet season variations. Other types of flow target estimates – diffusive, empirical, semi-empirical – discussed in this document fall within this range as well. In the absence of any robust hydrological modeling results which could reduce the range of estimates, the volumetric estimate will suffice as a flow target for comparison against the existing flows. Future work should focus on hydrological modeling results that will not only help refine the volumetric estimates, but also provide information concerning the expected spatial and temporal distribution of the freshwater flows.

The existing flows are comprised of the managed water flows through the control structures at the end of the canals that empty directly in or adjacent to the WBZ; groundwater flows were omitted from hydrologic analysis in this assessment. The SFWMM was chosen to create a retrospective time series of surface water flows from 1965-2000. Time series of observed (canal discharges) and modeled (SFWMM Alt7r5e) canal discharges were compared to each other to establish the validity of the SFWMM flow time series.

The target flow and retrospective flow time series in the region of concern were then compared, and those flows that could be classified as beneficial were summed on both a daily and monthly basis. The annual average of these flows was then computed for each period. For the 1.1 M acre-ft/yr seasonally-varying flow target, the daily Alt7r 1965-2000 retrospective time series of coastal flows that empty directly into the park or flow through park boundaries (416 K acre-ft/yr average) provides 341 K acre-ft/yr of flows (82%) that are determined to be required for the protection of fish and wildlife. The monthly time series, due to the relatively short duration of most of the peak flows through the canals following storms, allowed 397 K acre-ft/yr or 92% of the flows to be determined as required for the protection of fish and wildlife (Table 3). The high standard deviation of the annual flow volumes is indicative of the large amount of interannual variability in these freshwater flows.

Table 3. Estimates of the monthly surface flow volumes using Alt7r (1965-2000) and observed flows (1985-2003) for S-22, G93, S123, S21, S21A, S20F, S20D, and S197, and the annual average of flows that are classified as beneficial to fish and wildlife as per GM #4 (based upon the comparison of the monthly Alt7r and seasonal target time series).

	Average annual flow volumes (K acre-ft/yr)	Standard deviation (K acre-ft/yr)	Estimated beneficial flow volume
Observed (1985-2003)	490	391	455
Alt7r (1965-2000)	416	382	397

However, the current timing and distribution of these waters is largely ineffective at preventing hypersalinity. The islands ringing the bay and the many shallow banks under its waters act to compartmentalize the bay. South Bay, comprising perhaps 70% of the bay's entire area, and subject to about 100 K acre-ft/yr of evaporative loss, today only receives 40% of the canal-based freshwater flows. The other 60% are released in the North Bay, where these freshwater flows are quickly flushed to sea via the tidal cycle and thus, do not remain in the bay. These volumes of water could arguably be much more beneficial to South Bay, which not only receives less surface water inputs and has more restricted connectivity to the ocean, but also has more extensive potential estuarine habitat that would benefit from more surface water inputs. Surface waters redirected from North to South Bay would not only counter the evaporative losses, but would remain in South Bay much longer (weeks) than they do in North Bay (days). The timing is also critical. Without the pre-drainage groundwater flows and historic creeks that used to provide waters to South Bay during the dry season, there is not enough flow to South Bay to prevent evaporation-driven hypersalinity. The situation is even more pronounced in Barnes and Card Sounds, located to the south of Biscayne National Park. With tidal inflows restricted to those spilling from South Bay over the shallow Cutter Bank at the mouth of Card Sound, characteristic long residence times (months), and with few freshwater surface inputs (C-111), Barnes and Card Sounds quickly become hypersaline during the dry season and periods of mild drought.

This paper has treated ecological targets for Biscayne National Park and annual estimates of freshwater flows needed to reach them. Further analysis is needed to develop metrics for the seasonal and interannual variability associated with hydrologic restoration targets for the park. These ecological and hydrologic targets will be critical to evaluate potential benefits of restoration projects for Biscayne National Park and to assess progress toward ecosystem restoration.

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APPENDIX A: ADVECTION VERSUS DIFFUSION

A one-dimensional flow of water and salt in the x direction can be expressed in a steady-state, vertically-mixed form as:

$$\frac{d(US)}{dx} = \frac{d}{dx}\left(A\frac{dS}{dx}\right)$$

where S is the salt content, U is the horizontal velocity, and A is the horizontal turbulent diffusion coefficient. If one assumes that U is independent of the distance x from the coast (which is a very reasonable assumption for a flow distributed all along a coastline, and an unreasonable assumption for a point source flow), and that A is likewise independent of x (a poor but pragmatic choice) then:

$$U\frac{dS}{dx} = A\frac{d^2S}{dx^2}$$

Given the assumptions, the analytical solution is exponential. The importance of this solution is that, in the absence of other transient forcing, a steady flow offshore gives a persistent exponential gradient located near the coast. As the speed of the flow increases, this gradient will move farther offshore and will become sharper (larger magnitude). As the mixing becomes more intense or efficient (i.e., the magnitude of A increases) the gradient will move closer to shore and the gradient's magnitude will decrease. The ratio of A/U is the length, or e-folding scale, and, as such, is a good estimate of the width of the offshore gradient region. While the velocity U along a coastline can be determined by metering out a known volume of water at a known rate along a length of shoreline, the horizontal turbulent diffusion coefficient A is not as simple and is often several orders of magnitude greater than equivalent molecular diffusivities. It is a function of the flow and resulting friction in the area and, as such, will be dependent on the tides, winds, and topography, and can vary by several orders of magnitude.

The advection dispersion estimate provided on page 21 is derived from a horizontal diffusivity of A = 1 m^2/s and steady offshore velocity U= 0.001 m/s for 26 km of coastline with an average depth of 1 m. The value of the diffusivity A has been shown by Wang et al. (1978) to vary from 0.5 m^2/s to 5 m^2/s along the western shoreline, producing a theoretical range of net offshore velocities from 0.0005 m/s to 0.005 m/s. These velocities translate to freshwater fluxes of 400 K acre-ft/yr to 4 Maf/yr, respectively – a considerable span of values. However, the diffusivity is highly variable with time and space, including dependencies on wind speed, current speed, water depth, and the distance to the shoreline. Since the shallow areas adjacent to the coastline are not subject to the largest tidal velocities and wind/wave effects, they will likely have effective diffusivities on the lower end of the range in all but the most extreme (storm) events. The 800 K acre-ft/yr target flow estimate was arrived at by a conservative evaluation of these factors and assuming an average diffusivity in the Western Bay Zone of 1 m^2/s.

Inside back cover photograph by Brett Seymour, NPS Submerged Resources Center, Santa Fe, NM

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