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Water Quality and Nuisance Species Management in the Fort Pulaski National Monument Moat

Natural Resource Report NPS/SECN/NRR—2009/134

ON THE COVER
Moat surrounding Fort Pulaski National Monument.
Photograph by: Jud McCraine

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Natural Resource Report NPS/SECN/NRR—2009/134

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NPS 348/100194, July 2009

Contents

Page

Figures

Tables

Abstract

In 2008, the staff at Fort Pulaski National Monument (FOPU) staff requested assistance from the Southeast Coast Network (SECN) to assist in water quality sampling in their moat. After experiencing a fish kill and an increase in nuisance weeds in the moat SECN worked with the park to develop a plan to manage these issues. The decision was made to attempt three partial water changes in the moat surrounding Fort Pulaski. Both short-term and long-term water sampling was planned in order to measure the benefits of these water changes.

The two nuisance weeds were lesser duckweed (*Lemna minor*) and widgeon grass (*Ruppia maritima*), which began thriving in the moat in the early summer. Various water quality tolerance levels for each plant were researched and it was determined that a change in water column temperature, salinity, pH or nutrients may decrease survival of these weeds. In an attempt to manipulate these water quality parameters, the moat's floodgates were opened to flush the moat with estuarine water from the mouth of the Savannah River. During this time water quality was regularly monitored for pH, dissolved oxygen, temperature, salinity, turbidity, total dissolved nitrogen, total dissolved phosphorus and chlorophyll *a*. Ultimately, both the duckweed and widgeon grass were successfully eliminated from the moat.

An additional benefit of the partial water changes was an increase in dissolved oxygen. Dissolved oxygen levels control species composition and abundance, and with the exception of anaerobic microbes, living things cannot survive without adequate oxygen levels. The capacity of water to hold oxygen is inversely proportional to temperature. Therefore, warmer waters in summer months hold less oxygen than colder waters in winter months. The moat has previously experienced fish kills during the summer. This is likely a result of algal blooms due to high nutrient levels and a decreased dissolved oxygen concentration.

Introduction

The fort at Fort Pulaski National Monument (FOPU) was constructed on Cockspur Island, a low-lying island with abundant salt marshes. Due to the marshy conditions, an elaborate drainage system was constructed to direct water flow. This drainage system includes gates, ditches, and a moat surrounding the fort. Both the fort and the demilune (the triangular earthen area constructed across from the fort entrance) are surrounded by the moat. Water can be added or released from the moat by opening two floodgates on either end of a ditch that connects the moat to the Savannah River.

The park has had a history of occasional fish kills in the moat due to low dissolved oxygen events. In 2007 FOPU staff contacted the Southeast Coast Network (SECN) for assistance in collecting some basic water quality data from the moat. At that time SECN began collecting water quality data (temperature, salinity, dissolved oxygen, pH and turbidity) at seven separate locations in the mote on a quarterly basis unless otherwise instructed. After several months of high dissolved oxygen and pH levels (both suggesting a phytoplankton bloom), on August 15, 2007 the park experienced a fish kill in the moat. In response to this fish kill the park flushed the moat via tides for approximately 2 days, and the moat was refilled with tidal and rain waters.

In June, 2008 FOPU staff contacted SECN . This time the moat surrounding Fort Pulaski was experiencing a bloom of *Lemna minor* (lesser duckweed, Figure 1) and *Ruppia maritima* (widgeon grass, Figure 2). Park managers feared that these two unsightly plants would diminish visitor experiences. Eradication of these nuisance plants was desired without the use of chemicals if possible. At that time a meeting was scheduled at the park for SECN (Eva DiDonato, Julie Dingle, Kayla Nimmo), park (Charlie Fenwick and Mike Hosti) and WASO staff (Mike Martin) to discuss possible solutions for dealing with the unwanted vegetation and the typical summertime low dissolved oxygen. As a result of the meeting it was decided that periodically over the summer park staff would help open the tide gates to flush moat waters. In return, SECN staff would closely monitor water quality and vegetation in the moat during and after the water changes. Goals of this project included:

1. The eradication of lesser duckweed and widgeon grass from the moat, and
2. An understanding of how water chemistry changes during tidal flushes of the moat, and how those changes vary across space and time throughout the moat.

Moat Issues

Duckweed and Widgeon Grass

In 2008, duckweed was a big concern for FOPU management. This small brightly colored plant can quickly grow into thick mats. It grows well in slightly acidic fresh to mildly brackish water of a moderate temperature (Table 1). Duckweed prefers high nutrient waters and given adequate growing conditions, can double in mass in less than two days (Hodgson, 1970).

Figure 1. Duckweed.

Figure 2. Widgeon Grass

Table 1. Salinity, temperature, and pH ranges required for optimal growth of *Lemna minor* and *Ruppia maritima* are shown, along with survivable ranges for these parameters (Hicks, 1932; Hodgson, 1970; Kantrud, 1991; Sutton et al., 1974).

		Lemna minor	***Ruppia maritima***
Salinity (ppt)	Optimal Range	0.82 – 3.33	5 – 20
	Survivable Range	0.0 – 16.65	0.6 – 74.0
Temperature (°C)	Optimal Range	12.5 – 17.5	20 – 25
	Survivable Range	6 – 33	13 – 35
pH	Optimal Range	5.4 – 6.5	7.7 – 9.4
	Survivable Range	5.0 – 7.8	6.0 – 10.4

Widgeon grass is a submerged perennial plant. It also prefers high-nutrient waters, but only as long as there is no resulting algal bloom (Burkholder, 1994). It requires high amounts of sunlight, and therefore low turbidity levels. It can survive in wide a range of salinities; however, rapid salinity changes (10 ppt over 48 hours) have been shown to impede growth, even if the salinity remains within the range for optimal growth (LaPeyre, 2003). It grows best at salinities less than that of seawater (Verhoeven, 1979) and germination rates are highest in salinities between 0 and 10 ppt (Kahn, 2005). Widgeon grass prefers slightly alkaline waters of a moderate temperature (Table 1). Mid-summer die-offs are common in estuaries throughout the southern United States, likely due to increased temperatures (Swiderek, 1982). It is believed that temperatures above approximately 30° C are harmful, if not lethal, to widgeon grass (Vicars 1976, Verhoeven 1979).

Based on a literature review, it was determined that a change in temperature, salinity, pH or nutrients may decrease weed survival. The initial water quality parameters in the moat varied drastically from those in the Savannah River. Therefore, the floodgates connecting the moat to the Savannah River were opened periodically throughout the summer, altering the water quality parameters in the moat in an attempt to cripple the nuisance weeds. Gates were not permanently left open because it is feared that leaving these gates open constantly may damage the mortar due continuous water movement and high salinity levels. Therefore, gates were opened as infrequently as possible.

The park has experienced previous widgeon grass blooms, and they have successfully implemented partial water changes to reduce the weed abundance. Changes in water quality parameters were not recorded during these prior partial water changes. Duckweed has never been a problem in the moat, and it was unclear if altering the water quality parameters would control this weed.

Table 2. Change in water quality parameters as a result of unmonitored partial water change. The Savannah River water increased salinity in the moat by an average of 5.45 ppt.

	Before unmonitored water change (6/3)	**After unmonitored water change (morning of 7/10)**
Salinity (ppt)	5.16-5.19	10.6-10.65
pH	7.11-7.27	7.47-7.66
Temp (°C)	28.7-29.4	27.89-28.55
TDN (mg/l)	n/a	0.74-0.95
TDP (mg/l)	n/a	0.0704-0.087
Chl *a* (μg/l)	n/a	4.49-5.72

Fish Kills

Low dissolved oxygen levels during previous summers have led to fish kills in the FOPU moat. Dissolved oxygen levels are highly dependent on temperature and productivity. The solubility of oxygen decreases with increasing temperature, and therefore, dissolved oxygen in water bodies drops during summer months. Oxygen primarily enters water through diffusion from the atmosphere and by photosynthesis of phytoplankton and aquatic macrophytes. The dissolved oxygen is consumed during respiration and decomposition processes. Respiration and decomposition occur continually, while oxygen-producing photosynthesis only occurs during daylight hours (Unknown, 2008). Therefore, dissolved oxygen levels drop during the night, while rising during the day, often stressing the system at night. These daily fluctuations can become problematic if an imbalance between oxygen production and usage arises. High levels of nutrients stimulate algal growth, leading to possible algal blooms. Even though the algae produce oxygen during the day, respiration and a high level of decomposition occur at night. This may lead to oxygen depletion and ultimately fish kills. Therefore, it is important to not only monitor dissolved oxygen, but also the limiting nutrients (nitrogen and phosphorus) and productivity (correlated with chlorophyll *a* concentrations).

Methods

In summer 2008, three partial water changes were performed by opening the moat's floodgates (on 6/17/08 (approximately), 7/10/08, and 8/26/08). On 7/10/08, a water-quality monitoring study was initiated to monitor changes in moat conditions during partial water changes. Limited data was collected on the first partial water change as it occurred before the start of the study. Water quality parameters were monitored regularly for the second and third partial water changes, and unless otherwise indicated, this report deals with the two monitored partial water changes that occurred during the study period.

Water quality measurements were collected using three methods:

1. Discrete sampling with datalogger

2. Semi-continuous sampling with datalogger

3. Nutrient sampling

Data on pH, dissolved oxygen, temperature, salinity, and turbidity were collected using a Yellow Springs Instrument Company (YSI) model 6600 Extended Deployment multiparameter datalogger using two methods. In the first method (what will hence be referred to as discrete sampling), readings were made just below the surface and just above the bottom at seven pre-determined sites (Figure 4). Each round of discrete sampling therefore had fourteen different points where measurements were recorded. Discrete sampling measured spatial variation. These samples were collected while walking around the moat in a counter-clockwise direction. Each round of sampling started with site 1, with the near surface measurements recorded at each site just prior to the near bottom recording. Each round of discrete sampling took approximately 35 minutes, with discrete sampling occurring most frequently during and right after water changes.

Additionally, semi-continuous data were recorded by a fixed-site datalogger near site 1. The semi-continuous sampling measured temporal changes at the fixed site. The protocol used was the same as that used by the SECN for fixed-site monitoring and was established by the national Estuarine Research Reserve Program (Wenner and Geist, 2001). The datalogger was set to record readings on DO, pH, temperature, salinity, and turbidity every 30 minutes. The instrument was housed in a protective PVC casing that had several large holes drilled in it for proper water circulation. The housing was attached via a rope and eyehook to the under-side of the bridge, and positioned such that the probes were approximately 0.5 meters from the bottom. The deployed datalogger was retrieved and replaced with another calibrated datalogger at least once a month.

Data on nutrient concentration (total dissolved nitrogen, total dissolved phosphorus and chlorophyll *a*) were collected by taking a water sample and sending it in for analysis at the Chesapeake Biological Laboratory at the University of Maryland. Nutrient samples were taken on six dates during the study approximately 0.5 meters from the bottom from sites 1 and 5. The Secchi depth was also recorded whenever nutrient samples were collected. However, due to the shallow depth of the moat, and the low turbidity levels, actual Secchi depth always exceeded the depth of the moat.

Data were analyzed in conjunction with weather data and visual observations of the duckweed and widgeon grass. Figure 3 illustrates the timeline of sampling events along with photos of duckweed decline and Table 3 shows a summary of moat activities (See Appendix A for additional photos and Appendix B for detailed timeline).

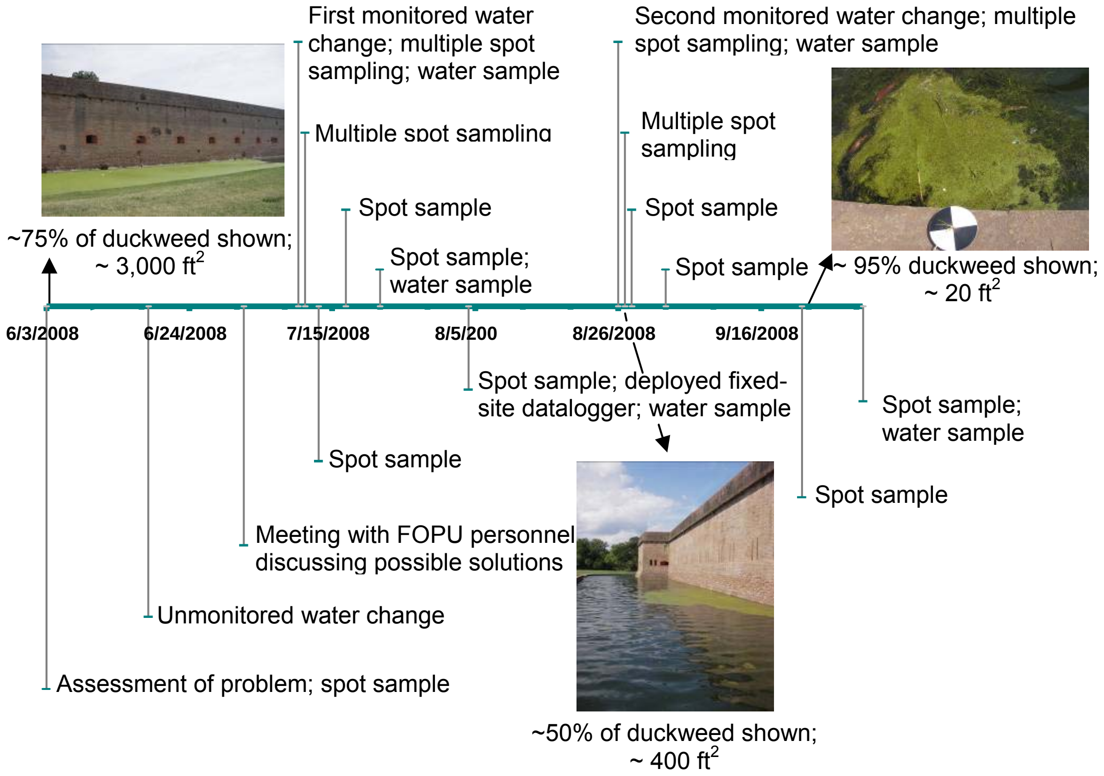

Figure 3. Timeline showing all moat activities (spot sampling, partial water change events and fixed-site datalogger deployment). Time series photographs indicate the change in duckweed coverage. For full details and additional pictures refer to Appendices 2 and 3.

Table 3. Summary of sampling activities that took place at the Fort Pulaski Moat during this study.

	6/3	6/18	7/10	7/11	7/13	7/17	7/22	8/4	8/26	8/27	8/28	9/2	9/22	10/1
Partial Water change		x	x						x					
Nutrient sample			x				x	x	x				x	x
Discrete sampling	x		x	x	x	x	x	x	x	x	x	x	x	x
Deploy fixed-site datalogger								x						
Swap fixed-site datalogger									x			x		

Site Descriptions

Water quality parameters were measured at seven different sites around the moat. Measurements were taken as closely to a site as possible, therefore a detailed description of site locations was created. Site 1 was at the bridge going from the mainland to the demilune and both discrete and semi-continuous data measurements (temperature, turbidity, pH, dissolved oxygen, salinity) were taken with the datalogger at this site. Discrete measurements were taken at all other sites (sites 2-6). These sites are distributed relatively evenly around the moat, located in bends of the moat (Figure 4). Each of these sites (2-6) is located at approximately the mid-point in the moat bends. Sites 2-6 were located flush against the outer moat wall. This outer moat wall is paved with large sandstone blocks, and sites 1-3 and 4-7 are at the junction between sandstone blocks. The following site descriptions pinpoint site locations. Sites 1 and 7 are part of the demilune moat, which was filled in at one point in time. This part of the moat was eventually dug back out, though not to the original depth and therefore these sites are shallower than sites 2-6 (Table 4).

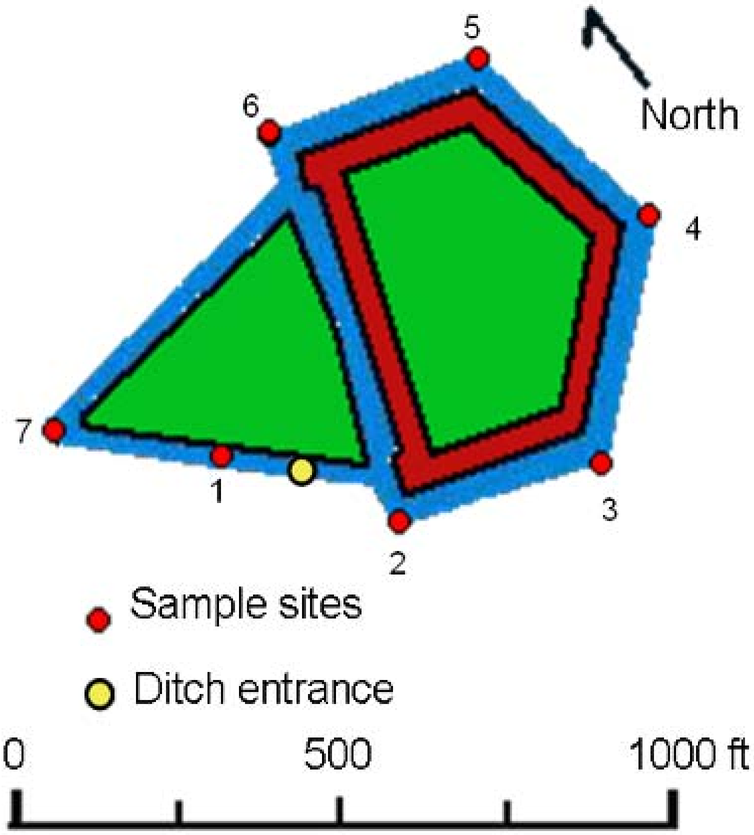

Figure 4. Map showing sample sites. Site 1 was at the bridge to the demilune and was also the site for the fixed-site semi-continuous datalogger.

Table 4. Discrete sampling site depth and coordinate summary.

Site	Depth (m)	Coordinates	Description
1	0.76	N 32° 01.600' W 080° 53.488'	Shallowest site and is on the left side of the bridge when facing the fort. Only discrete sampling site that is not located flush against the outer moat wall. Located on about the third board in from the mainland, and Mike marked this site with a small notch in the middle of the board. The fixed-site datalogger was located about ten feet away and was deployed on the right side of the bridge when facing the fort approximately in the middle of the moat.
2	1.23	N 32° 01.580' W 080° 53.462'	First demi-bastion going counter-clockwise from site 1. To find it, walk to the approximate mid-point in the turn. Then, look towards the road and try to line up the smallest break in the treeline with the telephone pole on the horizon.
3	1.28	N 32° 01.574' W 080° 53.401'	To find this site, line up the left leg (facing away from the fort) of the wayside with the nearest palm tree.
4	1.34	N 32° 01.617' W 080° 53.372'	Only site in the middle of a sandstone block (all others are at the junctions of two blocks). There are three abnormally sized blocks at this angle. The site is the middle of the center one.
5	1.28	N 32° 01.668' W 080° 53.398'	Line up the evergreen and palm tree as best as possible palm tree, such that the evergreen is slightly to the left of the palm tree.
6	1.35	N 32° 01.668' W 080° 53.462'	Located at an unusually thick layer of mortar between sandstone blocks.
7	0.97	N 32° 01.625' W 080° 53.543'	To find this site, line up the left leg (facing away from the fort) of the wayside with the tall evergreen behind it.

Results

Each partial water change (6/18/09, 7/10/09, and 8/26/09), including the unmonitored, increased overall salinity in the moat, while heavy rains associated with tropical storm Fay (8/20/09-8/24/09) decreased overall salinity (Figure 5). Following each partial water change, a salt-wedge formed, with the relatively dense high-salinity water from the Savannah River settling to the bottom, while the lower-salinity moat water remained at the surface. The salt wedge increased bottom salinity up to 9.98 ppt over just a few hours. Saline water was first detected near the bottom at the sites 1 and 2 (nearest the gate), and slowly spread out to the remaining sites within fifteen hours after gate opening (Figure 6). The wedge persisted for several days after each water-change, and took about a week to disappear (Table 5, Figure 5). After salinity equilibrium was reached, each partial water change increased overall salinity by 3.98 – 5.48 ppt.

Results from the nutrient analysis indicated that nitrogen concentrations at all sites (range of 0.5-0.98 mg/l; average 0.81 mg/l) remained within the fair range (0.5 – 1.0 mg/l) throughout the study according to National Coastal Condition Report assessment criteria (Tables 5, 6) (U.S. EPA, 2001). Phosphorus concentrations (0.054 – 0.094 mg/l; average 0.073 mg/l) remained within the poor range (>0.05 mg/l) according to these criteria. Chlorophyll *a* concentration (range 4.37 – 50.04 µg/l; average 4.37 µg/l) was typically within the good to fair range; however one instance was in the poor range. There was no difference in nutrient concentrations for nitrogen, phosphorus, or chlorophyll *a* between sites 1 and 5 suggesting consistent nutrient concentrations throughout the moat (Table 6).

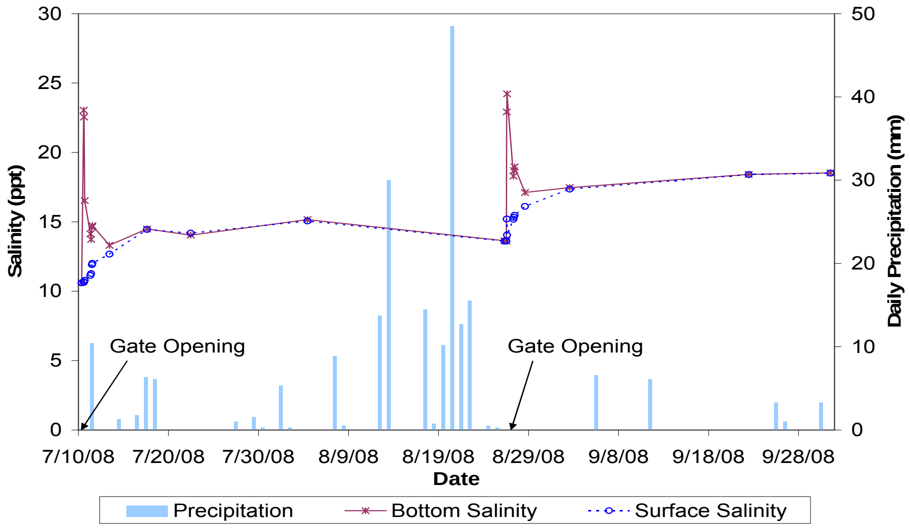

Figure 5. Recorded levels of salinity at sample site 1 on the surface and bottom. Note the formation of a salt-wedge after each partial water change. Salinity equilibrium reached one week after each partial water change. Rainfall associated with tropical storm Fay reduced salinity (8/20-8/24). Weather courtesy of www.NOAA.gov.

Table 5. Minimum and maximum values for salinity, pH, temperature, and nutrients throughout the study, including data before and after the unmonitored gate opening. Data for temperature, salinity, and pH are summarized for all stations; data for nutrients and chlorophyll a are summarized for sites 1 and 5 only.

	Initial (6/3)	**After gate-opening 1; salinity equilibrium (7/10)**	**After gate-opening 2; salt wedge present (7/10-7/17)**	**After gate opening 2; salinity equilibrium (8/17/8/26)**	**After gate opening 3; salt wedge present (8/26-9/2)**	**After gate opening 3; salinity equilibrium (9/2-10/1)**
Near surface salinity (ppt)	n/a	10.6-10.65	10.79-12.96	13.61-15.28	13.68-16.22	17.36-18.4
Near bottom salinity (ppt)	5.16- 5.19	10.62-10.65	13.31-20.63	13.58-15.29	17.12-24.55	17.47-18.42
Near surface pH	n/a	7.52-7.57	7.23-8.27	6.96-7.86	6.91-8.76	7.33-7.61
Near bottom pH	7.11- 7.27	7.47-7.66	6.87-8.1	7.00-7.62	6.65-8.12	7.24-7.55
Temp (°C)	28.7- 29.4	27.89-28.55	28.45-32.99	28.21-29.33	29.39-31.1	23.14-29.21
TDN (mg/l)	n/a	0.74-0.95	n/a	0.76-0.86	0.96-0.98	0.5-0.77
TDP (mg/l)	n/a	0.0704-0.087	n/a	0.0554-0.094	0.0612-0.0616	0.0538-0.0815
Chl *a* (µg/l)	n/a	4.49-5.72	n/a	5.92-50.02	6.7-9.35	4.37-5.44

The high chlorophyll *a* reading on August 4th was not accompanied by an increase in turbidity. Turbidity remained low and was less than 5 ntu 98.9% of the time. Increases in turbidity were observed for several hours after the gates were opened (Figure 7).

The pH increased following partial water changes (Table 5, Figure 8). Surface pH was higher than bottom pH 96.9% of the time, with an average surface pH of 7.68 and an average bottom pH of 7.35 (Table 5). Even after salinity equilibrium was reached, pH remained unequal with regard to depth (Figure 9).

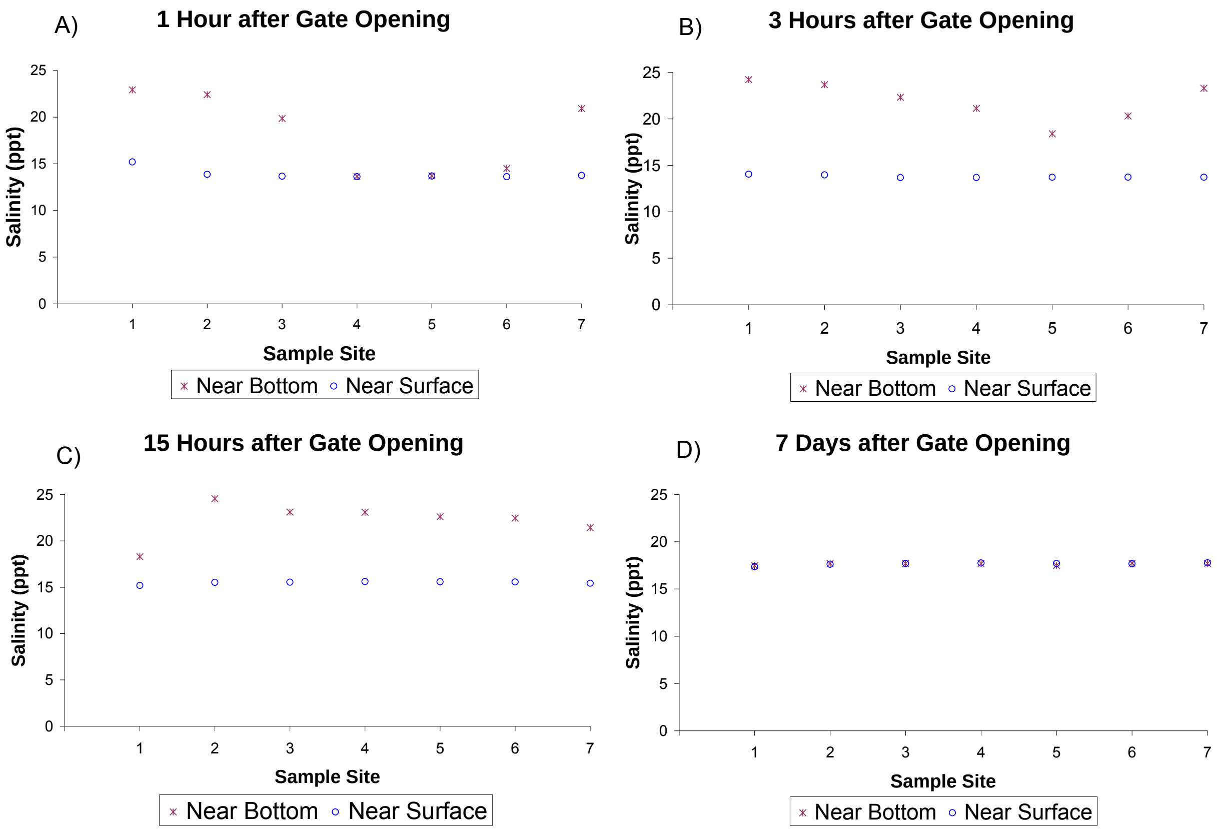

Figure 6. Salinity changes over a one-week timeframe at the seven sites following the 8/26/08 gate opening. Higher saline water first appeared in the sites nearest the gate (sites 1 and 2), and appeared last in sites furthest from the gate (sites 4 and 5). After 15 hours (C), a salt wedge had formed with fairly constant bottom salinity across most sites. Site 1 had reduced bottom salinity while the wedge was present, possibly due to it being about 0.5 m shallower than the other sites. All sites had uniform surface and bottom salinity seven days after gate opening.

Table 6. Raw nutrient data. Unless otherwise indicated, samples were collected from site 1. Samples collected in duplicate prior to gate openings on 7/10/08 and 8/26/08.

Sample ID	Date Collected	Chlorophyll (ug/l)	Total N (mg /l)	Total P (mg/l)
FOPU Moat	7/10/08	5.72	0.95	0.087
FOPU Moat Dup	7/10/08	4.49	0.74	0.0704
FOPU Moat 1	7/22/08	7.31	0.85	0.094
FOPU Moat 5	7/22/08	5.92	0.86	0.09
FOPU Moat	8/4/08	50.04	0.76	0.0554
FOPU Moat	8/26/08	6.7	0.96	0.0616
FOPU Moat Dup	8/26/08	9.35	0.98	0.0612
FOPU Moat 1	9/22/08	4.66	0.77	0.0789
FOPU Moat 5	9/22/08	4.37	0.5	0.0538
FOPU Moat	10/1/08	5.44	0.7	0.0815

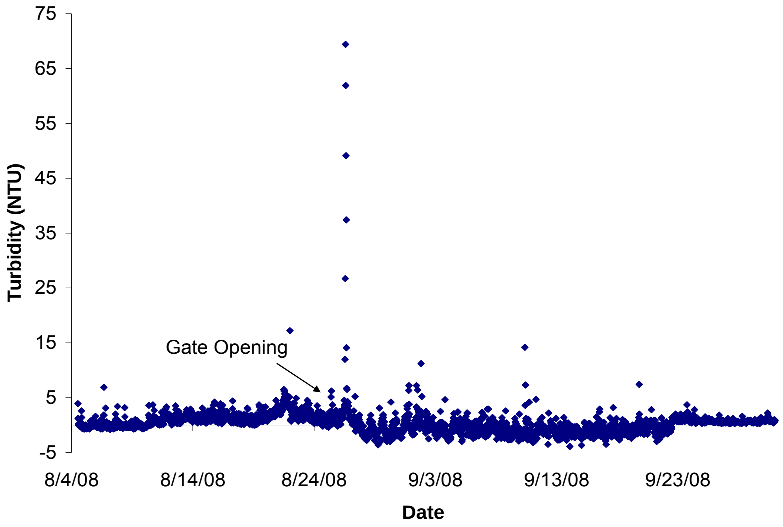

Figure 7. Turbidity readings remained low throughout the study, but increased for a short period of time following the partial water changes. Turbidity spiked during gate opening events as water flow stirred up sediments.

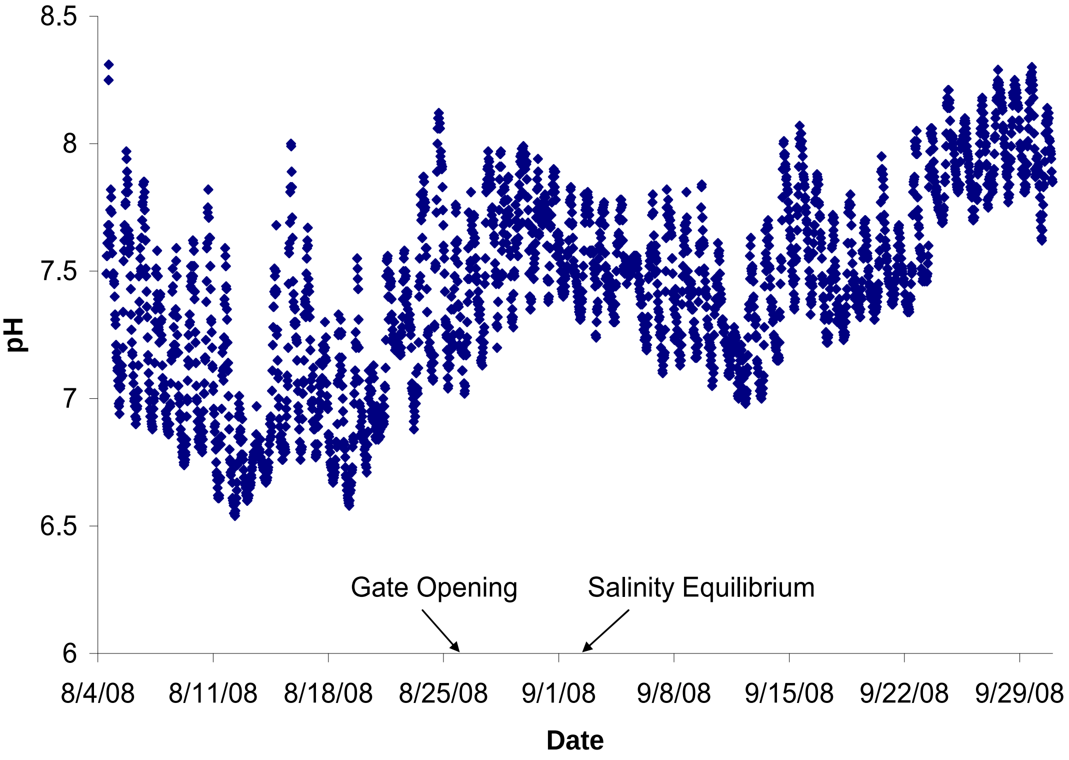

Figure 8. pH increased following third gate opening.

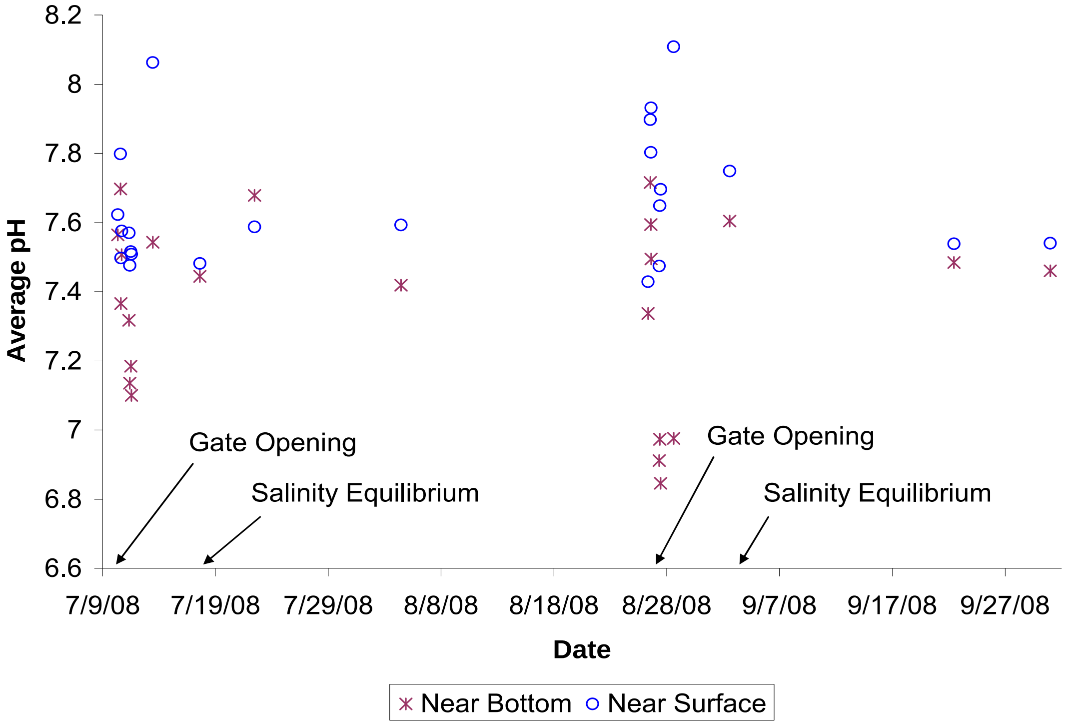

Figure 9. Average pH readings (sites 1-7) at the surface and near the bottom. pH was consistently higher near the surface than near the bottom, even after salinity equilibrium was reached.

Surface water quality parameters (temperature, turbidity, dissolved oxygen, pH, and salinity) were fairly uniform around the moat at the surface between the seven sites during any given round of sampling (i.e. salinity in Figure 6). In contrast, water quality measurements recorded along the bottom by the datalogger were not uniform at any given time. Sites 2-6 tended to have similar readings, however, measurements from site 1 often varied slightly from the other bottom sites. Prior to salinity equilibrium, site 1 bottom had a lower salinity and higher temperature than the other sites (Figure 3c). After salinity equilibrium, pH remained higher along the bottom of site 1 than along the bottom of other sites.

Dissolved oxygen at the fixed site (8/4/2008 – 10/1/2008) had an overall range of 0.64-11.15 mg/l with an average of 4.34 mg/l, therefore ranging between poor and good values according to the National Coastal Condition Report (U.S. EPA 2001, Table 7). Dissolved oxygen increased following the second monitored gate opening and increased further when water temperatures started dropping (Figure 10). Dissolved oxygen was always higher at the surface than near the bottom, and the surface readings (Range 4.04-13.31 mg/l) were all within the good range (Table 7, Figure 11). Near-bottom readings ranged from good to poor (Range 0.23-8.36 mg/l), and were often within the poor range during the nighttime and early-morning hours (Figure 11). On the morning of 7/10/08 when dissolved oxygen concentrations were within the poor range, crabs were observed swimming near the middle of the water column.

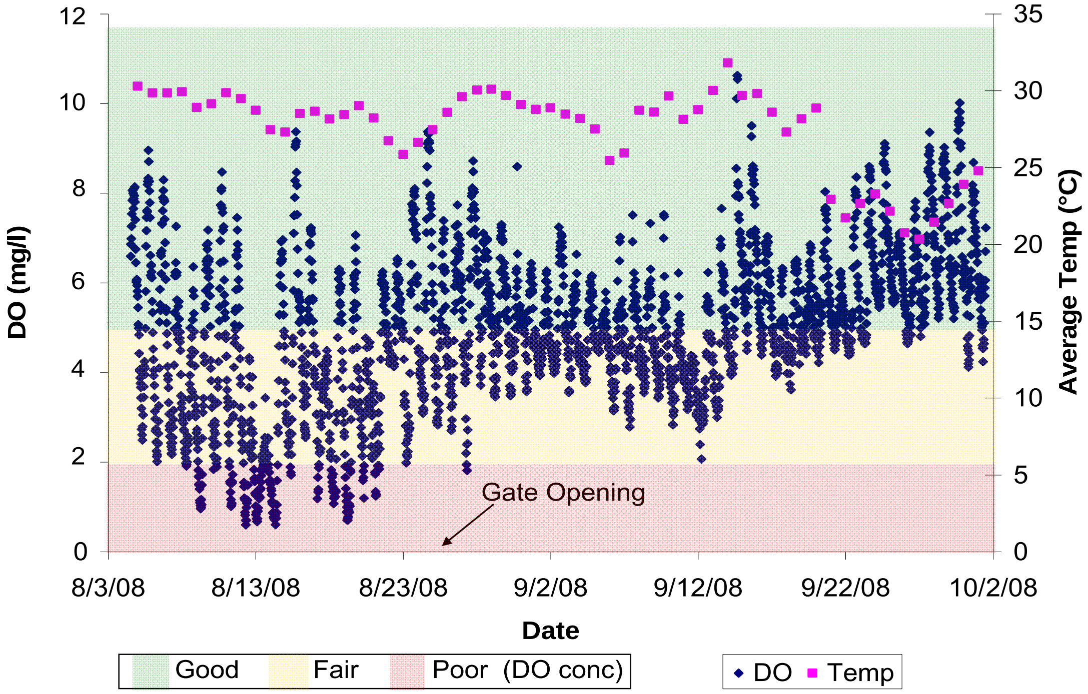

Figure 10. DO changes over time at fixed-site. DO increased after partial water change and increased further when temperatures started dropping around 9/21/08. Good, fair, and poor indicate assessment criteria according to U.S. EPA 2001.

Table 7. Criteria for assessing nutrients (U.S. EPA 2001).

	Good	**Fair**	**Poor**
Chl *a* (µg/l)	< 5	5 – 20	> 20
TDN (mg/l)	< 0.1	0.5 – 1.0	> 1
TDP (mg/l)	< 0.01	0.01 – 0.05	> 0.05
DO (mg/l)	< 2	2 – 5	> 5

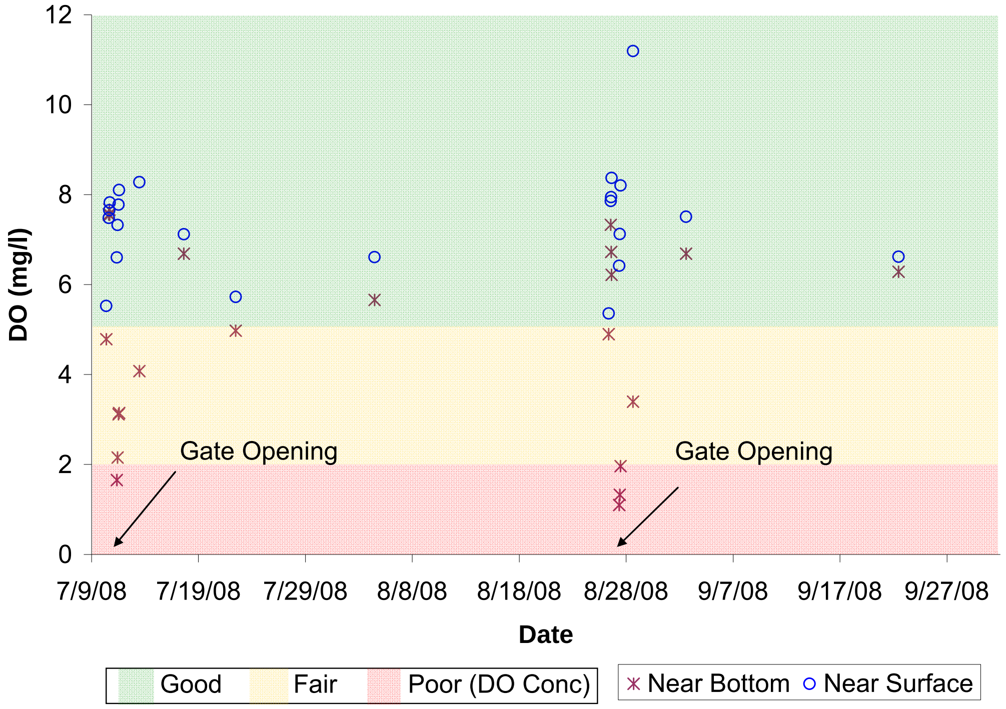

Figure 11. Average DO readings (sites 1-7) at the surface and near the bottom. Good, fair, and poor indicate assessment criteria (U.S. EPA 2001). All near-surface readings were within the good DO range, however near bottom readings were often within the fair to poor range.

Discussion

Despite very favorable nutrient conditions, duckweed was ultimately eradicated from the moat. This is most likely due to a combination of factors, with salinity being the primary cause of death. After mixing following the final partial water change, the moat salinity (17.47-18.42 ppt) was above the survivorship threshold (16.65 ppt) for duckweed (Haller 1974). Additionally, throughout sampling surface pH (average 7.68) was near the upper limit for the survivable range of 7.8 (Hicks, 1932). Water temperature was above the optimal growth range for duckweed (Hodgson, 1970). We assume a combination of these environmental stressors and herbaceous fish led to the loss of the weed from the system.

Additionally, widgeon grass died shortly after the last partial water change even though turbidity levels were highly favorable all summer. Widgeon grass has a high salinity tolerance; however, rapid salinity changes (10 ppt over 48 hours) have been shown to decrease survival (LaPeyre, 1991). The sudden change in salinity during the moats partial water changes likely induced plant mortality. The formation of the salt-wedges most likely compounded the effect of increased salinity, as the bottom of the moat where the widgeon grass is anchored changed in salinity very rapidly (up to 9.98 ppt over a few hours). This very-rapid initial change to the lower portion of the plant likely shocked them, leading to plant mortality. Additionally, following the first partial water change (on 6/3/08), salinity rose above that for germination (Kahn, 2005); therefore new plants were not recruited. In addition, the water temperature and pH remained at non-optimal values (Kantrud, 1991).

Results from this sampling suggest that partial water changes using estuarine water from the Savannah River led to unfavorable water quality parameters for both widgeon grass and duckweed. It is unclear to what extent water quality (salinity, pH, temperature) or ecological stressors may have contributed to, or caused the weed suppression.

All sites had similar surface water quality readings. However, site 1 differed slightly from the other sites in bottom parameters most likely because it is about 0.5 meters shallower than the other sites. Concerning nutrients, there was no difference between sites 1 and 5. Because water quality is fairly uniform around the moat, a single sample site should be adequate in the future. However, care must be taken if sample site 1 is used, as its shallowness slightly affects bottom water quality readings, though these minor differences are likely negligible.

Turbidity remained low throughout the study; however, there was a chlorophyll *a* spike in the 8/4/08 sample. Chlorophyll *a* was sampled near the middle of the water column (0.5 meters from the bottom), while turbidity was measured near the bottom and near the surface. It is possible that an algal bloom occurred in the middle of the water column, not affecting surface or bottom turbidities. With the exception of this sample, chlorophyll *a* remained within the good range, indicating low algal levels and a healthy system despite high nutrient conditions.

Dissolved oxygen remained high enough over the summer of 2008 to prevent a fish kill, despite frequently dropping into the "poor" range along the bottom at night. Dissolved oxygen was increased after the partial water changes and increased further once temperatures started to cool as summer ended. Higher dissolved oxygen levels at the surface perhaps served as a refuge for animals during low nighttime oxygen conditions.

Based on these data, it is recommend to attempt to use saline water to both control future weed outbreaks in the moat and to reduce dissolved oxygen stress. A minimum of a week between partial water changes is needed to allow saline waters to fully mix to assess water quality changes. The moat salinity should be increased above 16.65 ppt (the upper survivable limit) for duckweed control. Multiple partial water changes leading to step-wise salinity increases may be needed to shock the widgeon grass enough for death. Due to uniformity between sites, water quality only needs to be monitored at a single site.

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Appendix A. Photos of Changes in Duckweed Cover

Figure A.1. July 1, 2008 (nine days before project began). Calm day. Duckweed mostly in a single layer.

Figure A.2. July 11, 2008 (Day after first monitored gate opening). Windy day. Duckweed pushed all together and in “thick layer”. On the 10th, the duckweed was spread sparsely all the way along the moat – not stuck together. Surface salinity is about 10.6

Figure A.3. July 13, 2008 (two days after gate opening). Duckweed looks less bright. Still clumped together in a "thick" layer. Surface salinity is 12.8.

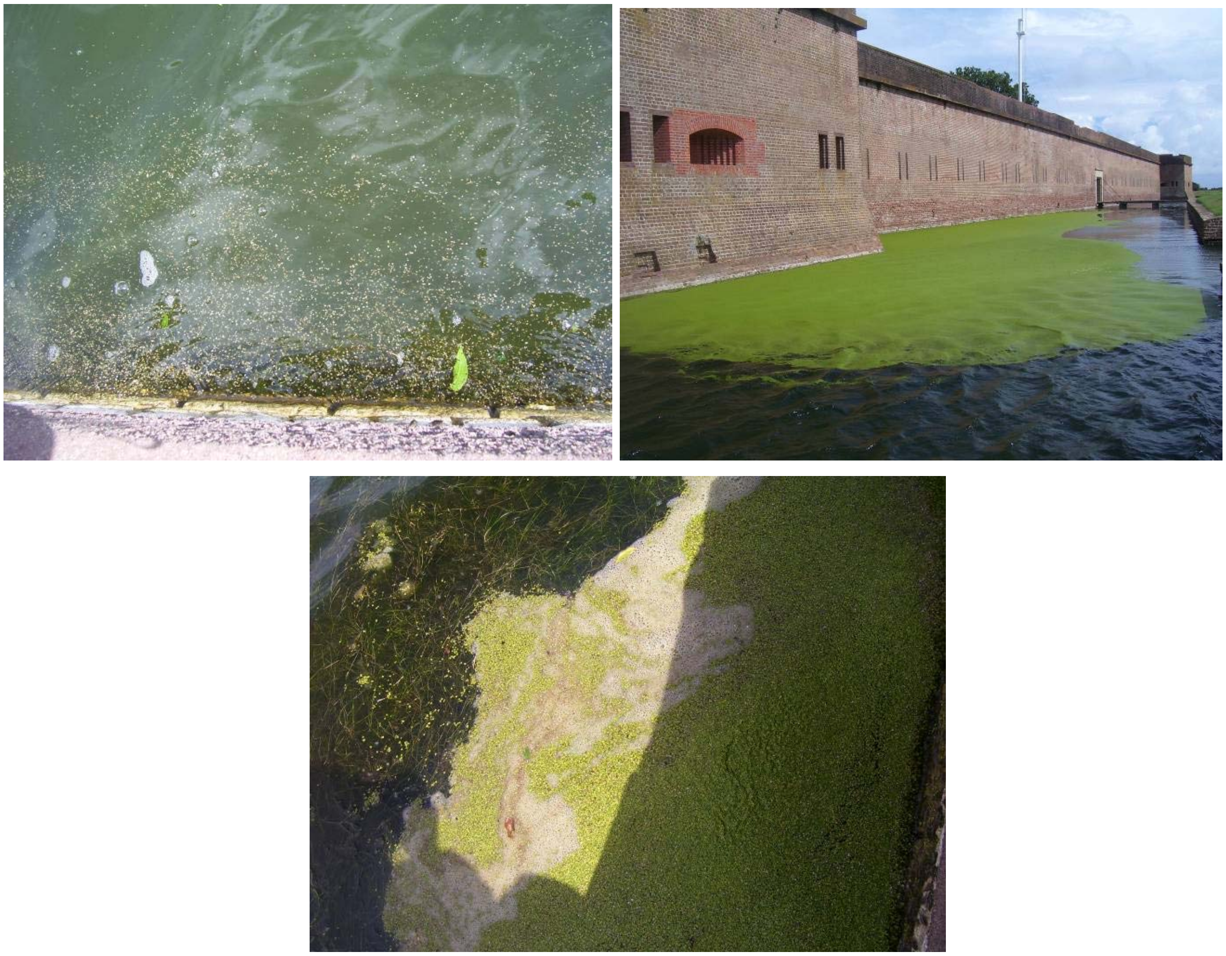

Figure A.4. July 17, 2008 (four days after opening). Duckweed visibly dying. Decaying pieces floating in the water column. Duckweed looks unhealthy. Salinity is 14.5. However, last week, the widgeon grass was abundant, but not thriving. Now it has tons of new green growth. Additionally, at sample site 7, there is this surface algal film that was not present previously.

Figure A.5. August 4, 2008 (three weeks after opening). Surface salinity is about 15.2. Duckweed yellower than previously, especially that present in thick clumps. Appears to be about half the duckweed as was there initially.

Figure A.6. August 26, 2008 (day of 2nd opening; six weeks after first opening). Salinity about 13.5. much less duckweed. Only two patches on either side of the drawbridge between the demilune and the fort. The widgeon grass is less green than last time. Site 7 has lots of widgeon grass though (lower DO?)

Figure A.7. September 2, 2008 (one week after 2nd opening). Much less duckweed. Salinity is about 17.7 on the surface. Widgeon grass still relatively abundant, but not thriving. Dead duckweed in water column.

Figure A.8. September 22 (a little over 3 weeks after 2nd moat opening). Surface salinity about 18.4. Almost no duckweed or widgeon grass. Cooler temps as well. Different fish community than original one. The pictures show almost all of the widgeon grass (there was one other plant left at site 7, but it appeared almost dead with only a little bit of green on it). Pictures show about half the duckweed (the rest was sprinkled along the wall).

Appendix B. Detailed Time Line

June 3rd

Initial visit to the moat to assess the problem and identify the weeds. Samples were brought back to the lab and Eva determined that they were Lemna minor (duckweed) and Ruppia maritime (widgeon grass). A series of spot samples were taken at the seven sites approximately 0.5 m from the bottom (all subsequent spot sampling was taken near the surface and just above the bottom). Measurements were taken between 12:18 and 12:38.

June 18th

Approximate date of unmonitored partial water change.

July 1st

Phone conference between members of NPS I&M network, park staff, and park managers. A decision was made to open the floodgates approximately once a month in order to alter water-quality parameters to reduce the weed presence. Water-quality parameters will be measured frequently during the 24 hours after gate opening events, and approximately once every 1-2 weeks between gate opening events.

July 2nd – 3rd

Mike Hosti and several park employees/interns removed several golf-cart loads of duckweed in attempts of making the moat presentable for July 4th. According to park staff, this made little impact.

July 10th

First day for opening gates. Performed a round of discrete sampling and took a duplicate water sample at site 1 before gates opened. The gate nearest the moat was opened just after 9am on 7/10 to allow the water level in the moat to drop (low tide 9:38 dst). The gate was closed around 11:30 to prevent the moat from draining fully. The closure of the gate nearest the fort also allowed the ditch to drain before the tide reversed. The gate was then re-opened around 13:00 dst allowing river water to enter the moat (high tide 15:07 dst). The first discrete measurements were not taken until 14:00, as there was expected to be a delay of up to 2 hours before the water entered the moat. This was not the case, as the water was pouring in rapidly at this time. By 16:05, no more water appeared to be entering the moat, so the gates were re-closed. Discrete measurements were taken every hour and a half or so between 14:00 and 17:00 when the fort closed (approximately 30-45 minutes in between the last sample of one round and the first sample of the subsequent round). *note: the flapper gate on the river side of the ditch remained open the entire day. Mike Hosti assisted with gate openings and closings.

Before water was added to the moat, salinity was around 10.5 ppt regardless of station or depth. For stations 2-6: After the water was added, a salt wedge formed with initial bottom salinity around 20 ppt, with a top salinity of 10.5 ppt. Crabs were swimming in mid-water column during the morning hours possibly due to low dissolved oxygen conditions at the bottom.

July 11th

Discrete measurements were again taken about every hour and a half from 7:00 until 14:00. For stations 2-6, the salt wedge had decreased in intensity with the top salinity around 11.5 and the bottom salinity around 18.

July 13th

Took a round of discrete measurements. Salt wedge still present, but less intense in sites 2-6. Sites 1 and 7 no longer have a salt wedge (shallower sites).

July 17th

Took a round of discrete measurements. Salt wedge has disappeared with a salinity of about 14.4 around the moat regardless of depth.

July 22nd

Took a round of discrete measurements. Also took nutrient samples from site 1 (the bridge site) and site 5.

August 4th

Took a round of discrete measurements. Salinity increased to about 15.2 possibly due to a loss of approximately 3 inches of water due to evaporation. Nutrient sample taken from site 1. Deployed datalogger near site 1. Sites 1 and 7 have new patches of widgeon grass.

August 26th

Opened the flood gates again for the second monitored partial water change. Mike was unavailable to assist this time. Took discrete measurements at 8:00 and lifted duplicate nutrient samples from site 1 before gates were opened. Gates opened at 9:00, closed at 11:00, re-opened at 13:00, and closed for a final time at 15:25. Low tide at 9:47 and high tide at 15:58. Moat was lowered by about 21 inches (7 bricks), and filled to the previous level. Hourly discrete measurements began at 13:00 and ended at 15:15 when the fort closed. Did not get to talk to Mike today. Flapper gate nearest the river was left open all day. Salt wedge formed again, with a top salinity around 13.6 and a bottom salinity (sites 2-6) around 23.5 ppt. The water flowing into the moat was turbid due to swirling around at both sides of the gate, allowing you to see the layer of this water with the naked eye, unfortunately it was not visible in photographs. Sites 1 and 7 still have patches of widgeon grass.

August 27th

Performed discrete measurements on an hour to an hour and a half cycle. Surface waters had increased in salinity to about 15.5ppt, increasingly slightly throughout the day.

August 28th

Took discrete measurements. Salt wedge has decreased in intensity (nearly 16 ppt at the surface and about 20 ppt at the bottom for sites 2-6).

September 2nd

Met with Mike to discuss moat opening/closing last week. Took a sample of discrete measurements. Salt wedge was gone, however salinity varied slightly between stations and depths. Checked deployed datalogger to see if the salinity changes were visible. Temperature probe appears to have failed. Widgeon grass at both sites 1 and 7 beginning to die.

September 22nd

Took a series of discrete measurements. Swapped moat datalogger. Took nutrient samples at stations 1 and 5. Salinity increased to about 18.4 ppt around the moat. Moat was about 3 inches (one brick) lower than last time. No remaining widgeon grass at site 1, but a few plants remain at site 7. Only one small patch of duckweed remaining covering just a few square meters. Just a handful of widgeon grass plants remaining.

October 1st

Final series of discrete measurements taken. Nutrient sample also taken from site 1. No duckweed or widgeon grass present.

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