EPA Public Access

Author manuscript

Ecol Eng. Author manuscript; available in PMC 2018 November 01.

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Published in final edited form as:

Ecol Eng. 2017 November 1; 108: 537–546. doi:10.1016/j.ecoleng.2017.06.063.

A mangrove creek restoration plan utilizing hydraulic modeling

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Abstract

Despite the valuable ecosystem services provided by mangrove ecosystems they remain threatened around the globe. Urban development has been a primary cause for mangrove destruction and deterioration in south Florida USA for the last several decades. As a result, the restoration of mangrove forests has become an important topic of research. Using field sampling and remote-sensing we assessed the past and present hydrologic conditions of a mangrove creek and its connected mangrove forest and brackish marsh systems located on the coast of Naples Bay in southwest Florida. We concluded that the hydrology of these connected systems had been significantly altered from its natural state due to urban development. We propose here a mangrove creek restoration plan that would extend the existing creek channel 1.1 km inland through the adjacent mangrove forest and up to an adjacent brackish marsh. We then tested the hydrologic implications using a hydraulic model of the mangrove creek calibrated with tidal data from Naples Bay and water levels measured within the creek. The calibrated model was then used to simulate the resulting hydrology of our proposed restoration plan. Simulation results showed that the proposed creek extension would restore a twice-daily flooding regime to a majority of the adjacent mangrove forest and that there would still be minimal tidal influence on the brackish marsh area, keeping its salinity at an acceptable level. This study demonstrates the utility of combining field data and hydraulic modeling to aid in the design of mangrove restoration plans.

Keywords

Hydrologic Engineering Center's River Analysis System (HEC-RAS); Naples Bay; Florida; coastal wetland tides; coastal wetland freshwater inflows; tidal creek restoration; *Rhizophora*

1. Introduction

Mangrove ecosystems provide a wealth of potential ecosystem services including habitat provision, coastal protection, and carbon sequestration (Costanza et al., 2014; Marois and Mitsch, 2015; Mitsch and Gosselink, 2015). Despite these valuable services, they have continued to be destroyed and deteriorated across the globe in recent decades as a result of silviculture, aquaculture, and urbanization (Duke et al., 2007). Valiela et al., (2001) estimated that 35% of the world's mangroves were lost between 1980 and 2000. Hydrology

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is a principal factor that determines mangrove ecosystem function and health, and tidal creeks are often the principal conduit for maintaining this health (Mitsch and Gosselink, 2015). If this hydrology is altered it could affect both the supply of nutrients to the system and flushing of waste products, such as hydrogen sulfide, out of the system (Lewis, 2005; Mitsch and Gosselink, 2015). Because of this, the primary focus in many mangrove restorations involves creek restoration to return the hydrology and creek bathymetry to its natural conditions.

The effects of altered hydrology on a mangrove forest are not immediately noticeable using measurements of ecosystem health, such as tree mortality rates (Lewis, 2005). Even slight reductions of tidal influence within a mangrove creek can worsen over time due to the tendency of mangrove species like *Rhizophora mangle* to grow inwards towards a shrinking creek channel to gain access to the water. This inward growth of dense prop roots subsequently decreases channel size by increasing bank sedimentation rates (Lewis, 2005). Over time, this feedback loop of decreasing tidal influence and decreasing channel size can result in a hydrologic disconnection, causing the mangroves to lose access to allochthonous nutrients brought in by the tide, tidal flushing of toxins, and upland freshwater inflows.

While the mangroves might not immediately die off in an area of altered hydrology, they may lose their resiliency to disturbance, a key trait of coastal ecosystems (Field, 1998). Mangrove ecosystems are found largely on tropical and subtropical coastlines, which often have high risks of natural disturbances such as cyclones (Marois and Mitsch, 2015). A mangrove forest's ability to undergo secondary succession after a disturbance event is essential to its long-term existence. However, altered hydrology can affect natural propagule recruitment and mangrove seedling re-establishment in impacted areas (Field, 1998). In a study of restored mangrove systems, McKee and Faulkner (2000) found that without hydrologic conditions that provide tidal flushing, disturbed forests developed slower and were less similar to natural systems in structure and biogeochemical function than when the hydrology was properly restored. In summary, while a mangrove forest with altered hydrology might not appear in need of immediate restoration, when it is inevitably disturbed, its chances of successfully re-establishing itself may be significantly reduced.

When planning the restoration of a mangrove ecosystem, particular attention must be paid to natural hydrologic patterns, including the flooding intervals, flooding duration, and flooding depth of the mangrove area (Lewis, 2005). All of these factors have the potential to affect the long-term success of any vegetation planted for restoration purposes. These hydrologic properties are influenced by the surface elevation of the mangrove forest relative to tidal data. In a survey of mangroves in Florida, Crews and Lewis (1991) determined that mangrove trees are typically found growing in areas between mean higher-high water level (MHHW) and mean high water level (MHW). Depending on the local tide regimes, these areas are typically flooded once or twice daily for a period of a few hours.

Hydraulic models can provide predictions of the resulting hydrology of a mangrove restoration plan. Because of this, modeling is an integral tool in the planning and design stage of a restoration. They enable the user to predict the outcome of different restoration scenarios with relatively small time and cost expenses. Inputs for these models are often

gathered through a combination of field measurements and remote-sensing data such as LIDAR and satellite imagery. One such hydraulic model is the U.S. Army Corps of Engineers' Hydrologic Engineering Center's River Analysis System (HEC-RAS). HEC-RAS is a one-dimensional hydraulic model that uses energy and flow equations to simulate steady and unsteady flow scenarios in rivers (Brunner, 2010). Previous studies on tidally influenced rivers have successfully used HEC-RAS to aid in simulating tidal hydrology, often combining it with a water quality model (Fan et al., 2009, 2012; Mashriqui et al., 2014).

Several large-scale coastal restoration plans have used other hydraulic models to help in the design process and prediction of outcomes. One such restoration plan used a model that integrated hydrodynamics and salinity within an estuary in Taiwan to evaluate the impact of removing a tidal dike on a wetland restoration (Hsu et al., 1998). A similar approach was used for several large salt marsh restorations on the Delaware Bay (Weishar et al., 2005). After establishing the specific hydrology and sedimentation needed, a two-dimensional hydrodynamic numerical model was used to evaluate design alternatives. This proved to be an invaluable tool in what was deemed a successful tidal creek restoration (Hinkle and Mitsch, 2005; Teal and Weishar, 2005). These models can also be used to predict the effect of restoring freshwater flows to impacted coastal systems. For example, Zacharias and Gianni (2008) used a hydrodynamic model paired with a salinity model to predict the effects of diverting freshwater to a hyper-saline lagoon in Greece.

In this study we provide an ecological engineering design for returning the natural hydrology to a disturbed mangrove creek located on Naples Bay, Florida. Field sampling and remote-sensing data were analyzed to assess both the historic and current conditions of the mangrove creek topography, hydrology, and water quality and a hydraulic model of the creek was developed, calibrated, and used to simulate the effects of implementing our restoration plan. Using the empirical and simulated data, we developed a tidal creek management plan designed to restore the tidal influence to "inland" mangrove forests while also increasing freshwater inflows to the mangrove forest from the uplands.

2. Methods

2.1. Site description

The Hamilton Avenue mangrove creek is located on the Gulf of Mexico coast of Florida in Naples Bay (26° 5' N, 81° 47' W) (Figure 1). Naples Bay has mixed semi-diurnal tides with a mean high water level (MHW) of 0.29 m above mean sea level (MSL) and a mean low water level (MLW) of 0.29 m below MSL for a mean tidal amplitude of 0.58 m (NOAA, 2015a). Southwest Florida has a sub-tropical climate with a distinct wet season lasting from approximately May 15 to November 15. Average annual precipitation for the region is approximately 1400 mm yr⁻¹ (NOAA, 2015b).

Currently, the impacted tidal creek is ~ 650 m long and is located nearly opposite of a channel that connects Naples Bay to the Gulf of Mexico. While the study creek has no official name, it has been referred to as Hamilton Avenue Creek in previous publications (Marchio et al., 2016; MacDonnell et al., 2017). Mangrove species include *Rhizophora*

mangle (red mangrove), *Avicennia germinans* (black mangrove) and *Laguncularia racemosa* (white mangrove). *Rhizophora* is the most dominant species along the banks of the creek with *Avicennia* and *Laguncularia* becoming increasingly intermixed with *Rhizophora* at increasing distances away from the creek.

A brackish marsh, located approximately 1 km inland from the end of the creek and described by Li and Mitsch (2016), was restored in 2008 from a forested brackish swamp dominated by the invasive tree, *Melaleuca quinquenervia*. The restored brackish marsh is now dominated by the native grass, *Spartina bakeri*. Before wide-scale residential and commercial development began in this area in the 1960s, the brackish marsh was likely hydrologically connected to Naples Bay through Hamilton Avenue Creek. Dredge spoils from Naples Bay were deposited in mangrove areas on the east coast of the bay, which may have clogged creek channels and reduced tidal influence in more inland areas (McKee and Faulkner, 2000). The mature red and black mangroves within this marsh provide evidence for a previous hydrologic connection as a source of mangrove propagules.

2.2. Field data collection

Beginning in mid-2012, water quality including temperature, salinity, pH, and dissolved oxygen was continuously measured in-situ using a YSI™ 6920-V2 multi-parameter sonde installed in the inland brackish marsh area upstream of the disturbed tidal creek. Water depth was also monitored at this location using a NexSens™ pressure transducer water level logger. The bathymetry of this marsh was measured in 2012 using water depths at a resolution of 50 × 50 m.

To assess current water quality conditions in Hamilton Avenue Creek, two profiles were taken, one during an ebb tide and one during a flood tide. These profiles consisted of *in-situ* sampling approximately every 10 m at 25 cm and 75 cm depths using a YSI™ Quatro multi-parameter sonde. Profiles started from the entrance of the creek from the bay and ended at the furthest navigable point (approximately 650 m from the entrance). The flood tide profile was performed on September 22, 2014 and the ebb tide profile on October 24, 2014. Water quality parameters measured in each profile include pH, dissolved oxygen, temperature, and salinity.

To determine latitudinal hydrologic patterns, for three separate two-week periods, water temperature, salinity, and elevation were recorded at the creek entrance and an additional point within the creek using Onset HOB0 sensors (Models U20-001-04 and U24-002-C) installed at the bottom of the creek (Figure 2). In 2014, the sensors were placed at the entrance (site C-1) and the end of the creek (site C-4) on September 16-30, 2014 at the entrance and the basin (site C-2) on October 7–24, 2014, and at the entrance and 300 m from the entrance (Site C-3) from November 6–23, 2014. Some small precipitation events (~1–2 cm) occurred during each of these sampling periods. Naples Bay water levels were collected from a United States Geological Survey (USGS) monitoring station (Station ID: USGS-02291325) located approximately 0.5 km from the Hamilton Avenue Creek entrance (USGS, 2014).

To quantify groundwater patterns, similar data were recorded for groundwater in four sites (GW-1, GW-2, GW-3, and GW-4) adjacent to the creek using the HOBO sensors installed in 1-m deep wells (Figure 2). Sampling periods lasted for a minimum of 14-day tidal cycles (GW-1 on May 1 – 6, 2014; GW-2 on May 17 – June 2, 2014; GW-3 on June 3 – 17, 2014; and GW-4 on June 20 – July 5, 2014). Groundwater quality was also sampled 2 km inland from the Naples Bay coast from four well pumping stations located at the Naples Botanical Garden. Well samples were taken on May 14, 22, and 29, 2015 and analyzed in the laboratory for pH and salinity using a YSI™ Quatro multi-parameter sonde.

To quantify the physical dimensions of the existing creek system, bathymetric cross-sections were measured at approximately 50-m intervals along the creek for a total of 13 cross sections (Figure 2). Three bathymetric cross-sections were also measured in the basin area connected to the creek that is located 250 m from the creek entrance. To estimate the historic creek flow path, a field survey was done in which local points of lowest elevation were recorded with a GPS unit while moving from the inland marsh area to the edge of the mangrove creek. This path was then compared to historical aerial photos from 1962 (see Figure 1) to establish a more accurate estimation of the main creek channel's previous location.

Aerial LIDAR data retrieved from the International Hurricane Research Center at Florida International University was analyzed to determine the topography of the area around the creek (FIU-IHRC, 2014). LIDAR is a remote-sensing system that uses laser reflectance to gather high-resolution elevation data over large areas. The software LASTools™ was used to parse the ground points out of the full LIDAR dataset in order to remove the confounding vegetation elevations. This topography was used for model development and for creating a restoration plan.

2.3. HEC-RAS model development

Water level data recorded over time at various locations in the creek was combined with measured bathymetric and LIDAR topographic data to create a calibrated hydraulic model using the software HEC-RAS of the tidal influence on the mangrove creek restoration. The model requires inputs of cross-section bathymetry, creek dimensions, Manning's roughness coefficients (n) for the channel and banks, and hydraulic boundary conditions. The 16 cross-sections measured within the creek (Figure 2) were input into model and formed the basis of the physical dimensions of the model creek. Cross-section inputs also included 50 m of creek bank area on either side of the channel.

LIDAR data were used to create a topographical map of the areas adjacent to the creek and within the mangrove forest between the creek and the marsh area. Based on LIDAR topographical data, an average slope of 0.01 m/m increasing away from the creek channel was used for the mangrove forest. This allowed for the simulation of bank flooding within the model, an important consideration for assessing the efficacy of our restoration plan. An n value of 0.04 was calculated for the main channel using the procedure outlined by the United States Geological Survey (USGS, 1989). This calculation considered bed material, channel variation and tortuosity, occurrence of obstructions, and presence of vegetation. An n value of 0.14 was used for the mangrove-covered banks based on a calibrated value in the

literature that was used for modeling water flow through mangrove forests in southwest Florida (Zhang et al., 2012).

To simulate Naples Bay tides, a water stage boundary condition was implemented at the bay entrance to the creek using water levels recorded by the HOBO sensors in 15-minute intervals. The basin area located approximately 250 m from the entrance of the creek was treated in the model as a split in the main channel. HEC-RAS provides an output of an animated 3D visualization of the creek bathymetry and water level changes over time. This output allowed us to predict how much of the mangrove forest adjacent to the creek would be flooded during high tide events before and after the creek restoration.

3. Results

3.1. Existing tidal hydrology and salinity

Historic aerial imagery, the presence of mature mangroves in the marsh, and the still-existing low points in topography between the bay and the marsh provide evidence that the marsh was likely at one time hydrologically connected to Naples Bay through Hamilton Avenue Creek. However, when recent tidal water levels at upstream sites are compared with tidal fluctuations of Naples Bay (Figure 3), the lack of semi-diurnal fluctuations in the marsh level indicates that the marsh is not significantly connected hydrologically to Naples Bay through surface water (Figure 3a). This lack of tidal influence was also observed in the mangrove forest adjacent to Hamilton Avenue Creek at groundwater sampling site GW-4 (Figure 3b). Groundwater levels at this site were only slightly influenced by Naples Bay's tidal cycle.

The potential for a sub-surface hydrologic connection between Naples Bay and the brackish marsh was also considered. Increasing salinity levels were measured in the marsh as the dry season progressed and water levels fell (Figure 4), suggesting a potential saline groundwater influence on the marsh. This influence is more noticeable as the natural freshwater inflows of precipitation and surface runoff decreases during the dry season (Figure 4). This also indicates that if the marsh and its surrounding areas are further disconnected from their watershed due to development, salinity levels are likely to further increase and stay more saline throughout the wet season. Groundwater salinity levels were taken from wells adjacent to the creek and also from pumping wells located inland from the brackish marsh (Table 1). Results from the inland pumping wells show that groundwater inland from the marsh has relatively low salinity levels (< 1 ppt) and is likely not a significant source of the salinity measured in the marsh area.

To gain a better understanding of the current water quality of the mangrove creek and the factors that control it, latitudinal profiles were taken during a flood tide on September 22, 2014 and during an ebb tide on October 24, 2014 (Figure 5). The two profiles are similar in that salinity was always higher at the 75 cm depth than at the 25 cm depth. However, this difference was more pronounced in during the flood tide. The salinity also increased from the entrance towards the end of the creek during the flood tide, but decreased from the entrance during the ebb tide. This indicates that during the low tide when bay water has flowed out of the creek, salinity levels drop, but rise back up when tidal waters return. Two

precipitation events (both ~1 cm) that occurred a few days before the September 22, 2014 sampling might explain the overall lower salinity levels seen on that day when compared to salinity levels measured on October 24, 2014.

3.2. Creek restoration plan

Our proposed tidal creek restoration plan focuses on cutting a channel that connects the end of the existing mangrove creek to the brackish marsh area at the Naples Botanical Garden (Figure 6). The proposed channel should improve the hydrology by restoring the essential tidal influence to the inland mangrove forests. It should also increase surface freshwater inflows from the inland side of the mangrove forest. The location of the channel cut follows the local low points recorded during the field survey and reflects the historic channel observed in aerial photography shown in Figure 1a.

The proposed channel path would extend approximately 1.1 km beyond the end of the existing creek, ending with a connection to the restored brackish marsh area near the Naples Botanical Garden. The restored creek would have a meandering path typical of natural mangrove creeks. Tortuosity (creek channel length divided by direct distance between creek ends) of the existing creek was calculated to be 1.60. Our proposal would restore the channel with a comparable tortuosity of 1.45.

Dimensions of the restored channel were chosen to reflect those of the existing channel in locations nearer the bay, where there does not yet appear to be a significant decrease in cross-sectional area due to sedimentation. The channel would have a trapezoidal cross-section; 7.5 m wide from bank to bank with a bank slope on both sides of 0.6 m/m that level off to a bottom depth of 1.2 m below the bank height (width of channel bottom is ~ 6.1 m). Because the landward end of the existing creek is currently narrower and shallower than this proposed channel, the channel cutting should begin 150 m in from the end of the existing creek (500 m from the creek entrance), where the channel first shows a substantial reduction in its cross-sectional area. In total, the channel cutting will involve the excavation of approximately 9,000 m³ (11,800 yd³) of soil.

The channel could be dug starting from the inland side with a small track hoe and excavated sediment could be removed by boat or truck depending on what is easiest at the given point in the excavation. Mangrove roots in the excavation area would have to be cut and some mangrove trees might be lost in sections where the creek channel does not currently exist. Once the channel has been dug, mangrove roots should grow back and stabilize the banks and channel slope. Nonetheless, the dimensions of the channel should be monitored to ensure they are staying close to the design. Maintenance of the channel will likely be required throughout the lifetime of the project as any mangroves that regrow too far into the excavated channel should be removed to prevent the channel from closing again. Additional maintenance may also be needed after the occurrence of a hurricane or large tropical storm, which could bring in large amounts of sediments to the channel.

3.3. Hydraulic model results

The model was verified by analyzing the simulated water levels across a 14-day tidal cycle. This tidal cycle period should be relatively consistent across seasons, with a possible

increased influence of precipitation on the creek hydrology during the wet season (approximately June–September). The model behaved as expected, with low tide water levels being contained within the main channel and high tide water levels flooding the areas adjacent to the creek (Figure 7). We then calibrated the model by comparing the simulated water levels to measured water levels at site C-4, located 650 m from the entrance of the creek (Figure 8). The model provided an adequate simulation of the water levels at this point in the creek, with an r^2 value of 0.99 over a 14-day tidal cycle.

Once the model was calibrated, it was used to simulate the effects of the proposed restoration on the hydrology of the creek, the adjacent mangrove forest, and the marsh. The creek restoration scenario was simulated by extending the length of model creek and altering its channel dimensions to match the restoration design specifications (Figures 6 and 7). Simulations of the restored creek were run using measured tidal data from the 14 to 30 of September 2014. The resulting simulated water levels showed that twice a day near high tide, a large proportion of the mangrove forest would be inundated (Figure 9). Areas up to 1.5 km in from the entrance of the creek still experienced at least some overbank flooding. This is a large improvement from the existing conditions; at GW-4, only 300 m from the end of the existing creek, we measured minimal tidal influence (Figure 3b).

The volumetric flow rates of water within the restored creek were also simulated throughout several tidal cycles (Figure 10). The results show that tidal flow at the entrance of the creek reaches an approximate average of $3.5 \text{ m}^3 \text{ s}^{-1}$ during high tide. This flow remains substantial 600 m in from the entrance with an average flow rate of approximately $2.5 \text{ m}^3 \text{ s}^{-1}$ during high tide. Conversely, at the end of the restored creek channel where it connects with the marsh, modeled flows are very low with average flow rates of approximately $0.05 \text{ m}^3 \text{ s}^{-1}$ during high tide. As such we expect the tidal influence on the salinity of the inland marsh to remain minimal.

To predict how the restored creek would affect freshwater flows into the mangrove system, inflow hydrographs for 2.0-cm, 3.5-cm, and 5.0-cm rainfall events were added as an upland boundary condition to the restored creek (Figure 11). The model inflow hydrographs were determined from analyzing the brackish marsh's measured water level response to various precipitation events. The resulting simulation of this pulsed freshwater flow showed that the 2.0-cm precipitation event would cause a freshwater flow (calculated as the difference between flow during the storm and creek baseflow) of $1.0 \text{ m}^3 \text{ s}^{-1}$ into the restored creek area during the highest point of the hydrograph. The simulations of the 3.5-cm and 5.0-cm precipitation events predicted peak freshwater flows into the restored creek area of $2.2 \text{ m}^3 \text{ s}^{-1}$ and $3.6 \text{ m}^3 \text{ s}^{-1}$, respectively (Figure 11). For comparison, during high tide, average inflow rates from the bay into the existing creek are approximately $3.5 \text{ m}^3 \text{ s}^{-1}$ (Figure 10). Achieving this balance of freshwater and saltwater inflows is an integral component of restoring a mangrove system's hydrology.

4. Discussion

4.1. Existing tidal connectivity

We found that the tidewaters of the bay have a minimal influence on the inland mangrove forest and the marsh, suggesting a hydrologic disconnection from Naples Bay. This disconnect is evident when considering a site that is only 300 m from the end of the creek (GW-4) shows such small tidal influence especially when considering the flat topography of the area. This suggests that the tidal influence of the bay is quickly reduced after the creek channel begins to narrow. The presence of mature mangroves currently in the brackish marsh and the visible flow paths in the 1962 aerial photograph support that this hydrologic disconnect was not always the case and is likely a result of human activity. One possible explanation is the creek channel getting clogged over time by the increased sediment load resulting from the dredging of Naples Bay. A very similar effect was observed by McKee and Faulkner (2000) in another mangrove creek also on Naples Bay, located only 3 km from our study site. The natural freshwater inflows from upland have also likely been altered as the watershed has been largely segmented by urban development over the past several decades. The presence of more roads, ditches, and artificial lakes will intercept stormwater runoff that historically would have flowed to the coast. These freshwater inflows can be a vital characteristic of a mangrove system's hydrology and have been shown to be significant fluxes in the hydrologic budget of other mangrove forests (Hughes et al., 1998)

4.2. Restoration plan and model predictions

The simulation of the tidal influence on the existing creek in the HEC-RAS model gave accurate results, comparable to Mashriqui et al. (2014), who also used HEC-RAS for similar purposes. The simulations of the restored tidal creek provided evidence for the efficacy of the restoration plan in regards to restoring natural hydrology. Simulation outputs that showed flooding up to 1.5 km inland from the entrance of the creek during high tides demonstrate the potential to restore the natural flooding regime to a large portion of the inland mangrove forest. This twice a day flooding for a period of a few hours is the typical condition found in a natural mangrove forests in southwest Florida and was a primary goal of the proposed restoration (Crewz and Lewis, 1991).

One potential stakeholder concern is the possible increase of saltwater flowing into the brackish marsh area as a result of the creek restoration. This marsh area was restored in 2008 and has since stabilized as a system dominated by native plant species, thus further ecosystem alteration is likely undesirable. Simulations showed the proposed restoration only allowed small flows ($0.05 \text{ m}^3 \text{ s}^{-1}$) into the marsh during high tide (Figure 10). However, if virtually no flow is desired, an alternative design option would be the installation of a weir before the point where the restored creek connects to the marsh. This alternate design was tested with the HEC-RAS model by simulating the installation of a broad-crested weir within the tidal creek and analyzing the model output for flows on the inland side of the weir during high tide conditions. The model weir was installed into the restored creek 75 m from the edge of the marsh and its top was 0.25 m above the restored bank height. The resulting simulations showed that even during high tide, no significant flow ($< 0.01 \text{ m}^3/\text{s}$) was being measured on the inland side of the weir.

This design alternative would have the negative consequence of also reducing upland freshwater inflows through the creek towards the bay. A check valve system that only allows flow in one direction would be ideal, but simulating such a structure was not possible in HEC-RAS. Nonetheless, considering both the simulated effects of installing the weir on tidal flow into the marsh and the simulated increase in freshwater flow into the creek through the restored channel (without the weir) provides a reasonable estimation of the hydrologic outcome of installing a one-way flow system.

Another potential concern is the possibility of the restoration increasing saltwater intrusion into wells near the coast used for drinking water and irrigation. This concern is particularly relevant due to the Naples Botanical Garden's proximity to the proposed restoration. However, the HEC-RAS model results indicate that the restoration of the creek will also increase freshwater flow into these areas from the marsh, potentially mitigating saltwater intrusion (Figure 11). Increased tidal flushing within the mangrove forest will also ensure that groundwater salinity levels never reach extreme levels due to impounding of saltwater. While our restoration plan is relatively simple, previous mangrove restoration projects have shown that they do not need to be complex in order to succeed (Field, 1998; Lewis, 2005). A study in America Samoa by Gilman and Ellison (2007) showed that projects can be relatively simple and low budget yet still be effective as long as hydrology is a primary focus. In their community-based restoration project, they assessed that their site elevation was too low relative to tide levels and used infilled tires to establish planted mangroves at the target elevation (Gilman and Ellison, 2007). Brockmeyer et al. (1997) restored an impounded mangrove forest's hydrology located in Florida using culverts (not a long excavated channel as proposed here) at the remarkably low cost of \$225 ha⁻¹. Installing culverts in this way restores a large tidal prism through a small opening, resulting in consistently high flows that reduce the occurrence of channel blockage due to mangrove regrowth which in turn reduces the amount of maintenance required. Adequate planning with the aid of modeling can help keep the restoration process relatively simple and reduce unnecessary expenses. The costs of conducting our proposed restoration include the removal, transport and disposal of 9,000 m³ (11,800 yd³) of soil, the attainment of Federal and State dredge and fill permits, and the post-restoration maintenance. The true project costs can only be determined after an engineering firm performs the pricing of an engineered and permitted design.

4.3. Future Research

Future work on the modeling of mangrove creek restoration should involve the integration of our calibrated hydraulic model with additional types of models to predict the effects of the restoration on other aspects of the system. Linking HEC-RAS with a water quality model as has been done in previous studies would provide the ability to better predict effects on salinity in the mangrove forest, and brackish marsh (Hsu et al., 1998; Zacharias, 2008). Coupling with a groundwater model similar to what was done by Langevin et al. (2005) would prove beneficial in predicting effects on salt intrusion into groundwater wells.

Since increased sediment loads from Naples Bay were the likely cause of the hydrologic disconnect in the mangrove forest, combining the hydraulic model with a sedimentation

model may also prove beneficial for predicting future changes to the restored channel. A combination of hydrodynamic and sediment models was used for the successful restoration of 1,800 ha of salt marshes Delaware Bay from previously diked salt hay farms (Hinkle and Mitsch, 2005; Teal and Weishar, 2005; Weishar et al., 2005; Mitsch and Gosselink, 2015). This allowed for the prediction of how the coastal topography and vegetation would develop over time after the restoration was implemented. Another potential direction would be to combine these models with an ecological model that can predict the development of mangroves as was done in a study by Twilley et al. (1998). While the mangroves still exist at the current study site, this addition could help predict the second-stage succession of the mangrove forest after a significant disturbance such as a hurricane or wildfire.

Although this study only discusses a plan for a future restoration, if it were implemented, the restored creek would be an ideal location for post-restoration university research. The hydrology, ecology, and biogeochemistry of the restoration area could be studied over decades to see the effects of the restoration and how the system develops over time. This type of long-term post-restoration study can provide a wealth of knowledge and insight into mangrove ecosystems and their restoration.

5. Conclusions

The results of reviews of maps from the 1960s and salinity sampling done in this study suggest that the inland mangrove forest and the brackish marsh, which are now mostly isolated from freshwater and marine flows, were once hydrological connected to Naples Bay by Hamilton Avenue Creek. Current measurements of water level and salinity in these areas indicate that there is little tidal influence on these areas through the surface water. This is an issue because tidal fluxes and freshwater inflows from uplands are both essential to the sustained health of mangrove systems. We proposed a restoration plan based on historical flow paths that focused on widening and extending the tidal channel to reconnect the mangroves to the Naples Bay. We then demonstrated how hydraulic models can provide a test of the restoration plan for a mangrove creek that has been impacted by both coastal development and dredging of the adjacent bay.

HEC-RAS in particular is a relatively easy to learn modeling software with few data requirements, making it ideal for low-budget restoration planning when data are available for calibration. We were able to calibrate the model using existing creek hydrology, and as such, provide predictions of the resulting hydrology from the proposed restoration plan. Simulation results suggest that constructing the new channel would increase the tidal influence on the inland mangrove forest, while also causing minimal tidal inflow to the marsh area. The simulated inundation frequency and duration of the mangroves on the channel banks are comparable to measurements from other Florida mangrove systems. The model simulations show that the relatively simple restoration plan of widening and extending the existing mangrove creek channel has the potential to restore natural hydrology to an area impacted for decades by urban and residential development.

Acknowledgments

This publication was assisted by U.S. National Science Foundation grant number 1619948, project title: U.S. Science International Collaborations and Contributions to Ecosummit 2016 – Ecological Sustainability: Engineering Change. The authors would like to thank Florida Gulf Coast University's College of Arts and Sciences and the Everglades Wetland Research Park for providing the equipment and lab space needed for field sampling and processing and the Olentangy River Wetland Research Park, the School of Environment and Natural Resources and Ohio Agricultural Research and Development Center, The Ohio State University, for providing early support. We also appreciate the reviews of various versions of this manuscript by an anonymous reviewer and by Drs. Charles Goebel and Jay Martin of The Ohio State University. We would also like to thank Chad Washburn, the Naples Botanical Garden, and the City of Naples for allowing us to sample on their property. Additionally, we thank Daniel Marchio, and Dr. Piotr Banaszuk for their assistance with field sampling. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. This document has been reviewed by the U.S. Environmental Protection Agency, Office of Research and Development, and approved for publication.

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Figure 1.
Comparison of aerial images of the Hamilton Avenue tidal creek area in Naples, Florida, from a) 1962 before significant urban development and b) in current (2015) conditions.

Figure 2.

Satellite image of the Hamilton Avenue tidal creek study area on Naples Bay with sampling locations and transects included. 'HOBOS' refers to the water level and salinity sensors used (models U20-001-04 and U24-002-C), 'GW' refers to sites where HOBOS were installed in piezometers to measure groundwater, 'C' refers to sites where HOBOS were installed within the creek channel to measure surface water.

Figure 3. Comparison of Naples Bay tidal fluctuations with upstream water elevations (NAVD Datum) of a) surface water of upstream brackish marsh area (August 1 to 7 of 2012) and b) groundwater in inland mangrove forest (GW-4 well, January 25 to 31 of 2015).

Figure 4. Salinity and water level measurements in the brackish marsh area upstream of the recommended mangrove restoration area from October 2012 to April 2013, showing the trends in a normal dry season.

Figure 5. Water quality longitudinal profiles at 25 and 75 cm depths starting from the Naples Bay entrance of Hamilton Avenue Creek, a) was taken on during the flood tide on September 22, 2014, b) was taken during the ebb tide on October 24, 2014.

Figure 6.

Map of recommended Hamilton Avenue tidal creek restoration path based on historical aerial photographs and the lowest local points measured during the bathymetric survey.

Figure 7.
3D Visualization of HEC-RAS model of existing creek at a) low tide and b) high tide, with light grey area showing the water level within the main channel which is denoted by the inner set of dark grey lines. The numbered lines crossing the channel are the measured transects that were used as inputs for the model.

Figure 8. Comparison of calibrated HEC-RAS model outputs and recorded water levels at the 650 m from the creek entrance (Site C-4) from September 18 to 21, 2014 ($r^2 = 0.99$)

Figure 9.

3D Visualization of HEC-RAS model of rehabilitated creek at high tide, with the grey area showing the water level flowing over channel banks (inner set of lines). For reference, the cross section labeled '0.72' is approximately 1,500 m from the entrance of the creek.

Figure 10.

Simulated flows at three places along the restored tidal creek, from the entrance of the creek to then proposed end of the creek where it meets the marsh area. Distances in the legend are the distance from the entrance of the creek. Measured tidal data from September 16 to 24, 2014 were used as model inputs. The 1,700 m location is at the connection between the restored creek and the brackish marsh.

Figure 11. HEC-RAS simulation hydrographs of stormwater flow into the restored creek area for 2.0, 3.5, and 5.0 cm precipitation events. 'Baseflow' indicates the flow rate in the creek before the precipitation events occur.

Table 1

Average salinities ($\pm$ standard errors) for groundwater samples adjacent to the existing creek and further inland (see Figure 2). GW site averages are for full 14-day tidal cycles measured between May 1, 2014 and July 5, 2014. The pumping wells average includes all four inland pumping wells measured from May 14, 2015 to May 29, 2015.

Site Name	Average Salinity (ppt)
GW-1	29.13 ± 0.00
GW-2	28.04 ± 0.01
GW-3	27.86 ± 0.01
GW-4	26.54 ± 0.00
Pumping Wells	0.54 ± 0.02