WATER DEPTH (MTL) AT THE DEEP EDGE OF SEAGRASS MEADOWS IN TAMPA BAY MEASURED BY DIFFERENTIAL GPS PHASE PROCESSING: EVALUATION OF THE TECHNIQUE

FINAL REPORT

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EXECUTIVE SUMMARY

The Tampa Bay Estuary Program (TBEP) has selected seagrass restoration target depths for each major bay segment at which adequate light conditions (20.5% of subsurface PAR irradiance) shall be maintained to ensure seagrass growth and the long-term Tampa Bay seagrass restoration goal of 15,400ha.

To evaluate the progress towards the seagrass restoration goal, information on today's seagrass depth distribution is needed. Specifically, a need exists to accurately determine the water depth at the deep edge of the meadows for each different seagrass species in different sections of the bay. This depth information, combined with light attenuation data from routinely conducted water quality monitoring programs, can be used to relate current Tampa Bay water quality conditions to the TBEP seagrass restoration goal. Further, light requirements for different seagrass species in the major bay segments may also be determined.

A relatively simple technique that provides elevation measurements related to the mean tide level (MTL), of Tampa Bay seagrass meadows is described and evaluated. The technique uses mapping grade differential Global Positioning System (GPS) phase processing equipment that is currently owned by several TBEP partners. This study may be the first to utilize GPS phase processing methodology for determination of seagrass elevations.

The elevation of a specific seagrass location is determined by placing one GPS instrument as a base station at a surveyed bench mark with a known altitude above MTL and a second instrument at the seagrass site to be surveyed. Tests of measurement errors suggest that the technique yields elevation measurements with an error that is less than +/- 10cm for survey sites located up to 10km from bench mark sites. Further, repetitive elevation measurements (n=2) conducted at four specific seagrass areas resulted in a standard deviation of the determined elevations that ranged from 3 to 4cm and a coefficient of variation that ranged from 4.1 to 7.7%.

Field evaluations of the technique were conducted at ten Tampa Bay seagrass study sites, that included measurements in the four major bay segments and the deep edge of the three major Tampa Bay seagrass species, Halodule wrightii, Thalassia testudinum, and Syringodium filiforme. Further, numerous bench mark locations were inspected and evaluated for suitability as GPS base station locations.

Relatively shallow deep edges of H. wrightii meadows were found in the upper section of Hillsborough Bay (-0.30 to -0.34mMTL) and at intermediate depths in lower Hillsborough Bay and at the Wolf Branch area in northeastern Middle Tampa Bay, just south of Hillsborough Bay (-0.48 to -0.58mMTL). The deepest H. wrightii surveyed was found at Big Island in western Old Tampa Bay and at Port Manatee in eastern Lower Tampa Bay (-0.71 to -0.76mMTL). Deep edges of T. testudinum meadows ranged from -1.53mMTL at Bel Mar Shores in eastern Old Tampa Bay to -1.73mMTL at Port Manatee. Isolated patches of T. testudinum located on the shallow sandbar at Picnic Island in southeastern Old Tampa Bay and at the Wolf Branch area.
were found at considerably shallower elevations (-0.53 to -0.90mMTL). Deep edges of _S. filiforme_ meadows in eastern Old Tampa Bay and Port Manatee ranged from -1.19 to -1.46mMTL. However, the deepest _S. filiforme_ edges were found outside the well developed offshore sandbars at Coffeepot Bayou and Coquina Key on the western side of Middle Tampa Bay. The depth of these edges ranged between -1.79 and -1.81mMTL at Coffeepot Bayou and between -1.93 and -1.96mMTL at Coquina Key. The latter measurements were the deepest seagrass elevations recorded in this study.

All sites surveyed had deep edge elevations shallower than the TBEP seagrass restoration target depth for the respective bay segment. The greatest deviation from the target depth was found in western Old Tampa Bay, where the deep edges of the _H. wrightii_ meadows were about 1.30m shallower than the -2.0mMTL target depth selected for this bay segment. The least deviation was found at three sites: the _H. wrightii_ meadow in southeastern Hillsborough Bay, the _T. testudinum_ meadow at Bel Mar Shores in eastern Old Tampa Bay, and the _S. filiforme_ meadow at Coquina Key in southwestern Middle Tampa Bay. These three areas had deep edges that were approximately 0.50m shallower than the respective bay segment targets.

The estimated average percent of subsurface incident light available at the deep edges of the surveyed seagrass meadow was estimated from elevation measurements and water column light attenuation data. Light availability at the _H. wrightii_ meadows ranged from 59.8 to 28.9% and was substantially above the adopted TBEP seagrass restoration light target of 20.5%. Deep edges of _T. testudinum_ at Bel Mar Shores and Port Manatee appeared to receive less light than the target (19.0 to 16.9%). The deep _S. filiforme_ meadows at Coquina Key and Coffeepot Bayou received the least amount of light of all study sites, 16.7 and 16.2%, respectively.

The differential GPS phase processing technique was field practicable and measured seagrass elevations with acceptable quality. Further, the field evaluation provided an important first-step in understanding the current depth distribution of the major Tampa Bay seagrass species. However, many more elevation measurements should be conducted to yield a more complete understanding of the seagrass depth distribution in the bay. Recommendations for additional elevation measurements have been outlined below.

Recently, seagrass recovery has stagnated in several areas of Tampa Bay, despite ambient water quality and light availability conditions that appear adequate to support continued seagrass expansion. One theory proposed for the poor expansion focuses on the importance of the offshore unvegetated sand bar to protect the main seagrass meadow from wave action and to allow seagrass to expand into deeper waters. However, studies examining the dynamics of the shallow sand bars and their interaction with the development of seagrass meadows are lacking for Tampa Bay.

Additional elevation measurements are recommended to learn more about the seagrass depth distribution and the dynamics of the shallow sand bars in Tampa Bay. The GPS phase processing technique could be used to establish permanent elevation markers at most, if not all, of the nearly
60 bay-wide seagrass monitoring transects included in the cooperative Tampa Bay seagrass monitoring program. Once these were established, traditional level and rod elevation surveys could be conducted periodically to accurately and quickly determine the topography of each transect. Further, deep edge elevation measurements for the different seagrass species found on each transect could easily be incorporated during the topography measurements.

The proposed elevation measurements will provide important information to compliment the high altitude aerial seagrass photography conducted every two years by the Southwest Florida Water Management District and the yearly cooperative Tampa Bay seagrass transect monitoring program conducted by TBEP partners and others. Combined, the three programs would become a powerful tool to evaluate the progress of the Tampa Bay water quality and seagrass restoration effort.
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INTRODUCTION

The Tampa Bay Estuary Program (TBEP) has adopted a long-term Tampa Bay seagrass restoration goal of 15,400ha, which is approximately 95% of the estimated Tampa Bay seagrass cover present in 1950. Protection of the 10,400ha existing in 1994 and the restoration of an additional 5,000ha will primarily be accomplished through management of external nitrogen loadings and bay water quality.

The Tampa Bay seagrass restoration goal was established through a multi-step process that included the identification of specific seagrass restoration areas from comparisons of ca. 1950 and 1990 high altitude aerial photography. Areas that had lost seagrass over the 40 year period, and that had not been physically altered to prevent future seagrass recolonization were selected for restoration (Janicki and Wade 1996). It was further determined, through field studies conducted in Lower Tampa Bay, that Thalassia testudinum required a minimum of 20.5% of subsurface irradiance to ensure healthy growth (Dixoo 2000). This finding was adopted by the TBEP as an overall Tampa Bay seagrass light requirement target. Subsequently, water quality conditions and external nitrogen loading rates required to sustain a minimum of 20.5% of subsurface irradiance at the seagrass restoration areas in the major bay segments were determined from empirical models (Janicki and Wade 1996).

To link the seagrass restoration areas with the water quality and nitrogen loading based light target, it was necessary to determine to what depth seagrass grew in 1950. The 1950 seagrass depth distribution was estimated from apparent seagrass areas visible on ca.1950 high altitude vertical photographs that were overlaid on NOAA National Ocean Survey (NOS) sounding data collected between 1947 and 1958. The soundings were corrected to mean tide level (MTL) (Janicki and Wade 1996).

Estimates of the 1950 seagrass depth distribution were then used to develop bay segment specific seagrass target depths for Tampa Bay (Janicki and Wade 1996). The adopted approximate target depths were: 1.0m(MTL) for Hillsborough Bay, 2.0m(MTL) for Old Tampa Bay, 1.6 to 2.4m(MTL) for Middle Tampa Bay (depending on sub-segment), and 2.5m(MTL) for Lower Tampa Bay (see Fig 4 for location of bay segments). The Tampa Bay seagrass restoration goal will be accomplished when the deep edges of the seagrass meadows, delineated from the Southwest Florida Water Management District (SWFWMD) high altitude aerial photography, eventually extend to these depths in the respective bay segments.

The estimated 1950 Tampa Bay seagrass depth distribution was important for the development of the TBEP seagrass restoration and protection goal. Likewise, information on today’s seagrass depth distribution is needed to evaluate the progress of the seagrass restoration process. Present-day depth information would yield a comparison to the estimated seagrass depth distribution in 1950. However, more importantly, the present seagrass depth information combined with light attenuation data from routinely conducted water quality monitoring programs, could be used to calculate the percentage subsurface irradiance available for different seagrass species found in the
different bay segments. This information would relate current water quality conditions to the TBP seagrass restoration goal and serve as a check on the Tampa Bay resource-based management plan (Johansson and Greening 2000). Also, seagrass depth measurements could be used to estimate specific seagrass species light requirements in the major bay segments, and therefore, complement the T. testudinum light requirement studies in Lower Tampa Bay (Dixoo 2000). Finally, seagrass elevation measurements would also compliment the cooperative Tampa Bay permanent seagrass transect monitoring program by providing elevation reference points on the transects (see City of Tampa 2000 and Avery et al. in prep). These reference points could be used for detailed measurements of seagrass elevations and also to measure potential sediment losses or gains along the transects. Lewis et al. (1985) suggested that erosion of offshore unvegetated sandbars, that separates the main seagrass meadow from the open bay waters, may have reduced seagrass coverage in the basin between the bar and the shore.

The present study evaluated a relatively simple and practical field technique to measure the depth to which seagrass meadows extend in Tampa Bay. The technique uses mapping grade differential Global Positioning System (GPS) equipment (Trimble Pathfinder PRO XR) to measure elevations related to a defined tidal datum (MTL). The current cost of the system is approximately $11,000 and several TBP partners have purchased the system. The study included evaluations of measurement errors and numerous field surveys that measured seagrass elevations in the four major bay segments and for the three major Tampa Bay seagrass species, Halodule wrightii, T. testudinum, and Syringodium filiforme. Further, numerous bench mark locations were inspected and evaluated near the periphery of the bay for suitability as GPS base station locations.

METHODS

Determination of Measurement Errors

Trimble specifications for the GPS Pathfinder PRO XR system with carrier phase processing reports the accuracy of position determinations, expressed as root mean square error (RMS), as 10cm+5ppm with 20 minutes of satellite tracking (occupation time). The 5ppm error is caused by the distance between the base and the rover stations (baseline) and equals 0.5cm of error for each kilometer of separation. To achieve 10cm+5ppm accuracy, a minimum of 5 satellites should be tracked, PDOP (position dilution of precision), which is a measure of the current satellite geometry, should be less or equal to 6, the signal to noise ratio, which is a measure of the of the strength of the satellite signal relative to the background noise, should be less or equal to 6, and the satellite elevation mask, which excludes satellites low on the horizon, should be set at 15 degrees. Further, optimal accuracy is obtained by collecting data in an environment that has a clear view of the sky and that is devoid of large reflective surfaces, such as buildings, that extend above the satellite elevation mask.

The Trimble specifications do not differentiate between horizontal and vertical accuracy levels for carrier phase processing. However, a report that characterizes the accuracy of the Trimble PRO
XR receiver (Trimble 1997) states that the vertical error for phase processing solutions is similar to the horizontal error. The report also shows that the accuracy increases with increasing occupation time. As shown in Fig. 1, modified from Trimble (1997), an error of less than 5cm RMS can be expected with an occupation time of 30min. For these tests, Trimble used a relatively short baseline (less than 1km), 5 or more satellites, a maximum PDOP of 4, and the satellite elevation mask set at 15 degrees for the rover station and at 10 degrees for the base station.

Thirty-five tests were conducted over several days on the roof of the City of Tampa Bay Study Group (COT) laboratory to specifically test the vertical measurement performance of the PRO XR system (Fig. 2). This location provided a clear view of the sky and lacked potentially interfering reflective surfaces. Two PRO XR instruments were placed on the roof at a location with a known MTL elevation. The phase centers (the location within the antenna where the receiver detects the GPS signal) of the two antennas were located at near identical elevations and separated less than 1.0m horizontally. One instrument was used as a base station and the other as a rover station. The instruments were configured to the Trimble recommendations (see above and Trimble 1996). As recommended in the Trimble manual, the base station instrument had the satellite elevation mask set at 10 degrees. Further, predicted daily satellite schedules were examined prior to testing to insure optimum data collection periods (Fig. 3). Generally, periods with a minimum of 6 available satellites and a PDOP of less than 3 were selected for data collections. These requirements should provide measurements with an accuracy comparable to that reported by Trimble (1997). The satellite data collection period for the 35 tests ranged from 30 to 41 minutes.

The potential baseline errors affecting the seagrass elevation measurements in the current study were not tested specifically (see below). This error was assumed to be 5mm, or 0.5cm for each kilometer of separation between the base and rover stations, as specified by Trimble (1997).

Seagrass elevation measurements were replicated with n=2 at four specific seagrass sites to estimate the variability of field measurements, including variations caused by GPS errors and other errors, such as antenna height measurements. At one of these sites, measurements were repeated on two separate dates with the base station located at two different bench mark locations.

**Measurements of Seagrass Elevations**

A total of 38 seagrass elevation measurements were performed in Tampa Bay between October 1999 and February 2000 (Table 1). Measurements were conducted at ten general areas in the four major bay segments (Fig. 4). Most study areas were located at, or close to, an established Tampa Bay fixed seagrass transect (see City of Tampa 2000 and Avery et al. in prep) and included different seagrass species when present. Two study areas were located in Hillsborough Bay, four in Old Tampa Bay, three in Middle Tampa Bay, and one in Lower Tampa Bay. Of the 38 measurements, 21 were conducted on *H. wrightii*, eight on *T. testudinum*, and nine on *S. filiforme*. Twenty-nine measurements were conducted at distinctive deep edges of either large
seagrass areas (meadows) or isolated smaller areas (patches) that were visible on recent, most often 1999, aerial photographs. The remaining nine measurements were done in seagrass areas other than the defined deep edge. These included measurements near the center of *H. wrightii* and *T. testudinum* patches in Hillsborough Bay and Middle Tampa Bay; and at the shallow edge of a *H. wrightii* meadow in Hillsborough Bay.

Prior to conducting the field measurements at the selected seagrass areas, suitable bench marks had to be located, preferably within 50m of the survey sites in order to minimize the baseline error. Several publications and sources of bench marks were examined; however, NOS tidal bench marks were the primary type used (see www.opsd.nos.noaa.gov). The NOS bench marks are referenced to mean lower low water and mean high water, however, the MTL elevation can easily be calculated from the tide station data provided for each set of bench marks. The NOS bench marks are not directly referenced to the National Geodetic Vertical Datum (NGVD)-29 datum, although, several tide stations (e.g. St. Petersburg and Ballast Point) have been tied to NGVD-29. The lack of a direct reference to NGVD-29 for some of the tidal bench marks used was not of concern since the purpose of the study was to estimate the depth of the water above the seagrass meadows at the MTL.

After the selection of a suitable bench mark location, it was necessary to visit the bench mark site and locate (recover) the specific marker to be used and also to determine that the location was suitable for GPS observations (i.e. a relatively open area with a clear view of the sky and with no large reflective surfaces near). Most bench mark locations were not directly usable for GPS observations and a suitable location for the base station had to be marked and offset from the bench mark by using standard level (Carl Zeiss N2) and rod surveying techniques. All offset distances were relatively short (<200m) and all level readings were duplicated.

Elevation measurements at the ten selected seagrass study sites (Fig. 4) followed the establishment of base stations. Figs. 5 through 14 are aerial photographs of the survey sites that show the approximate locations of the seagrass elevation measurements. The specific locations to be measured within each seagrass study site (most often the deep edge of the meadow), were determined in the field by comparing aerial photographs of the area with on-site observations. The majority of the seagrass study sites had a very distinct and easily defined deep edge of the meadow, however, several sites had sparse (low shoot density) seagrass coverage that extended from the edge of the meadow into deeper waters. This sparse seagrass coverage was not considered to be part of the defined meadow.

Typical set-ups of the GPS instruments for measurements of the deep edge of seagrass meadows are illustrated in Fig. 15 and 16. The base station was placed with its antenna vertically above the bench mark and the rover station was placed on a tripod above the sea surface with its antenna vertically above the seagrass edge to be measured. As illustrated in Fig. 15, the base station antenna height (A), i.e. the distance between the antenna phase center and the center of the bench mark, was measured, using a weighted metric tape measure, and recorded. Similarly, the rover station antenna height (C), i.e. the distance between the antenna phase center and the top of the
sediment at the seagrass site, was also measured and recorded. The instruments were configured
to Trimble recommendations (Trimble 1996) and the daily satellite schedule was examined prior
to data collections to ensure optimum data collection periods (see above). Static satellite
observations were conducted for a period, sufficiently long, to ensure that the two stations
collected at least 30 minutes of overlapping data.

The collected satellite data was analyzed using the Trimble software products Pathfinder Office v.
2.1 and Phase Processor v. 2. The software calculated the relative elevation difference between
the two antennas (D in Fig. 15). Since the MTL elevation of the bench mark (B) was known and
the antenna heights (A and C) had been measured in the field, the MTL elevation of the deep edge
of the seagrass meadow (X) could easily be calculated using the equation shown in Fig. 15.

RESULTS

Measurement Errors

Results from the 35 tests conducted on the roof of the laboratory to determine elevation
measurement errors of the PRO XR system are shown in Fig. 17. As previously discussed,
the two instruments were assumed to be at identical elevation during all tests, i.e. the true elevation
difference was 0m. Measured elevation differences ranged between +6.0 to -2.7cm. The average
difference of the 35 tests was 0.2cm (SMTD 2.1cm). The 95% confidence interval ranged from 0 to
0.9cm, suggesting that the confidence interval contains the actual elevation 95% of the time.

The baseline error introduced during these tests was near zero since the two antennas were only
separated by less than 1.0m. However, the potential baseline error must be considered during field
measurements. Trimble reports this error to be 0.5cm for each kilometer of separation between
the base and rover stations. The baseline distance should, therefore, be kept as short as possible.
Baseline distances used during the seagrass elevation study ranged from 0.12 to 10.6km, resulting
in potential baseline errors ranging from 0.1 to 5.3cm. The average baseline distance of the 38
field measurements was 3.5km.

Results from the replicated seagrass elevation measurements with n>2 are discussed below.

Seagrass Elevations

Results from the 38 seagrass elevation measurements at the ten selected seagrass study sites are
shown in Table 2. The shallowest deep edge of the H. wrightii meadows was found in the upper
section of Hillsborough Bay (-0.30 to -0.34m MTL) and at intermediate depths in the lower
Hillsborough Bay and the north-eastern area of Middle Tampa Bay, just south of Hillsborough
Bay (-0.48 to -0.58m MTL). The deepest H. wrightii surveyed was found at similar depths at Big
Island in Old Tampa Bay and at Port Manatee in Lowers Tampa Bay (-0.71 to -0.76m MTL). Deep
edges of T. testudinum meadows were found at similar depths at Bel Mar Shores in eastern Old
Tampa Bay and at Port Manatee. Depths for these edges ranged from -1.53mMTL at Bol Mar Shores to -1.73mMTL at Port Manatee. Isolated patches of T. testudinum located on the shallow sandbar at Picnic Island and the Wolf Branch area were found at considerably shallower elevations (-0.53 to -0.90mMTL). Deep edges of S. filiforme meadows were also found at similar depths at the sites in eastern Old Tampa Bay and at Port Manatee. Depths for these edges ranged from -1.19 to -1.46mMTL. However, the deepest S. filiforme edges were measured at the two sites on the western side of Middle Tampa Bay. At Coffeepot Bayou the deep edge was found between -1.79 and -1.81mMTL and at Coquina Key between -1.93 and -1.96mMTL. The latter depths were the deepest seagrass elevations measured in this study.

Results from the four seagrass sites with replicated (n=2) elevation measurements (Table 2) show that the standard deviation of the determined elevations ranged from 3 to 4cm. The coefficient of variation for these measurements ranged from 4.1 to 7.7%. At one of these sites, the offshore bar in the Kitchen in southeastern Hillsborough Bay, four measurements were conducted in the center of different H. wrightii patches. Two of these measurements were performed with the base station located in Simmons Park, approximately 10.6km from the seagrass site. The other two measurements were performed on a different date and with the base station located on the Hillsborough Bay spoil island 3-D, approximately 2.7km from the seagrass site. The seagrass patch elevations based on the Simmons Park bench mark were -0.73 and -0.77mMTL; and elevations based on the 3-D bench mark were -0.69 and -0.73mMTL.

DISCUSSION

Technique Evaluation

Results from tests of measurement errors conducted by Trimble (Trimble 1997) and the present study, suggest that the technique using PRO XR instruments and Phase Processor software will yield seagrass elevation measurements with an error less than +/-10cm for survey sites located up to 10km from bench mark sites.

Further, the field evaluation of the technique, that included measurements of the deep edge of the three major Tampa Bay seagrass species, H. wrightii, T. testudinum, and S. filiforme in the four major bay segments found the method to be practical and that excellent replication of elevations were obtained when several measurements were taken in the same general area and also when different bench marks were used.

Seagrass Elevations

First, it should be recognized that the present study was primarily designed to evaluate the GPS phase processing technique and that seagrass elevation measurements were conducted at a limited number of Tampa Bay seagrass sites. Although, deep edge elevation measurements were conducted in all four major Tampa Bay segments and measurements included the three major
seagrass species, a much more intensive effort is required before comprehensive conclusions should be formulated about the Tampa Bay seagrass depth distribution. Elevation measurements should be conducted at most, if not all, of the nearly 60 the seagrass monitoring transects included in the Tampa Bay cooperative seagrass monitoring program. However, recognizing the limitations of the present study, several interesting findings warrant further discussion.

The deep edge elevations of the measured seagrass meadows ranged from -0.30m MTL for *H. wrightii* in the upper portion of Hillsborough Bay to -1.96m MTL for *S. filiforme* near Pinellas Point in Middle Tampa Bay. Further, all sites visited in the present study had deep edge elevations shallower than the TBEP seagrass restoration target depth for the respective bay segment. The greatest deviation from the target depth was found at the Long Branch and Big Island sites in western Old Tampa Bay, where the deep edges of the *H. wrightii* meadows were about 1.30m shallower than the -2.0m MTL target depth selected for this bay segment. The least deviation was found at three sites: the *H. wrightii* meadow in the Kitchen in southeastern Hillsborough Bay, the *T. testudinum* meadow at Del Mar Shores in eastern Old Tampa Bay, and the *S. filiforme* meadow at Coquina Key in southwestern Middle Tampa Bay. These three areas had deep edges that were approximately 0.50m shallower than the respective bay segment targets.

Similar deep edge depths were found for all three seagrass species at the Old Tampa Bay sites and the Port Manatee site in Lower Tampa Bay. This was surprising, considering the distance of these areas from the mouth of Tampa Bay. The Old Tampa Bay sites are approximately 50km from the mouth of the bay, while the corresponding distance for the Port Manatee site is only about 20km. It could be expected that water quality and light attenuation at the Port Manatee site would be superior due to its relative closeness to the Gulf of Mexico, and therefore, allow seagrass to grow deeper at this site. Analysis of Hillsborough County Environmental Protection Commission (HCEPC) water quality monitoring data, averaged over the last six years, generally supports this hypothesis. Light extinction (Secchi Disk depth), chlorophyll-a concentrations, and water color were all considerably lower near the Port Manatee site as compared to the Old Tampa Bay sites. However, turbidity was slightly higher near the Port Manatee site.

Additional elevation measurements of Lower Tampa Bay seagrass meadows may find deeper seagrass edges in this bay segment. Dixon (2000) conducted light requirement studies on *T. testudinum* sites in Lower Tampa Bay that ranged in depth from -1.98 to -2.37m MTL. These depths, which were estimated from sea surface observations, are approximately 0.3 to 0.6m deeper than the *T. testudinum* meadows surveyed at the Port Manatee site.

**Light Availability**

Light attenuation measurements of the water column directly above the deep edges of seagrass meadows in Tampa Bay are scarce. Light measurements are most often collected at deeper Tampa Bay sites during routine water quality monitoring. Light attenuation at the seagrass survey sites was, therefore, estimated from deeper site data. This method was previously used by the TBEP to establish the Tampa Bay seagrass restoration target (Janicki and Wade 1996; also see Giesen et al.
1990). In our study, monthly HCEPC Secchi Disk depths for the period 1994-1999 collected near the seagrass elevation survey sites were converted to light attenuation ($K_{epp}$) values using bay segment specific factors derived from concurrent Secchi Disk depth and PAR measurements by the COT at deep sites for the same six year period (Table 3 and Fig. 18).

The percentage of subsurface light remaining at the sediment surface at the deep edge of the seagrass meadows can be estimated from $K_{epp}$ and the seagrass elevation measurements using the Lambert-Beer equation:

$$I_z = I_0 e^{-Kz}$$

where:  
$I_z$ = the incident light at depth $z$  
$I_0$ = the incident light just below the surface  
$k$ = the diffuse PAR light attenuation coefficient  
$z$ = the depth (as mMTL) at $I_z$

The estimated average percent of subsurface incident light available at the deep edges of the seagrass meadows over the six year period 1994-1999 for the different seagrass survey sites and seagrass species are shown in Table 4. The available light at the deep edges of $H. wrightii$ meadows in all four bay segments ranged from 59.8 to 28.9% of subsurface incident light and was substantially above the adopted TBEF seagrass restoration light target of 20.5%. Deep edges of $T. testudinum$ at Belle Mar Shores in Old Tampa Bay and Port Manatee in Lower Tampa Bay appeared to receive less light than the target, 19.0 to 16.9%. The deep edges of $S. filiforme$ meadows at Coquina Key and Coffeepot Bayou in Middle Tampa Bay received the least amount of light of all study sites, 16.7 and 16.2%, respectively.

As discussed above, the estimated light availability at the deep edge of the seagrass meadows was calculated from Secchi Disk depth and PAR light attenuation data from the HCEPC and COT routinely conducted water quality monitoring programs at deep water sites. However, a limited amount of water quality information is available for the shallow near-shore areas in Tampa Bay that can be used to evaluate the assumption that water quality of the shallow areas is similar to the deep areas. The COT has measured chlorophyll-a and turbidity at five sites located on the nearshore sand bars in Hillsborough Bay on a monthly schedule since 1995. Three of these sites are located near deeper water quality monitoring stations. A comparison between the shallow and deep sites showed no consistent difference in chlorophyll-a concentrations. Turbidity on the other hand, was often higher and more variable at the shallow sites. Turbidity peaks in the shallow areas were often associated with strong wind events. The limited comparison from Hillsborough Bay suggests that the shallow and deeper water column light climate may at times be substantially different. Therefore, the use of water quality data from deep sites for estimating water column light attenuation at the seagrass meadows needs to be evaluated further by additional deep and shallow water quality comparisons.

The average percent of subsurface incident light available at the deep edges of the seagrass
meadows shown in Table 4 may not correspond to the minimum light requirement for maintaining sustained growth of the different Tampa Bay seagrass species. Determination of minimum light requirements for Tampa Bay seagrass species was beyond the scope of this study. Additional work is required to resolve uncertainties about extrapolating light availability data to seagrass light requirements. These uncertainties include, but are not limited to:

1. Light attenuation of the water column over the seagrass meadows may be different than that estimated from deep water data (see above).

2. The time period (six years) selected for calculating the average light attenuation of the water column above the seagrass meadow in this study may not properly reflect the lag-time of seagrass growth response to changes in light availability. The time-lag may be shorter or longer.

3. Seasonal light availability, specifically during the active seagrass growing season, may be more appropriate for estimating minimum seagrass light requirements than annual averaged values.

4. Epiphytic growth on the seagrass blades may have caused additional reductions in light availability.

Recommendations for Future Studies:

Recently, seagrass recovery has stagnated in several areas of Tampa Bay, despite ambient water quality and light availability conditions that appear adequate to support continued seagrass expansion. As shown above, the deep edges of the H. wrightii meadows in the Kitchen in southeastern Hillsborough Bay and the Wolf Branch area in eastern Middle Tampa Bay were estimated to receive an average 44 and 57% of the incident light, respectively. These light levels are considerably greater than the 20.5% light target adopted by the TBEP, however, no expansion of these meadows into deeper water have occurred over the last three to four years.

Many factors may limit seagrass expansion in Tampa Bay in addition to water quality. Lewis et al. (1985) discussed the importance of an offshore unvegetated sand bar, that separates the main seagrass meadow from the open bay waters, to protect the seagrass meadow by reducing wave impacts from storms and ship traffic. Destabilization and the ultimate loss of the bar may result in the shoreward migration of the seagrass meadow. However, studies examining the dynamics of the shallow sand bars and their interaction with the development of seagrass meadows are lacking for Tampa Bay.

Additional elevation measurements are recommended to learn more about the seagrass depth distribution and the dynamics of the shallow sand bars in Tampa Bay. The GPS phase processing technique could be used to establish permanent elevation markers at most, if not all, of the nearly 60 bay-wide seagrass monitoring transects included in the cooperative Tampa Bay seagrass monitoring program. To determine the elevation of these markers, the "centimeter" option, offered by Trimble to substantially improve the accuracy of phase processed solutions, should be
used. Trimble specifications for this option are 1cm+5ppm RMS with 45 minutes of occupation time. Once the permanent markers were established, traditional level and rod elevation surveys could periodically be conducted to accurately and quickly determine the depth profile of each transect. Further, deep edge elevation measurements for the different seagrass species found on each transect could easily be included during the depth profile measurements.

The proposed periodically conducted elevation measurements will provide important information to compliment the every two year high altitude aerial seagrass photography conducted by SWFWMD and the yearly cooperative Tampa Bay seagrass transect monitoring program. Combined, the three programs would become a powerful tool for evaluating the progress of the Tampa Bay water quality and seagrass restoration effort.

CONCLUSIONS

Evaluations of measurement errors suggest that the GPS phase processing technique will yield seagrass elevation measurements with an error less than +/-10cm for survey sites located up to 10km from bench mark sites. Further, repetitive elevation measurements (n=2) conducted at four specific seagrass areas resulted in a standard deviation of the determined elevations that ranged from 3 to 4cm and a coefficient of variation that ranged from 4.1 to 7.7%.

Elevation measurements at ten Tampa Bay seagrass study sites found relatively shallow deep edges of *H. wrightii* meadows in the upper section of Hillsborough Bay (-0.30 to -0.34m MTL) and at intermediate depths in the lower Hillsborough Bay and at the Wolf Branch area in northeastern Middle Tampa Bay, just south of Hillsborough Bay (-0.48 to -0.58m MTL). The deepest *H. wrightii* surveyed was found at Big Island in western Old Tampa Bay and at Port Manatee in eastern Lower Tampa Bay (-0.71 to -0.76m MTL). Deep edges of *T. testudinum* meadows ranged from -1.53m MTL at Bel Mar Shores in eastern Old Tampa Bay to -1.73m MTL at Port Manatee. Isolated patches of *T. testudinum* located on the shallow sandbar at Picnic Island in southeastern Old Tampa Bay and the Wolf Branch area were found as considerably shallower elevations (-0.53 to -0.90m MTL). Deep edges of *S. filiforme* meadows in eastern Old Tampa Bay and Port Manatee ranged from -1.19 to -1.46m MTL. However, the deepest *S. filiforme* edges were found outside the well developed offshore sandbars at Cafe Point Bayou and Coquina Key on the western side of Middle Tampa Bay. The depth of these edges ranged between -1.19 and -1.81m MTL at Cafe Point Bayou and between -1.93 and -1.96m MTL at Coquina Key. The latter measurements were the deepest *seagrass* elevations recorded in this study.

All survey sites had deep edge elevations shallower than the TEP seagrass restoration target depth for the respective bay segment. The greatest deviation from the target depth was found in western Old Tampa Bay, where the deep edges of the *H. wrightii* meadows were about 1.30m shallower than the -2.0 m MTL target depth selected for this bay segment. The least deviation was found at three sites: the *H. wrightii* meadow in southeastern Hillsborough Bay, the *T. testudinum* meadow at Bel Mar Shores in eastern Old Tampa Bay, and the *S. filiforme* meadow at Coquina.
Key in southwestern Middle Tampa Bay. These three areas had deep edges that were approximately 0.50m shallower than the respective bay segment targets.

The average percent of subsurface incident light available at the deep edges of *H. wrightii* meadows ranged from 59.8 to 28.9% and was substantially above the adopted TBEP seagrass restoration light target of 20.5%. Deep edges of *T. testudinum* at Bel Mar Shores and Port Manatee appeared to receive less light than the target (19.0 to 16.9%). The deep edges of *S. filiforme* meadows at Coquina Key and Côte au Beepot Bayou received the least amount of light of all study sites, 16.7 and 16.2%, respectively.

The field evaluation of the GPS phase processing technique provided an important first-step in understanding the current depth distribution of the major Tampa Bay seagrass species. However, many more elevation measurements should be conducted to yield a more complete understanding of the seagrass depth distribution in the bay.

Recently, seagrass recovery has stagnated in several areas of Tampa Bay, despite ambient water quality and light availability conditions that appear adequate to support continued seagrass expansion. One theory proposed for the poor expansion focuses on the importance of the offshore unvegetated sand bar to protect the main seagrass meadow from wave action and to allow seagrass to expand into deeper waters. However, studies examining the dynamics of the shallow sand bars and their interaction with the development of seagrass meadows are lacking for Tampa Bay.

Additional elevation measurements are recommended to learn more about the seagrass depth distribution and the dynamics of the shallow sand bars in Tampa Bay. The GPS phase processing technique could be used to establish permanent elevation markers at most, if not all, of the nearly 60 bay-wide seagrass monitoring transects included in the cooperative Tamp Bay seagrass monitoring program. Once these were established, traditional level and rod elevation surveys could periodically be conducted to accurately and quickly determine the depth profile of each transect. Further, deep edge elevation measurements for the different seagrass species found on each transect could easily be performed during the profile measurements.

The proposed elevation measurements will provide important information to compliment the every two year high altitude aerial seagrass photography conducted by SWFWMD and the yearly cooperative bay-wide seagrass transect monitoring program conducted by the TBEP partners. Combined, the three programs would become a powerful tool for evaluating the progress of the Tampa Bay water quality and seagrass restoration effort.
LITERATURE CITED


Table 1. Location of GPS seagrass elevation survey sites in Tampa Bay, including the number of measurements conducted for each surveyed seagrass species (also see Figs. 4 through 14 for locations of study sites).

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>BAY SEGMENT</th>
<th>SEAGRASS SPECIES and NUMBER OF SURVEYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAYSHORE</td>
<td>HB</td>
<td><em>H. wrightii</em> (4)</td>
</tr>
<tr>
<td>KITCHEN</td>
<td>HB</td>
<td><em>H. wrightii</em> (9)</td>
</tr>
<tr>
<td>LONG BRANCH</td>
<td>OTB</td>
<td><em>H. wrightii</em> (1)</td>
</tr>
<tr>
<td>BIG ISLAND</td>
<td>OTB</td>
<td><em>H. wrightii</em> (2)</td>
</tr>
<tr>
<td>BEL MAR SHORES</td>
<td>OTB</td>
<td><em>S. filiforme</em> (1); <em>T. testudinum</em> (1)</td>
</tr>
<tr>
<td>PICNIC ISLAND</td>
<td>OTB</td>
<td><em>S. filiforme</em> (2); <em>T. testudinum</em> (1)</td>
</tr>
<tr>
<td>WOLF BRANCH</td>
<td>MTB</td>
<td><em>H. wrightii</em> (4); <em>T. testudinum</em> (4)</td>
</tr>
<tr>
<td>COFFEEPOT BAYOU</td>
<td>MTB</td>
<td><em>S. filiforme</em> (mixed with sparse <em>T. testudinum</em>) (2)</td>
</tr>
<tr>
<td>COQUINA KEY</td>
<td>MTB</td>
<td><em>S. filiforme</em> (2)</td>
</tr>
<tr>
<td>PORT MANATEE</td>
<td>LTB</td>
<td><em>H. wrightii</em> (1); <em>S. filiforme</em> (2); <em>T. testudinum</em> (2)</td>
</tr>
<tr>
<td>SEAGRASS SPECIES</td>
<td>LOCATION and FIGURE REFERENCE</td>
<td>BAY SEGMENT</td>
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<td>--------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>H. WRIGHTII</strong></td>
<td></td>
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<tr>
<td>Bayshore North, Deep Edge of Meadow (Fig. 5, Symbol *)</td>
<td>HB</td>
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<tr>
<td>Bayshore South, Deep Edge of Meadow (Fig. 5, Symbol *)</td>
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<tr>
<td>Bayshore South, Patch Offshore Bar (Fig. 5, Symbol *)</td>
<td>HB</td>
<td>1</td>
</tr>
<tr>
<td>Bayshore South, Shallow Edge of Meadow (Fig. 5, Symbol *)</td>
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<td>5</td>
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<tr>
<td>Kitchen, Patch Offshore Bar (Fig. 6, Symbol *)</td>
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<tr>
<td>Big Island, Deep Edge of Meadow (Fig. 8, Symbol *)</td>
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<td>Wolf Branch, Deep Edge of Meadow (Fig. 11, Symbols * and +)</td>
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<td><strong>T. TESTUDINUM</strong></td>
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<tr>
<td>Prairie Island, Deep Edge of Patch (Fig. 10, Symbol *)</td>
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</tr>
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<td>Wolf Branch, Deep Edge of Patch (Fig. 11, Symbols *)</td>
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<td><strong>S. FILIFORME</strong></td>
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<td>Bel Mar Shores, Deep Edge of Meadow (Fig. 9, Symbol *)</td>
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<td>1</td>
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<td>Prairie Island, Deep Edge of Patch (Fig. 10, Symbol *)</td>
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<td>2</td>
</tr>
<tr>
<td>Crookset Bayou, Deep Edge of Meadow (Fig. 12, Symbol *)</td>
<td>MTB</td>
<td>2</td>
</tr>
<tr>
<td>Osprey Key, Deep Edge of Meadow (Fig. 13, Symbol *)</td>
<td>MTB</td>
<td>2</td>
</tr>
<tr>
<td>Port Manatee, Deep Edge of Meadow (Fig. 14, Symbol *)</td>
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<td>2</td>
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<td>HCEPC WATER QUALITY STATIONS</td>
<td>COT SECCHI DEPTH AND PAR STATIONS</td>
<td>BAY SEGMENT</td>
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<tr>
<td>-----------------------------</td>
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<td>-------------</td>
</tr>
<tr>
<td>6 AND 7</td>
<td>4, 12, 17, 18, 19, AND 20</td>
<td>HB</td>
</tr>
<tr>
<td>73</td>
<td>4, 12, 17, 18, 19, AND 20</td>
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</tr>
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<td>OTB</td>
</tr>
<tr>
<td>66</td>
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<td>OTB</td>
</tr>
<tr>
<td>50 AND 51</td>
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<tr>
<td>33 AND 36</td>
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<td>OTB</td>
</tr>
<tr>
<td>81</td>
<td>13 AND 23</td>
<td>MTB</td>
</tr>
<tr>
<td>32</td>
<td>13 AND 23</td>
<td>MTB</td>
</tr>
<tr>
<td>28</td>
<td>13 AND 23</td>
<td>MTB</td>
</tr>
<tr>
<td>90</td>
<td>95</td>
<td>LTB</td>
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Table 4. Estimated percentage of annual average subsurface irradiance (PAR) remaining at the sediment surface at the deep edge of seagrass meadows (or patches in areas lacking larger meadows) in Tampa Bay. The light attenuation coefficient (Ksub-s), used to calculate subsurface irradiance (%PAR), was estimated from the average 1994-1999 Secchi disk depth at HCEPC water quality monitoring stations located near seagrass study sites and COT bay segment specific light attenuation measurements for the same period.

<table>
<thead>
<tr>
<th>SEAGRASS SPECIES AND LOCATION</th>
<th>BAY SEGMENT</th>
<th>ANNUAL AVERAGE ATTENUATION COEFFICIENT (Ksub-s) (m⁻¹)</th>
<th>PERCENTAGE OF SUBSURFACE PAR REMAINING AT SEDIMENT SURFACE (%PAR)</th>
<th>Range</th>
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</thead>
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<tr>
<td>H. WRIGHTII:</td>
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<td>30.9 to 33.7</td>
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<td>52.4 to 57.1</td>
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<td>T. TESTUDINUM:</td>
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<td>OTB</td>
<td>-1.16</td>
<td>16.9</td>
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<td>Picnic Island (patch)</td>
<td>OTB</td>
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<td>17.1 to 20.9</td>
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<td>-1.16</td>
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<td>LTB</td>
<td>-1.02</td>
<td>29.8</td>
<td>27.3 to 31.4</td>
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Figure 1. Performance of the Trimble Phase Processor v.2 software with the GPS Pathfinder PRO XR system according to Trimble (1997). Figure modified from Trimble (1997). Horizontal errors are shown, however, Trimble (1997) states that vertical and horizontal errors are similar for phase processed solutions.

Figure 2. Trimble Pathfinder PRO XR instruments located on the roof of the City of Tampa Bay Study Group laboratory during tests of vertical measurements errors.
Figure 3. Example of quick plan graph from Trimble Pathfinder Office v.2.1. Excellent data collection windows (minimum of 6 satellites [SV] and maximum PDOP of 3) are shown as hatched bars.

Figure 4. Locations of seagrass elevation survey sites in Tampa Bay (map scale: 1cm is approximately equal to 6km). Also shown are major bay segments (HB=Hillsborough Bay; OTB=Old Tampa Bay; MTB=Middle Tampa Bay [including sub-segments]; and LTB=Lower Tampa Bay).
Figure 5. Vertical photograph of the Bayshore area in Hillsborough Bay taken on December 8, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.

Figure 6. Vertical photograph of the Kitchen area in Hillsborough Bay taken on October 26, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.
Figure 7. Vertical photograph of the Long Branch area in Old Tampa Bay taken on October 26, 1999. The symbol shows the approximate location of the GPS seagrass elevation survey site.

Figure 8. Vertical photograph of the Big Island area in Old Tampa Bay taken on October 26, 1999. The symbol shows the approximate location of the GPS seagrass elevation survey sites.
Figure 9. Vertical photograph of the Bel Mar Shores area in Middle Tampa Bay taken on October 26, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.

Figure 10. Vertical photograph of the Picnic Island area in Old Tampa Bay taken on December 8, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.
Figure 11. Vertical photograph of the Wolf Branch area in Middle Tampa Bay taken on December 8, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.

Figure 12. Vertical photograph of the Coffeepot Bayou area in Middle Tampa Bay taken on December 8, 1999. The symbol shows the approximate location of the GPS seagrass elevation survey sites.
Figure 13. Vertical photograph of the Coquina Key area in Middle Tampa Bay taken on December 8, 1999. The symbol shows the approximate location of the GPS seagrass elevation survey sites.

Figure 14. Vertical photograph of the Port Manatee area in Lower Tampa Bay taken on December 8, 1999. The symbols show the approximate locations of the GPS seagrass elevation survey sites.
Figure 15. Schematic of typical GPS stations set-up during elevation measurements.
A = Base station antenna height.
B = Bench mark elevation above MTL tidal stage.
C = Rover station antenna height.
D = Relative elevation difference between base station and rover station antennas.
X = Calculated elevation of the deep seagrass edge.

Figure 16. Field set-ups of base (A) and rover (B) stations during GPS seagrass elevation measurements in Tampa Bay.
Figure 17. Results from 35 tests of vertical measurement errors conducted on the roof of the City of Tampa Bay Study Group laboratory using two Pathfinder PRO XR instruments. The true elevation difference between the instruments was 0cm.

Figure 18. Location of HCEPC water quality monitoring stations (E) located near seagrass elevation survey sites (see Fig. 4). Also shown are COT stations (C) that, since 1994, have concurrently measured PAR attenuation coefficient and Secchi Disk depth information.