Northern Estuaries Performance Measure
Submerged Aquatic Vegetation

Last Date Revised: March 22, 2007

Acceptance Status: Accepted

1.0 Desired Restoration Condition

The restoration expectation for this performance measure is to improve the spatial and structural characteristics of submerged aquatic vegetation communities.

1.1 Predictive Metric and Target

(See NE Salinity Envelops for predictive metrics and targets).

1.2 Assessment Parameter and Target

SAV that are important in the South Indian River Lagoon (the portion of the Indian River Lagoon under the jurisdiction of the South Florida Water Management District) include three *Halophila* species (including the federally-listed *Halophila johnsonii), Halodule wrightii, Ruppia maritima, Syringodium filiforme* and *Thalassia testudinum*. These cover 7,808 acres (3160 ha) within the southern portion of the lagoon (SJRWMD and SFWMD 2002).

Studies have shown that the only areas in the St. Lucie Estuary that currently support SAV are in the lower estuary near Hell Gate Point (Woodward-Clyde 1999). The SAV identified in these recent studies were primarily shoots and not actual beds. Shoal grass (*Halodule wrightii*) was the dominant species throughout most of this area, with Johnson's seagrass (*Halophila johnsonii*) the secondary species. The only other documented occurrences of SAV during that study was a very small amount of Widgeon grass (*Ruppia maritima*), American wild celery (*Vallisneria americana*) and common water nymph (*Najas guadalupensis*) in the South Fork of the estuary as well as a small area of *R. maritima* in the North Fork.

The average maximum depth that seagrasses will grow in the South Indian River Lagoon and St. Lucie Estuary is 1.7 meters (Virnstein and Morris 1996). The St. Lucie Estuary has approximately 922 acres (373 ha) of suitable habitat. South Indian River Lagoon has 19,799 acres (8012 ha) of suitable habitat, including the 39% that currently house seagrass (SJRWMD and SFWMD 2002). These acreages are based on 1999 aerial photographic interpretations by the District.

American wild celery (*Vallisneria americana*) is the dominant SAV species in the upper Caloosahatchee Estuary and historically occurred as well-defined beds in shallow water (<1 m). Vallisneria americana is thought to be an important habitat for a variety of freshwater and estuarine invertebrate and vertebrate species, including some commercially and recreationally important fishes (Bortone and Turpin 1999). Additionally, it can serve as a food source for the West Indian manatee (*Trichechus manatus*). Shoal grass (*Halodule wrightii*), turtle grass (Thalassia testudinum) and manatee grass (*Syringodium filiforme*) are the most common higher salinity seagrasses in the Caloosahatchee Estuary. *Argopectin irradians*, (bay scallop) prefers *H. wrightii* and *T. testudinum* beds. The current goal of the Charlotte Harbor Estuary Program is to increase scallop populations to resemble historic distributions.

American wild celery (*Vallisneria americana*) in the Caloosahatchee Estuary:

- Current Conditions – Variable yearly, with reduction in area coverage during dry winters and springs that promote salinity above tolerance limits. High flows that decrease light anytime of year also limit coverage and size. Combination of drought in year 2000, followed by high flows with dark water caused a 100% loss of American wild celery. Currently only small plants (~10 cm lengths) have returned to the river but only to a portion of potential habitable area. Plant density and size currently do not provide significant habitat for other organisms and sexual reproduction does not occur (Robbins et al. 2006).

- Future w/o project– Over 50% of the flows are either too high (decreased clarity) or fall below that required to prevent salinity above plant limits, resulting in infrequent bed characteristics that support other organisms; and probably eventual loss of permanent beds.

- Restoration Expectation – Except following extreme droughts, achieve permanent presence of beds that improve WQ and provide viable habitat for other organisms.

- Ecological Target – American wild celery in the Beautiful Island area has a permanent coverage ≥ 20% to at least 1.0m and blade length ≥10cm.

Seagrasses in the Caloosahatchee Estuary:

- Current Conditions – Variable yearly, with some areas virtually disappearing in wet years. Average loss in San Carlos Bay was > 16% (1945-1982) + 38% (1982-1999). In lower Caloosahatchee River (Shell Point to Peppertree Point) losses have been nearly 100%. Losses are due in part to high flows that reduce salinity and water clarity that prevents appreciable coverage below 1 to 1.5 m.

- Future w/o project – Continued decline in seagrass coverage.

- Restoration Expectation – Recover the 38% lost in San Carlos Bay since 1982 and return of viable seagrass in lower Caloosahatchee River.

- Ecological Target – Permanent seagrass coverage ≥ 30% to at least 1.0m in the Iona Cove area and. Continuous viable seagrass coverage of ≥20% in San Carlos Bay area to ≥1.75 m, with blade length ≥10cm.

Seagrasses in the Loxahatchee River estuary:

- Current Conditions – Periodic catastrophic losses of seagrasses following excessive freshwater discharges (e.g., 2004), with recovery taking an extended period of time (3+ years). Seagrass diversity includes seven SAV species; 1). *Halodule wrightii* (shoal grass), 2).*Halophila decipiens* (paddle grass),3). *Halophila engelmannii* (star-grass), 4). *Halophila johnsonii* (Johnson's seagrass), 5). *Syringodium filiforme* (manatee grass), 6). *Thalassia testudinum* (turtle grass), and 7). the brackish water *Ruppia maritima*.

- Future w/o project – Continued decline in seagrass diversity, coverage, and function.

- Restoration Expectation – Increase the spatial extent of seagrasses in the upstream reaches of the estuary, and recover the extent and viability of *Syringodium filiforme* and *Thalassia testudinum* in the central embayment.

- Ecological Target – For the central embayment, seagrass occurrence, density, canopy height, and biomass should approximate seagrass conditions at the seagrass reference site in the Indian River Lagoon (Hobe Sound). Furthermore, seagrasses should slowly migrate upstream in each of the major forks of the Loxahatchee River (e.g., Northwest Fork) as excessive salinity variability is reduced.

Six species of seagrass are present in LWL: *Halodule wrightii* (shoal grass), *Halophila decipiens* (paddle grass), *Halophila engelmannii* (star-grass), *Halophila johnsonii* (Johnson's seagrass), *Syringodium filiforme* (manatee grass), *Thalassia testudinum* (turtle grass). *Halodule wrightii* is the most abundant species of seagrass in terms of areal extent, and occurs primarily in shallow areas. *Thalassia testudinum* and *Syringodium filiforme* are found infrequently, and are most abundant in the north end of the Lake Worth Lagoon. Seagrass covers at least 1,626 acres or 22% of LWL. The acreage is based on 2001 aerial photographic interpretations. The coverage varies throughout the three segments of the lagoon. The overall seagrass coverage within each of the segments is 33.5% in the north, 9% in the central, and 17% in the south segment of the lagoon. The average maximum depth that seagrass will grow in the north segment is 5.0 feet (NGVD), 4.4 feet in the central segment, and 3.4 in the south segment.

Seagrasses in Lake Worth Lagoon:

- Current Conditions – Baseline conditions measured in 2001 and will be quantified in 2007. Data from fixed-transect seagrass monitoring and water quality data has not been analyzed.

- Future w/o project – Decline in seagrass coverage.

- Restoration Expectation – Increase the spatial extent and density of seagrasses in the central segment as well as the southern segment of the lagoon.

- Ecological Target – For the central segment, increase coverage from 4.4 to 5.0 feet (NGVD). For the southern segment, increase coverage from 3.4 to 4.0 feet (NGVD).

<u>Targets are as follows:</u>

- South Indian River Lagoon – increase cover of SAV beds to areas that are less than 1.7 m MSL in depth. This depth represents a maximum depth for seagrass growth in the area; preliminary information (Rebecca Robbins, personal communication) indicates that the target for seagrass growth in this area will be 1.3-1.4 m MSL in depth. South Indian River Lagoon has 19,799 acres of suitable habitat, of which 7,808 (39%) is already colonized by seagrass.

- St. Lucie Estuary – increase cover of SAV beds to areas that are less than 1.0 m MSL in depth. The St. Lucie Estuary has 922 acres of suitable habitat, none of which contains seagrass.

- Caloosahatchee Estuary – specific targets for SAV will be developed following the establishment of baseline conditions of seagrass species abundance, distribution and health.
- Loxahatchee River Estuary – specific targets for SAV will be developed following the establishment of baseline conditions of seagrass species abundance, distribution and health.
- Lake Worth Lagoon – increase cover of SAV beds to areas that are less than 5.0 feet NGVD in the central segment and 4.0 feet NGVD in the south segment. The central segment has 729 acres of suitable habitat, of which only 192 is colonized by seagrass. The south segment has 536 acres of suitable habitat, of which only 300 is colonized by seagrass.

In addition, flows needed to achieve the proper salinity range for SAV need to be maintained within all northern estuaries.

2.0 Justification

Submerged aquatic vegetation (SAV) is important economically and ecologically, serving as major structural elements in estuarine and coastal waters. They provide food, habitat, and refuge to invertebrates, birds, marine turtles and mammals, and many marine recreationally and commercially targeted fishes during some stage of their life cycle. In addition to being important constituents of coastal food webs, SAV also stabilize sediments, inhibit their re-suspension, sequester atmospheric carbon and export carbon to other systems, improve water transparency, trap and cycle nutrients, and protect shorelines through wave energy attenuation (Duarte 2002). Because of these extensive ecosystem services, SAV ecosystems are among the most significant on the planet.

By definition, SAV includes both marine and freshwater aquatic angiosperms as well as macroalgal species. Native macroalgal species (attached and drift) are desirable constituents of estuaries occurring worldwide though an overabundance of these taxa may be detrimental to angiosperms (Onuf 1996). In the northern estuaries macroalgae most commonly occurs ephemerally as drift, although some attached species such as *Caulerpa prolifera* may be seasonally abundant. Because of this ephemeral nature and the mobility of drift species as they passively respond to temporal hydrological dynamics these species are difficult to manage and while important are outside the scope of this effort. Subsequently, herein only brackish and marine seagrasses and/or freshwater grasses will be considered SAV. Seven seagrass species are found in Florida's estuaries and nearshore coastal waters including *Halodule wrightii* (shoal grass), *Halophila decipiens* (paddle grass), *Halophila engelmannii* (star-grass), *Halophila johnsonii* (Johnson's seagrass), *Syringodium filiforme* (manatee grass), and *Thalassia testudinum* (turtle grass). Freshwater species of concern include *Vallisneria americana* (American wild celery) and *Sagittaria kurziana* (strap-leaf Sagittaria). One brackish water species *Ruppia maritima* (widgeon grass) is also found.

Although there are species-specific variations, generally speaking SAV distributions are limited by four environmental factors: light, salinity, temperature, and nutrients (Dennison et al. 1993, Kemp et al. 2004). The South Florida Water Management District's (District's) northern estuaries autecological studies on seagrasses have documented that SAV distribution and subsequently its functionality, is strongly related to limits on their physiology and growth characteristics by water depth as it relates to light attenuation (Gallegos and Kenworthy 1996, Kenworthy and Fonseca 1996, Dixon and Kirkpatrick 1999) and salinity (Lirman and Cropper 2003, Ridler et al. 2006, Dixon and Kirkpatrick

1999, Irlandi et al. 2002). Specifically, the expansion of SAV margins, at least at the lower (deepest) boundaries, has been linked to light (Dennison *et al*. 1993).

Superimposed upon this physiologically based template, however, are a variety of factors, such as impacts via grazing (Lewis 1986) or competitive interactions (Williams 1987), that may contribute to overall spatial arrangement and areal extent of SAV as well as its functionality. Additionally, bioturbation (Fonseca *et al*. 1994), hydrodynamics (tidal currents, waves *i.e.*, Fonseca *et al*. 1996; Fonseca and Bell 1998), and the variation of sediment grain size distribution across sites may influence both the arrangement (Mukai *et al*. 1980) and physical attributes of the SAV across of suite a spatial scales (Fonseca 1996).

Flow

Understanding the impact of the release or retention of freshwater by the District for management on SAV is complicated by timing, periodicity, magnitude, and duration. Freshwater input may and probably does influence the four environmental factors (light, temperature, salinity, and nutrients) that limit SAV growth in the northern estuaries. Also of concern are unregulated non-point source flows that may thwart management strategies intended to control rapid changes in a chemical and/or physical characteristic of a water body by circumventing the controlled releases of excess water.

Light

Light has been recognized as the primary limiting factor controlling the lower depth limit of SAV (see Kenworthy 1994 for review). Light requirements are typically determined by evaluating the species-specific needs of individual plants coupled with the maximum depth distribution of a given species. Alternatively, a comparison of a SAV species' maximum depth of occurrence within a body of water and the light attenuation coefficient can also be used to estimate that species' minimum light requirements (Dennison et al. 1993, Dunton 1994, Kenworthy and Fonseca 1996, Kenworthy and Haunert 1991, Morris and Tomasko 1993). As a result of these relationships, SAV productivity has been used to assess water quality in estuaries (Dennison et al. 1993). Minimum light requirements are usually expressed as a percentage of the light at 10cm subsurface (Io) that reaches the seagrass canopy (30cm above the substrate). For example, minimum light requirements have been calculated for certain seagrasses common to Florida such as *Halodule wrightii* and *Syringodium filiforme* in the Indian River Lagoon (~30% of Io; Beal and Schmit 2000; Kenworthy and Fonseca 1996) and *Thalassia testudinum* in Tampa Bay (~21% of Io; Dixon, 2000).

Light availability however, is not simplistic with several biotic and abiotic factors (sediment, epiphytes, phytoplankton, color and colloids) influencing light quantity and/or quality and therefore plant photochemistry (Gallegos and Kenworthy 1996). SAV requires specific quantities of light (i.e., minimum thresholds per unit time) and specific qualities of light (i.e., wavelengths, certain optical properties). SAV responses to the light regime include changes in areal extent, shoot density, blade length and width, carbon uptake, chlorophyll composition, and above- and below-ground biomass. Of chief concern is the influence of freshwater releases, especially their timing and duration on light quality and quantity. Releases may lead to an increase in light attenuation via increased water color, sediment suspension, elevated nutrient availability and associated plankton blooms, and other flocculants in the water column that limit light availability.

Seagrasses require more light than macroalgae or phytoplankton, therefore decreased light (increased light attenuation) will reduce the ability of seagrass to compete with these other species. *H. wrightii* and *S. filiforme* require less light than *T.testudinum*, therefore a prolonged increase in light attenuation will lead to a shift in species composition. Sulphide toxicity occurs as a result of increased light attenuation and a decreased ability for plants to photosynthesize and oxygenate the sediments surrounding the rhizomes (Carlson et al. 1994).

Salinity

Salinity affects growth, which may be seen in a phenotypic response by individual plants. For example, Montague and Ley (1993) found that SAV biomass was directly proportional to salinity, with biomass decreasing as salinity variation increased. This is important as timing of freshwater releases may result in salinity fluctuations, which may in turn, restrain SAV growth rates. See Woodward Clyde (1999) review of salinity requirements for FL seagrasses for this section.

In the upper estuary, the naturally occurring grass species, *Vallisneria americana*, will not survive prolonged periods of elevated salinity as a result of manipulated freshwater flow. *Halodule wrightii* persists in areas with high variation in salinity. *Thalassia testudinum* and *Syringodium filiforme* will not tolerate prolonged periods of reduced salinity as a result of manipulated water release, and persist in areas with relatively low variation in salinity. Recent work in the Loxahatchee River has shown that low minimum daily salinity and high salinity fluctuation resulted in significant losses of *S. filiforme* (Ridler et al. 2006). Nonetheless, *H. wrightii* persisted throughout these same conditions.

For example, during drought conditions the retention of freshwater in the upper Caloosahatchee River (i.e., above S-79) may result in salinities that reach a point that the extant populations of the freshwater SAV *V. americana* are extirpated from the lower river. Alternatively, the release of additional freshwater during El Niño events may result in freshening the river to a point that downstream euryhaline SAV species are negatively impacted.

Temperature

Temperature influences photosynthesis, respiration and ultimately growth of SAV species (Bulthuis 1987). However, because the effect of temperature on SAV is influenced in part by irradiance, it is difficult to separate the effects of light availability and temperature on SAV (Larkum et al. 1989). Similarly, temperature and hydrodynamics are strongly linked. In general, growth of seagrasses in saturating light increases with temperature, whereas growth in low light decreases as the temperature increases (Bulthius, 1987).

Relationships directly relating temperature and growth have not been established for most SAV in the northern estuaries. However, the inter-annual variation in seasonal high and low water temperatures expected in the northern estuaries may in some years reach lower tolerance levels (especially for tropical species) or upper levels (especially in shallow areas). Numerical modeling analyses for *Vallisneria americana* in the upper Caloosahatchee estuary shows that the temperature relationship used has an impact on the predicted growth and response to environmental changes and indicates that the tolerance or acute levels of stress for temperature should be better represented in order to make successful predictions (Hunt and Doering, 2005).

Nutrients

Nutrient loadings specifically, TN, TP and NO_x, may play a key role in SAV distribution and health (Dalla Via *et al*. 1998) as evidenced by the recovery of SAV in Tampa Bay following the curtailment of nutrient dumping via inadequate wastewater treatments. Macroalgae and epiphytic algae outcompete seagrasses for water-borne nutrients and can overgrow/smother seagrasses and cause declines in areal cover and shoot density (Onuf 1996). Nutrients have a major, indirect influence on SAV, because increased nutrients lead to algae blooms, which decrease light availability for SAV (Kemp et al. 2004).

Fast growing SAV (e.g. *Halodule wrightii*) requires higher nutrient levels in the sediment, than slower growing forms (e.g. *Thalassia testudinum*). Anoxic sediment will lead to sulphide intrusion in SAV rhizomes leading to dieback (Carlson et al. 1994). Microbial communities are important to the biochemical reactions occurring around the SAV rhizomes.

Sediments

Although still not well studied, sediment grain size and organic content may have significant influence on SAV growth and survival (e.g., Terrados et al., 1999) as evidenced by damage caused by anoxia and sulfides (Goodman et al., 1995) to the underground components of SAV species. Sediment nutrient content and mineral composition may also affect SAV growth. For example, carbonate sediments can bind dissolved phosphorus, reducing its availability to root (Short et al. 1990). Because current velocities affect sediment grain size and organic content, organic accumulation rates, sediments and their influence on SAV may be highly variable within and among estuaries.

Grazing

The relationship between SAV and herbivores is not well understood. The West Indian Manatee (*Trichechus manatus*) is among the few vertebrate grazers utilizing SAV as the main source of their diet although grass carp (*Ctenopharyngodon idella*) too have been documented as having an affect on freshwater SAV species (Hestand and Carter, 1978). Large herbivores such as manatees may graze destructively (Lefebvre et al. 2000) and thus inhibit the recovery of the SAV by disturbing their rhizospheric components when removing the photosynthetic leaves (Thayer *et. al.*, 1984). The gaps created by grazing within the SAV habitat may alter the functionality and subsequently the value of the SAV habitat by increasing landscape heterogeneity and thus influencing both floral (may initiate succession) and faunal relationships. Other herbivore impacts such as the grazing of epiphytes may be both beneficial and necessary for SAV survival within estuaries with high nutrient loading rates (e.g., Neckles et al. 1993).

Minimum Flows and Levels

Pursuant to the requirements of Sections 373.042 and 373.0421, Florida Statutes, of the “Florida Water Resources Act,” water management districts shall establish minimum flows and levels (MFL’s) for surface waters and aquifers within their jurisdiction. The minimum flow is defined as “…the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area” (section 373.042(1), F.S.).

For purposes of establishing minimum flows, significant harm is defined as a loss of water resource functions that takes more than two years to recover. Water resource functions protected under Chapter 373 include flood control, water quality, water supply and storage, fish and wildlife, navigation, and recreation.

Each district shall develop and have approved a priority list and schedule for the establishment of MFL's. "The priority list shall be based upon the importance of the waters to the state or region and the existence of or potential for significant harm to the water resources or ecology of the state or region, and shall include those waters which are experiencing or may reasonably be expected to experience adverse impacts."

Many waterbodies have been hydrologically altered by the canals and structures for the management of water and no longer serve their hydrologic function. The establishment of MFL's is not intended to restore waterbodies to their historical hydrologic function, therefore, additional measures may be necessary to maintain a sustainable resource or protect it from significant harm during the broad range of water conditions occurring in the managed system.

MFL's have been developed for the Caloosahatchee River and Estuary, the St. Lucie River and Estuary, and the Northwest Fork of the Loxahatchee River. The Lake Worth Lagoon is not on the 2005 Statewide MFL Water Body Priority List. Proposed minimum flow criteria for the northern estuaries are linked to the concept of protecting valued ecosystem components from significant harm.

Caloosahatchee River and Estuary MFL

Rule Language: *A minimum mean monthly flow of 300 cfs is necessary to maintain sufficient salinities at S-79 in order to prevent a MFL exceedance. A MFL exceedance occurs during a 365 day period, when: (a) A 30-day average salinity concentration exceeds 10 parts per thousand at the Ft. Myers salinity station (measured at 20% of the total river depth from the water surface at a location of latitude 263907.260, longitude*

815209.296; or

(b) A single, daily average salinity exceeds a concentration of 20 parts per thousand at the Ft. Myers salinity station. Exceedance of either paragraph (a) or (b), for two consecutive years is a violation of the MFL.

NE Salinity Envelope Metric recently updated the minimum mean monthly flow discharges from the C-43 canal into the Caloosahatchee River and Estuary from 300 CFS to 450 cfs based on new information.

Intent: To maintain *Vallisneria americana* habitat that will support both estuarine and juvenile marine organisms, a minimum mean monthly flow of at least 450 cfs is required to be delivered to the estuary between the months of November – March (dry season).

St. Lucie River and Estuary MFL

Rule Language: St. Lucie Estuary – mean monthly flows to the St. Lucie Estuary should not fall below 28cfs from the Gordy Road structure to the St. Lucie River North Fork for two consecutive months during a 365-day period, for two consecutive years.

Intent: Mean monthly flows to the St. Lucie Estuary of more than 28 cfs from the North Fork of the St. Lucie River represent the amount of water necessary to maintain sufficient salinities in the St. Lucie Estuary in order to protect the oligohaline organisms that are valued ecosystem components of this system.

Northwest Fork of the Loxahatchee River

Flows over Lainhart Dam decline below 35 cfs for more than 20 consecutive days; or the average daily salinity concentration expressed as a 20-day rolling average exceeds 2 ppt. The average daily salinity will be representative of mid-depth in the water column (average of salinities measured at 0.5 meters below the surface and 0.5 meters above the bottom) at river mile 9.2 (latitude 26.9839, longitude - 80.1609).

Intent: Flows below 35 cfs from Lainhart Dam cause salinities in excess of 2 ppt to occur at sites where remaining stressed and harmed plant communities exist along the Northwest Fork of the Loxahatchee River. Frequent exposure to salinity levels in excess of 2 ppt were associated with damage to freshwater vegetation.

3.0 Scientific Basis

3.1 Relationship to Conceptual Ecological Models

The indicator for this performance measure is an ecological attribute (SAV depth coverage) in the following conceptual ecological models:

<u>Regional Models (RECOVER 2004b)</u>

St. Lucie Estuary and Indian River Lagoon
Loxahatchee
Lake Worth Lagoon
Caloosahatchee Estuary

<u>Ecological Model for Hypothesis Clusters (RECOVER 2005)</u>

Submerged Aquatic Vegetation Conceptual Model

3.2 Relationship to Adaptive Assessment Hypothesis Clusters

Northern Estuary SAV Hypotheses:

Hypothesis 1: Extreme fluctuations in estuarine salinity resulting from hydrologic alterations and water management practices negatively affect SAV functionality and have resulted in large decreases in aerial extent of SAV in the Northern Estuaries.

Rationale: Species composition and density of SAV communities is directly linked to the mean salinity and the variation around the mean at any given location. In the SLE, wide fluctuations in salinity (over days/weeks) have caused nearly complete extirpation of SAV. Remnant populations of freshwater grasses (*Ruppia maritime* and *Vallisneria americana*) subsist in the upper estuary, visible during exceptional water quality periods. Remnant populations of seagrasses (*Halodule wrightii* and *Halophilia johnsonii*) subsist as low density, narrow fringes (roughly 20m long) downstream of Hell

Gate Point to the Bessemer spoil islands (MC5 and 6). During high flow years (e.g., 1998, 2005) as salinity reaches critical thresholds (<10ppt for days/weeks), these seagrasses are extirpated from this area. The SFWMD, in partnership with SJRWMD, DEP, and the LRD, monitor over 18 seagrass transects in the Southern Indian River Lagoon two times per year (Winter/Summer). Many of these transects have been monitored since 1994. Transects nearest to the mouth of the St. Lucie River tend to have the shallowest deep edge of bed depth. This observation is most likely attributable to high salinity fluctuation, prolonged low salinity events, and high light attenuation associated with freshwater discharges. Seagrasses along transects closest to the mouth of the St. Lucie River sometimes disappear completely during times of prolonged low salinity and high light attenuation.

Additionally, the SFWMD conducts monthly monitoring at two seagrass beds near the mouth of the St. Lucie River (one north and one south of the St. Lucie Inlet). Both sites were impacted by hurricanes in 2004 and 2005. The *Syringodium filliforme* bed south of the inlet was buried with sediment during the 2004 hurricanes and has not yet recovered. The *S. filliforme* bed north of the inlet also experienced some burial but much of the bed survived (at lower densities) following the 2004 hurricanes. Following Hurricane Wilma in 2005, low shoot density was observed throughout the bed. Complete loss of *S. filliforme* in many areas of the bed followed prolonged low salinity and low light conditions associated with Lake Okeechobee discharges in late 2005 and early 2006. Some recovery was observed in the Spring/Summer of 2006 but shoot counts are still well below pre-hurricane observations.

Within the Caloosahatchee Estuary extreme fluctuations are less pronounced although changes of >25 psu over a several week period has been recorded (Robbins et al. 2006). In the lower estuary recent high flows have resulted in the loss of some SAV (i.e., *Thalassia. testudinum*) beds and a shift in the dominant seagrass species (i.e. T. *testudinum* to *H. wrightii*) in others (Robbins et al. 2006). The submersed plants in the Caloosahatchee estuary are also negatively affected by high river flows. The fresh water inputs are high in particulates, nutrients, and blue absorbing DOM. These contribute to lowered light quality and quantity for the submersed plants. At high sustained river flows, salinities in the lower estuary are too low for the seagrasses. At low flows, salinities in the shallows upstream surpass the tolerance for *V. americana*.

The Loxahatchee River District monitors seagrasses and water quality in the Loxahatchee River and estuary. These monitoring efforts have revealed that excessive freshwater discharges (i.e., flood control releases through S-46) result in significant declines in minimum daily salinity and significant increases in daily salinity variation in the Loxahatchee River estuary (Ridler et al. 2006). More importantly, these data show that such effects (i.e., decreased minimum daily salinity and increased salinity variability) caused significant decline in the occurrence, density, and biomass of *S. filiforme* in the Loxahatchee River estuary.

Palm Beach County Department of Environmental Resources Management monitors seagrass in LWL as well as water quality with in partnership with other agencies. Freshwater inputs, particularly from the C-51 Canal, contribute substantial amounts of sediments and nutrients that impact water quality for seagrass. Anecdotal information indicates that extent and density of seagrass is impacted by freshwater inputs. Annual fixed-transect seagrass monitoring and water quality data have not been completely analyzed for correlations. A salinity model was developed to assist in setting appropriate targets.

Hypothesis 2: Large deposits of organics, fine silts and clay materials, i.e., muck, displaces normal sandy substrate in the Northern Estuaries contributing to the decrease in the aerial extent of SAV beds.

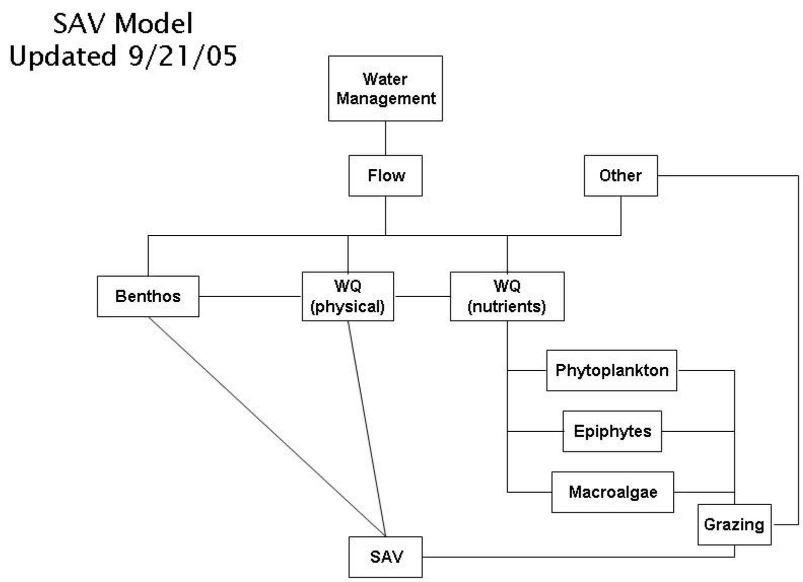
Rationale: Sediment characteristics (e.g. nutrients, oxygen, microbial communities) are important to SAV survival; these characteristics will be altered by the increased deposition of fine silts and organic matter. In the SLE, the deposition of muck has been greatly increased over the past 50 years and the current sedimentation rate is 0.5-1.0 cm per year. SLE muck generally contains a mean of 7.6% organic matter, containing high salt levels and low heavy metal concentrations. Certain areas (e.g., upstream of S-49, S-50, central North Fork) contain potentially harmful levels of toxins (e.g., arsenic, cadmium, mercury, zinc, copper, chlordane, DDT and derivatives, PCBs). Upstream portions such as 5-Mile and 10-Mile Creeks contain high levels of heavy metals, pesticides and herbicides. Manatee Pocket contains very high levels of certain harmful compounds (e.g., chlordane, mercury, PCBs, copper). The presence of elevated levels of harmful substances has contributed to the current listing of the SLE as a state impaired water body. Many of the harmful compounds found within the SLE have high affinities for fine particles (silts, clays) and organic matter. The high sedimentation rate of fine particles and muck in the SLE has contributed to the loss of SAV. Shallow nearshore areas with unstable and easily resuspended sediments as their substrates base will not house submerged aquatic vegetation. Anoxic muck deposits as deep as 4.26m, primarily located in the central portions of the North and South Fork Estuaries, are resuspended during high flow and/or wind-driven events, and by boat traffic. The resuspension of sediment and organics reduces water quality, increases light attenuation, and decreases DO, thereby preventing SAV survival in most areas. There is a paucity of data that address how sedimentation may affect SAV in the Caloosahatchee Estuary although Doering et al. (1999) suggested that the re-suspension of sediment increased light attenuation within the estuary. In the Caloosahatchee estuary, as well as all others, silty sediments can cause a reducing environment in the root zone and result in an added stress on submersed plants. In addition, fine particles are easily resuspended which increases light attenuation by the water column thus slowing or stopping plant growth. These particles also attach to epiphytic, benthic and drift algae, which can further reduce light for plant growth. In LWL expansive areas of the lagoon are covered with sediments that inhibit SAV. These muck deposits are most prevalent in the central portion of LWL adjacent the C-51 Canal. Approximately 44% of LWL is impacted directly by muck sediments in LWL. Although *Halophila johnsonii* is present in some areas with muck sediments, the density and diversity of this species is poor in these areas. The deposition of muck has also greatly increased over the past 60 years and the current sedimentation rate is approximately 0.43 cm per year. Many deep dredge holes exist in LWL characterized by anoxic conditions and low biological diversity. Shallow muck sediments are easily resuspended by wind, wave, and boating action further contributing to increased light attenuation.

Hypothesis 3: Increased levels of nutrients, dissolved organic matter and turbidity decreases light quantity and quality which negatively affects SAV functionality and aerial extent.

Rationale: Turbidity (sediment loads), color and chlorophyll all increase light attenuation, which is directly correlated to decreased SAV plant densities and their depth distribution. In the SLE, the nearly complete loss of extant SAV can be attributed to wide fluctuations in salinity as well as other water quality parameters in response to the facilitated drainage of the watershed (especially C-44, C-23, C-24, the narrow North Fork, 10-Mile Creek). In addition, drainage has resulted in high nutrient load events that have caused persistent algal blooms and are most likely contributing to outbreaks of fish lesions noted in the SLE. Little data are available on how nutrients, dissolved organic matter and turbidity and their influence on light attenuation may be affecting SAV in the Caloosahatchee Estuary although one study (Dixon and Kirkpatrick 1999) reported that color and turbidity are higher in this part of the estuary as compared to other areas within Charlotte Harbor. In all northern estuaries, the available blue light required for SAV growth is being limited by high dissolved organic concentrations from their surrounding watersheds. The Caloosahatchee River and the SLE also experience a decline in the blue band of the light spectrum during Lake Okeechobee releases. High nutrient loading rates may also increase epiphytic, benthic and drift algae biomass which may shade SAV. High turbidity reduces all light spectra resulting in reduced plant growth. In the fall of 2005, *Thalassia testudinum* areal extent decreased by 70% in the lower Caloosahatchee estuary after two years of high discharges from S-79. The combination of reduced light availability and reduced salinity probably accounts for this loss. The United States Geological Survey is currently studying sediment transport to LWL via the C-51 Canal. During 2004 and 2005, approximately 8000+ tons of suspended solids are delivered annually by freshwater inputs.

Hypothesis 4: Decreased SAV functionality results in changes in community structure, carbon energy flow and physiological characteristics of SAV and sediments.

Rationale: There is a quantifiable relationship between fish and invertebrate community structure and SAV habitat that is influenced by ambient salinity and water quality regimes. Estuarine SAV and nearshore hardbottom dependent populations of juvenile tropical reef fish (lutjanids, serranids, scorpeanids, gobiids, blenniids and labrisomids) show a positive relationship with salinity, e.g., higher densities at higher salinities. Extreme and rapid salinity fluctuations may degrade SAV habitat that many estuarine utilize as fish spawning, nursery and/or foraging habitat. The SLE, especially the upper reaches, contains a low diversity of predominantly pollution-tolerant benthic macroinvertebrates that are sand/mud associates. The fish community is commonly comprised of a low diversity of lower trophic level taxa preying on plankton and mid trophic level taxa feeding on invertebrates associated with sand/mud habitats. SAV-associated fishes and invertebrates (and their respective ontogenetic stages) are generally restricted to the lower estuary where seagrasses exist. In the SLE, high flow events (>2500 cfs from S-80) are associated with changes in fish and invertebrate community structure and abundance. For example, following an elevated flow event high densities of tubiculous Corophiid amphipods often replace seagrasses that normally occur between Hell Gate Point and the Bessemer spoil islands. Fishes become more widely distributed and freshwater associates move downstream into the middle estuary. In the upper Caloosahatchee Estuary, similar to the SAV community neither the fish nor the invertebrate communities have recovered from the 1999/2000 drought and its restricted flows as evidenced by limited biodiversity and the absence of freshwater species. In the lower estuary recent high flows have resulted in a decline in fish communities in terms of both diversity and abundance with at least one study (Robbins et al. 2006) suggesting a 54% decline in fish species abundance between 2005 and 2006). Time series analyses indicated a significant effect of seagrass density and salinity on seatrout growth in the lower Caloosahatchee estuary (Bortone et al. 2006).



SUBMERGED AQUATIC VEGETATION CONCEPTUAL MODEL

4.0 Evaluation Application

4.1 Evaluation Protocol

(See NE Salinity Envelopes Performance Measure for evaluation protocol)

Vallisneria americana Model: *Vallisneria americana* (wild celery) density was modeled under different environmental conditions using a numerical, process-based ecological model developed for the upper Caloosahatchee River. The model consists of a system of three simultaneous differential equations (finite difference), one for each of three state variables, solved by Euler numerical integration with a time step of 1 day. State variables represented by the model are: total biomass, number of rosettes (density), and number of blades (blade density). Primary inputs include water temperature, incident photosynthetically active radiation (PAR), secchi disk depth, water depth, and salinity. Site-specific in situ data and empirical laboratory data are integrated within the model. The *V. americana* model was first applied as part of the Caloosahatchee MFL update (SFWMD, 2003) to evaluate the effect of initial CERP alternatives on *V. americana* densities for two locations in the upper Caloosahatchee River. It has also been used to explore the effect of multiple environmental variables (light, salinity, and temperature) on the growth, survival, and re-establishment of this species within the upper Caloosahatchee estuary (Hunt and Doering, 2005). The existing model is currently being updated to include new experimental information. If complete input data are not available for the period of record to be assessed, ways to represent such data need to be developed dependent on the application objective. It may be possible to utilize this model with some modifications in other northern estuaries depending on available input and calibration data, and time constraints.

Halodule wrightii Model: Development of a numerical model for *H. wrightii* (shoal grass) is ongoing with the anticipation of similar function and capability to the *V. americana* model described above. Initially the model will be calibrated to several locations within the Caloosahatchee Estuary. It may be possible to utilize this model with some modifications in other northern estuaries depending on available input and calibration data.

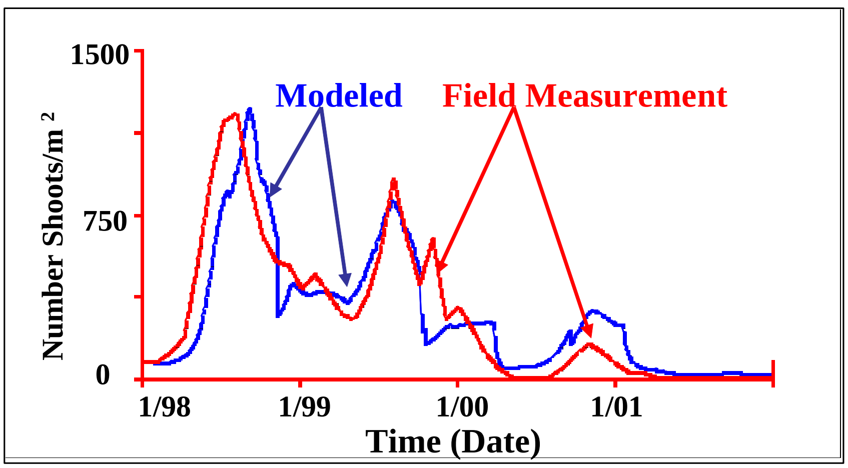
4.2 Normalized Performance Output

(See NE Salinity Envelopes Performance Measure for normalized performance output).

4.3 Model Output

(See NE Salinity Envelopes Performance Measure for model output)

Example of *V. americana* Model Output



Comparison of modeled and field measurements for *V. americana* shoot density from 1 January 1998 through 31 December 2001 at Station 2 in the Upper Caloosahatchee Estuary

Reference: Hunt, M. J. and P. H. Doering. 2005. Significance of considering multiple environmental variables when Using habitat as an indicator of estuarine condition. In Estuarine Indicator (ed) S. A. Bortone. CRC Press, Boca Raton, Florida. p 221-227

4.4 Uncertainty

(See NE Salinity Envelopes Performance Measure for uncertainty).

5.0 Monitoring and Assessment Approach

5.1 MAP Module and Section

See CERP Monitoring and Assessment Plan: Part 1 Monitoring and Supporting Research - Northern Estuaries Module section 3.3.3.3 through 3.3.3.5 (RECOVER 2004a). There have been a number of monitoring programs for SAV, some of which sporadically extend back to 1986. This historical monitoring includes in-water quantitative measurements within random quadrants. Hydroacoustic surveys of SAV began in 1996 and more recently aerial surveys are conducted every two years.

See *The RECOVER Team's Recommendations for Interim Goals and Interim Targets for the Comprehensive Everglades Restoration Plan* – Interim Goal 1.2 Submerged Aquatic Vegetation in Northern Estuaries (RECOVER 2005).

5.2 Assessment Approach

NA

6.0 Future Tool Development Needed to Support Performance Measure

6.1 Evaluation Tools Needed

SAV models for key species including but not limited to *Vallisneria*, *Syringodium* and *Halodule*. These models should predict effects of freshwater inputs (light, nutrients, and salinity) on wild celery and seagrass growth.

Biomass Models: Understanding the temporal dynamic of SAV is important to managers and researchers within this context, a metric such as biomass is important in that it does not vary linearly with changes in SAV areal extent thus allowing managers and researchers to discriminate potential spatial and temporal changes across a system (Moore et al. 1998). Understanding these dynamics is important if a SAV model is to be coupled or sub-modeled with another model (e.g. basic eutrophication model; see Malmgren-Hansen and Dahl- Madsen 1983). Biomass models include two components: aboveground (e.g. shoots) and belowground (e.g. rhizomes and roots) with one (e.g. Bach 1993) or both (e.g. Bocci et al. 1997) used to study temporal dynamics.

Biomass (or production) models (Bach 1993) typically utilize blade growth as a surrogate for production of an individual shoot. If used alone, this relationship restricts the model as static rather than dynamic. This may or may not be important depending upon the model's application. However, it should be noted that there is a strong seasonal dynamic in mean biomass that can be attributed to light and water temperature (Sand-Jensen and Borum 1983) and nutrient availability (Harlin and Thorne-Miller 1981; Orth 1977). Other factors that impact seagrass growth include environmental (water depth, salinity, wave action, etc.) and physiological variables (reproductive state, shoot age, etc.). Less studied is the influence of shoot density (*i.e*., space limitation *sensu* Bocci et al. 1997) on seagrass growth.

Light Models: The most common light model for SAV is the *Hsat* model (Dennison and Alberte 1982, 1985), which uses the daily light period coupled with a calculation of seagrass production to model seagrass growth. Unfortunately, the *Hsat* model is not robust enough to explain site-specific variation in the minimum light requirements of SAV (Herzka and Dunton 1998), and as such cannot accurately predict depth limits of growth and/or light requirements (Zimmerman et al. 1989, 1991). The *Hsat* model also suffers in that it was developed for *Zostera marina*, which limits its applicability to other SAV species. Although some researchers have begun to apply the model to other species such as *Halodule wrightii* (Herzka and Dunton 1998) more effort needs to be expended.

Additional Work: We really need to strengthen our understanding of when seagrasses (i.e., *Syringodium filiforme*) are stressed and experience mortality. This could be accomplished through additional field work and through mesocosm experiments.

6.2 Assessment Tools Needed

Same as above (6.1)

7.0 Notes

This Performance Measure supersedes and addresses NE-15 Northern Estuaries Submerged Aquatic Vegetation (Last Date Revised: September 21, 2005).

8.0 Working Group Members

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9.0 References

Bach, HK (1993) A dynamic growth model describing the seasonal variation in growth and the distribution of eelgrass (*Zostera marina* L.) I. Model theory. Ecological Modeling 65:31-50

Beal, J.L. and B.S. Schmit. 2000. The effects of dock height and light irradiance (PAR) on seagrass (*Halodule wrightii* and *Syringodium filiforme*) cover, p.49-63. In S. Bortone (ed.), Seagrasses: Monitoring, Physiology and Management, CRC Press, Boca Raton.

Bocci, M, Coffaro, G, Bendoricchio, G (1997) Modeling biomass and nutrient dynamics in eelgrass (*Zostera marina* L.): applications to the Lagoon of Venice (Italy) and Oresund (Denmark). Ecological Modeling 102:67-80

Bortone, S.A., A.J. Martignette, and J Spinelli. 2006. Spotted seatrout (Family Scianidae) growth as an indicator of estuarine conditions in San Carlos Bay, Florida. Florida Scient. 69(00S2) 126-139.

Bortone, S.A., and R.K. Turpin. 1999. Tape grass life history metrics associated with environmental variables in a controlled estuary. In: Bortone, S.A. (ed). Seagrasses: Monitoring, Ecology, Physiology, and Management. CRC Press, Boca Raton, Florida, pp. 65-79.

Carlson, P. R., L. A. Yarbro, and T. R. Barber. 1994. Relationship of sediment sulfide to mortality of *Thalassia testudinum* in Florida Bay. Bulletin of Marine Science 54:733–746.

Dennison, WC and Alberte, RS (1982) Photosynthetic responses of *Zostera marina* L. (eelgrass) to in situ manipulations of light intensity. Oecologia 55:137-144

Dennison, WC and Alberte, RS (1985) Role of daily light period in the depth distribution of *Zostera marina* (eelgrass). Marine Ecology Progress Series 25:51-61

Bulthius, D. A. 1987. Effects of temperature on photosynthesis and growth of seagrasses. Aquat. Bot. 27:27-40.

Dennison, W.C. , R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Batuik. 1993. Assessing water quality with submersed aquatic vegetation. Bioscience 43:86-94.

Dixon, L.K. Establishing light requirements for the seagrass *Thalassia testidinum*: an example from Tampa Bay, FL, p. 9-31. In S. Bortone (ed.), Seagrasses: Monitoring, Physiology and Management, CRC Press, Boca Raton.

Dixon L.K. and Kirkpatrick, G.J. 1999. Causes of light attenuation with respect to seagrasses in upper and lower Charlotte Harbor. Submitted to Southwest Florida Water Management District, Surface Water Improvement and Management Program, Sept. 20, 1999. Mote Marine Laboratory Technical Report #650.

Doering, P. H. 2005. Significance of considering multiple environmental variables when using habitat as an indicator of estuarine condition. In Estuarine Indicators. S. A. Bortone (ed.), CRC Press, Boca Raton FL.

Doering, P. H., Chamberlain, R. H., Donohue, K. M. and Steinman, A. D. 1999. Effect of salinity on the growth of *Vallisneria americana* michx. from the Caloosahatchee Estuary, Florida. Florida Scientist 62(2):89–105Dunton, K.H. 1994. Seasonal growth and biomass of the subtropical seagrass *Halodule wrightii* in relation to continuous measurements of underwater irradiance. Mar. Bio. 120:479-489.

Gallegos, C.L. and W.J. Kenworthy. 1996. Seagrass depth limits in the Indian River Lagoon: application of an optical water quality model. Estuarine, Coastal and Shelf Sci 42:267-288.

Goodman, J.L., Moore, K.A. and Dennison, W.C., 1995. Photosynthetic responses of eelgrass (*Zostera marina* L.) to light and sediment sulfide in a shallow barrier island lagoon. Aquat. Bot. 50(1):37-48.

Harlin, M. M., Hunt, M. J. and Thorne-Miller, B. 1981. Nutrient enrichment of seagrass beds in a Rhode Island coastal lagoon. Mar. Biol. 65:221-229.

Hestand, R. S. and Carter, C. C. 1978. Comparative effects of grass carp and selected herbicides on macrophyte and phytoplankton communities. Journal of Aquatic Plant Management 16:43-50.

Herzka, S. Z. and Dunton, K. H. (1998) Light and carbon balance in the seagrass *Thalassia testudinum*: evaluation of current production models. Marine Biology 132:711-721.

Hunt, M. J. and P. H. Doering. 2005. Significance of considering multiple variables when using habitat as an indicator of estuarine condition. In Estuarine Indicators. S. A. Bortone, (ed.). CRC Press, Boca Raton, FL

Irlandi, E. 2006. Literature Review of Salinity Effects on Submerged Aquatic Vegetation (SAV) found in the Southern Indian River Lagoon and Adjacent Estuaries. Final Report to South Florida Water Management District. West Palm Beach, Florida.

Kemp, W. M., R. Batiuk, R. Bartleson, P. Bergstrom, V. Carter, C. Gallegos, W. Hunley, L. Karrh, E. W. Koch, J. M. Landwehr, K. A. More, L. Murray, M. Naylor, N. B. Rybicki, J. C. Stevenson, and D. J. Wilcox. 2004. Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors. Estuaries 27: 363–377.

Kenworthy, W.J. 1994. Conservation and restoration of the seagrasses of the Gulf of Mexico through a better understanding of their minimum light requirements and factors controlling water transparency, p. 17-31. In H.A. Neckles (ed.), Indicator development: seagrass monitoring and research in the Gulf of Mexico. EPA/620/R-94/029.

Kenworthy, W.J. and M.S. Fonseca. 1996. Light requirements of seagrasses *Halodule wrightii* and *Syringodium filiforme* derived from the relationship between diffuse light attenuation and maximum depth distribution. Estuaries 19(3):74-750.

Kenworthy, W.J. and D.E. Haunert (eds.). 1991. The light requirements of seagrasses workshop proceedings. NOAA Tech Memorandum NMFS-SEFC-287.

Larkum, A. W. D., McComb, A. J., and Shepherd, S. A. 1989. Biology of seagrasses. Elsevier, Amsterdam.

Lefebvre, L. W., Reid, J. P., Kenworthy, W. J., Powell, J. A. 2000. Characterizing manatee habitat use and seagrass grazing in Florida and Puerto Rico: implications for conservation and management. Pacific Conservation Biology 5(4):289-298.

Lirman, D. and W. P. Cropper Jr. 2003. The influence of salinity on seagrass growth, survivorship and distribution within Biscayne Bay, Florida: Field, experimental and modeling studies. Estuaries 26:131–141.

Malmgren-Hansen, A. and Dahl-Madsen, K. I. 1983. Modeling the consequence of cooling water discharge from the “Vendsyssel” power plant. Water Science Technology 15:177-196.

Moore, K. A., Wilcox, D .J. and Orth, R. J. 1998. Biomass of submerged aquatic vegetation in the Chesapeake Bay: Final Report. CB993267-02 Chesapeake Bay Program, U.S. EPA, Annapolis, MD.

Morris, L. J. and D. A. Tomasko (eds.). 1993. SAV and PAR workshop proceedings. SJRWMD special publication SJ93-SP13.

Onuf, C. P. 1996. Seagrass responses to long-term light reduction by brown tide in upper Laguna Madre, TX: distribution and biomass patterns. Mar. Eco. Prog. Ser. 138:219-231.

Orth, R. J. 1977. Effect of nutrient enrichment on growth of the eelgrass *Zostera marina* in the Chesapeake Bay, Virginia, USA. Marine Biology 44:187-194.

Neckles, H. A., Wetzel, R. L. and Orth, R. J. 1993. Relative effects of nutrient enrichment and grazing on epiphyte-macrophyte (*Zostera marina* L.) dynamics. Oecologia 93(2):285-295.

Ridler, M. S., R. C. Dent and D. A. Arrington. 2006. Effects of Two Hurricanes on *Syringodium filiforme*, Manatee Grass, Within the Loxahatchee River Estuary, Southeast Florida. Estuaries and Coasts 29(6A):1019–1025.

Robbins, B. D., Gittler, M., and Boyes, A. 2006. Caloosahatchee River and Estuary Research. Y2 Annual Letter Report. Submitted to South Florida Water Management District, CP-050281, October 2006. Mote Marine Laboratory Technical Report No. 1142.Sand-Jensen, K and Borum, J (1983) Regulation of growth of eelgrass (*Zostera marina* L.) in Danish coastal waters. Marine Technology Society Journal 17: 15-21.

Short, F. T., Dennison, W. C. and Capone, D. G. 1990. Phosphorus-limited growth of the tropical seagrass *Syringodium filiforme* in carbonate sediments. Mar. Ecol. Prog. Ser. 62:169-174.

RECOVER. 2004a. CERP Monitoring and Assessment Plan: Part 1 Monitoring and Supporting Research. Restoration Coordination and Verification Program, c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida.

RECOVER. 2004b. Draft Conceptual Ecological Models. In: RECOVER. CERP Monitoring and Assessment Plan: Part 1 Monitoring and Supporting Research, Restoration Coordination and Verification Program, c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida, Appendix A.

RECOVER. 2005. The RECOVER Team's Recommendations for Interim Goals and Interim Targets for the Comprehensive Everglades Restoration Plan, c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida.

SFWMD, 2003. Technical Documentation to Support Development of Minimum Flows and Levels for the Caloosahatchee River and Estuary, Draft Status Update Report. South Florida Water Management District, West Palm Beach Florida. May 2003.

SJRWMD and SFWMD. 2002. Indian River Lagoon Surface Water Improvement and Management (SWIM) Plan Draft 2002 Update. St. John's River Water Management District, Palatka, FL, and South Florida Water Management District, West Palm Beach, Florida.

Terrados, J., C. M. Duarte, L. Kamp-Nielsen, N. S. R. Agawin, E. Gacia, D. Lacap, M. D. Fortes, J. Borum, M. Lubanski and T. Greve. 1999. Are seagrass growth and survival constrained by the reducing conditions of the sediment? Aquat. Bot. 65:175-197.

Virnstein, R.W., and L.J. Morris. 1996. Seagrass Preservation and Restoration: a Diagnostic Plan for the Indian River Lagoon. Technical Memorandum 14, St. Johns River Water Management District, Palatka, Florida.

Woodward-Clyde, Inc. 1999. Distribution of oysters and Submerged Aquatic Vegetation in the St. Lucie Estuary. Final Report to South Florida Water Management District, Contract No, C-7779, West Palm Beach, Florida.

Zimmerman, R. C., Smith R. D. and Alberte, R. S. 1989. Thermal acclimation and whole-plant carbon balance in *Zostera marina* L. (eelgrass). Journal of Experimental Marine Biology and Ecology 130:93-109.

Zimmerman, R .C., Cabello-Pasini, A., Alberte, R. S. 1994. Modeling daily production of aquatic macrophytes from irradiance measurements: a comparative analysis. Marine Ecology Progress Series 114:185-196.