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# Evaluating the effect of slot size and environmental variables on the passage of estuarine nekton through a water control structure

Matthew E. Kimball [a,b,*], Lawrence P. Rozas [b], Kevin M. Boswell [c], James H. Cowan Jr. [c]

[a] School of Renewable Natural Resources, Louisiana State University AgCenter, Baton Rouge, LA 70803, USA
[b] NOAA/NMFS/SEFSC, Estuarine Habitats & Coastal Fisheries Center, 646 Cajundome Boulevard, Lafayette, LA 70506, USA
[c] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA

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ABSTRACT

Water control structures (WCSs) installed to regulate water levels can alter both the hydrology and ecology of salt marshes. WCSs are thought to limit nekton ingress into, and egress from, managed marshes. Slots (vertical openings that span most of the water column) incorporated into WCSs are thought to facilitate nekton passage through structures, but little research has directly examined how slot size affects passage rates. We used dual-frequency identification sonar (DIDSON) acoustic imaging to examine the effect of slot width (10, 15, 30, or 60 cm), tidal cycle, diel period, and season on nekton passage at a WCS located in a tidal salt marsh canal. Few individuals (total numbers and relative percentages) used the slots for passage through the structure during any stage of the tidal cycle, day or night, or seasonally. The number and size of migrants were similar for all four slot sizes examined. Nekton used the slots most often on flood tides to access the managed marsh (i.e., swim inside), primarily at night. Individuals entering the managed marsh were larger than those observed leaving the managed marsh. Whereas the majority of migrants were observed during winter months, season did not affect nekton passage in our study. Acoustic imaging allowed a unique and comprehensive evaluation of nekton passage by permitting an examination of factors such as swimming direction and proportion of migrants that are unobservable with other sampling techniques.
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## 1. Introduction

Salt marshes are a mosaic of multiple interconnected habitats that include the vegetated marsh surface, marsh ponds and pools, intertidal creeks, subtidal creeks, and open water habitats (Minello et al., 2003). Numerous fish and natant invertebrate species (nekton), including early life stages of these species, routinely use marsh habitats for critical functions such as refuge, foraging, and reproduction (Kneib, 1997; Able and Fahay, 1998; Cattrijsse and Hampel, 2006). Nekton utilization of salt marsh habitats varies temporally and spatially driven by physical and biological factors such as tidal cycle and diel and seasonal migration patterns (Kneib, 1997; Cattrijsse and Hampel, 2006). In addition, nekton movement through estuarine habitats, or eventual emigration to coastal and ocean habitats, provides an important pathway for the trophic transfer of marsh production (i.e., energy) to the wider estuary and coastal waters (Weinstein et al., 2000). Thus, the ability of resident and transient nekton to move among various estuarine habitats determines the relative value of those habitats for supporting secondary production (Minello et al., 2003; Able et al., 2007).

The use of structural marsh management to establish stable hydrological conditions and enhance the growth of marsh vegetation within managed areas has altered many northern Gulf of Mexico marshes (Rogers et al., 1992). Structural marsh management typically involves constructing levees around an area of marsh to be managed and incorporating at least one water control structure (WCS) to regulate water levels within the managed marsh. The structures most commonly employed throughout US Atlantic and Gulf coast marshes include fixed-crest or variable-crest weirs, gated, and slotted types (Rogers et al., 1994; Rulifson and Wall, 2006).

WCSs vary according to management objectives and physical factors endemic to a particular marsh system, but all are thought to impede the movement of nekton (Rogers et al., 1994). Ingress into, and egress from, marsh nursery areas by fishery species (e.g., brown shrimp, *Farfantepenaeus aztecus*; white shrimp, *Litopenaeus setiferus*; red drum, *Sciaenops ocellatus*; spotted seatrout, *Cynoscion nebulosus*) are often reduced by WCSs (Knudsen et al., 1989; Herke et al., 1992, 1996). Therefore, WCSs could negatively affect the recruitment into salt marshes of the early life history stages of transient nekton that must migrate to estuarine nursery habitat from nearshore and offshore spawning areas and subsequently limit their emigration to other coastal habitat types as older juveniles or adults. Comparisons of managed and unmanaged marshes show that transient nekton species are relatively less abundant in managed areas where WCSs

* Corresponding author. School of Renewable Natural Resources, Louisiana State University AgCenter, Baton Rouge, LA 70803, USA. Tel.: +1 337 291 2121; fax: +1 337 291 2106.
*E-mail address:* mekimball@agcenter.lsu.edu (M.E. Kimball).

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reduce access by young recruits to those marshes (Herke et al., 1992, 1996; Rozas and Minello, 1999). While research has been conducted comparing nekton utilization of various managed and unmanaged marshes, little effort has focused directly on nekton movement through WCSs and thus the mechanisms by which WCSs affect nekton movement remain unknown (Rogers et al., 1992).

Slots are narrow vertical openings designed to allow water exchange and enhance the passage of nekton through WCSs. Slots are thought to improve the passage of nekton because they can extend the full height of the WCS, and when open (some are adjustable), permit water flow throughout the entire water column. Improved nekton passage has been observed for slotted WCSs compared to other WCS types (Rogers et al., 1992; Rulifson and Wall, 2006). Similarly, vertical slots incorporated into dam fishways improve fish passage for riverine species (Stuart and Mallen-Cooper, 1999; Stuart and Berghuis, 2002).

Since, first and foremost, WCSs are designed to regulate water level, managers are limited in their ability to incorporate features into WCSs that facilitate nekton passage. Their task is made more difficult by the paucity of information regarding the effectiveness of various WCS designs for nekton passage. For instance, it is generally accepted that slots improve nekton passage compared to other WCS openings (Rogers et al., 1992; Rulifson and Wall, 2006), but no studies have examined the effect of slot width on nekton passage through WCSs in salt marshes. Consequently, various slot widths (e.g., 4, 10, and 60 cm) are currently utilized in existing WCSs in salt marshes, likely solely reflecting hydrological design requirements rather than dimensions favorable for nekton passage. Information on the effect of slot width on nekton passage would offer managers the flexibility necessary to ensure that adequately sized slots (for nekton) are incorporated into future WCS designs in salt marshes. Further, recent advances in the use of imaging sonar technology for fisheries applications (Moursund et al., 2003), particularly in shallow salt marsh habitats (Boswell et al., 2007a,b), suggest that the novel application of acoustic imaging to examine nekton passage through WCSs in salt marshes may elucidate fine scale temporal and spatial nekton utilization and movement patterns that could previously only be inferred or were impossible to observe using conventional nekton sampling techniques. Therefore, the main objective of our study was to examine the effect of slot width on nekton passage through a WCS by comparing the number and size of individuals migrating through different slot widths. We also examined the effects of tidal cycle, diel period, and season on nekton passage. We addressed these objectives by recording and analyzing nekton movement patterns at a WCS in southeast Louisiana using imaging sonar techniques with a dual-frequency identification sonar (DIDSON).

## 2. Materials and methods

### 2.1. Study area

The study area was located within the upper Breton Sound estuary near Hopedale, Louisiana, USA (29°49′8.07″N, 89°36′48.32″W). Our study focused on a WCS installed in a canal connecting a 1540 ha managed mesohaline marsh and Bayou La Loutre (Fig. 1). The Hopedale WCS has three 2.1 m diameter flap-gates and two 0.6 m wide × 2.1 m high slots (Fig. 1). The slots are located 5.2 m apart, one near the center of the canal and the other off to the side of the center channel (henceforth referred to as the side-channel slot). This WCS is positioned across a canal, 125 m upstream from the channel mouth. The canal is approximately 30 m wide and lined with rip-rap between the WCS and the protective barriers (Fig. 1). During our study, the center channel slot remained fully open, and the flap-gates opened only during ebb tides to discharge water from the managed marsh.

### 2.2. Field sampling

To determine the effect of slot width on nekton migration through the WCS, four variable slot widths were examined: three experimental (10, 15, and 30 cm) and the control (60 cm). Slot height was not altered. Individual slot covers were manufactured so that when installed, each experimental slot was centered over the slot opening in the structure. Slot covers were made of reinforced aluminum sheeting (6 mm) and held in place with bolt-on clamps to prevent any movement while in position. Each slot width was applied to the side channel slot position for a full tidal cycle defined as the period between successive slack low tides (approximately 24 h). Nekton sampling began at slack low tide of day 1 and proceeded through four consecutive tidal cycles (one cycle per slot width). The sequence of slot width treatments applied to the four consecutive tidal cycles was determined randomly. We sampled the structure seasonally to coincide with peak annual occurrence periods for economically important Gulf coast species in December 2008 and January, March, and May 2009.

Nekton movement through the side channel slot was examined for each slot width using an imaging sonar (dual-frequency identification sonar, DIDSON; www.soundmetrics.com). The DIDSON operates as an acoustic video camera (4–21 frames $s^{-1}$) and permits sampling in turbid waters and at night. We used the high frequency mode (1.8 MHz), which uses 96 beams (0.3° horizontal [H] × 14° vertical [V]) for a total field of view of 29° H × 14°V (see Boswell et al., 2008), as this mode is most appropriate to collect high-resolution data at short ranges (<12 m). The DIDSON was mounted on an adjustable platform, which provided a highly stable yet portable platform

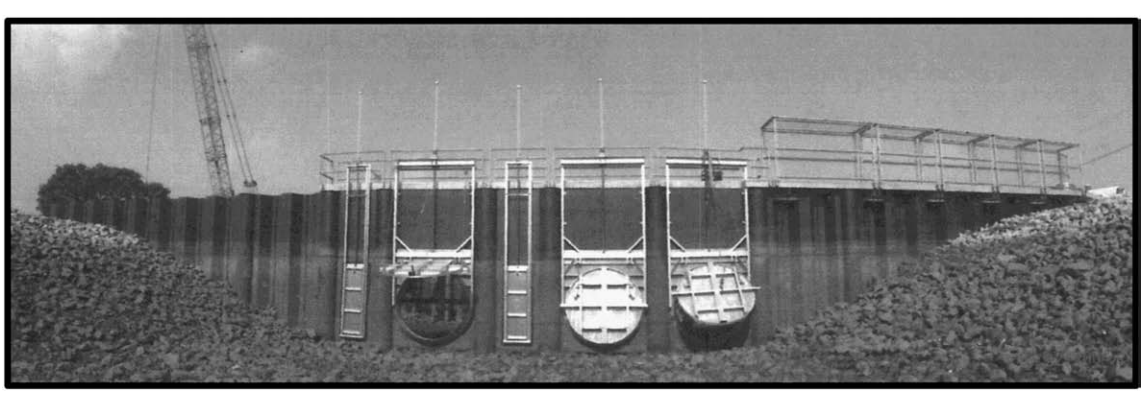

**Fig. 1.** A de-watered view of the WCS from the canal outside the managed area showing two slots (each 0.6 m wide by 2.1 m high) and three flap-gates (each 2.1 m diameter) (Photo courtesy of NMFS HCD, Baton Rouge, LA). The platform-mounted DIDSON was focused on the side-channel slot (i.e., the slot closest to the creekbank on the left side). Note, the slots are closed in this picture and two flap-gates are partially open.

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suitable for horizontally aimed acoustic monitoring in shallow (~2 m) estuarine habitats (described in Boswell et al., 2007a). The platform-mounted DIDSON was positioned approximately 9 m away from the side-channel slot in the canal outside the managed area. The DIDSON was aimed directly at the side-channel slot and adjusted to center the sonar in the water column. This position optimized data quality and minimized the potentially confounding effect of introducing structure immediately in front of the slot opening, yet still permitted viewing of the entire water column at the slot. Once properly positioned, the platform-mounted DIDSON was left in place to continuously record the four consecutive tidal cycles each sampling month. Power supply and data acquisition were controlled from the channel bank, where the DIDSON interfaced with a laptop computer for real-time viewing and data storage.

Acoustic sampling was complemented with traditional sampling gears, cast nets to target small individuals (<20 cm) and gill nets for large individuals (>20 cm), to qualitatively catalog species presence and migration periods in the study area. Cast nets (4.8 mm monofilament mesh, 2.4 m radius) were used to sample nekton in the canal at three stations (0, 30, and 60 m away) on the managed (inside) and unmanaged (outside) sides of the WCS. For each tidal cycle, casts ($n=3$) were thrown at each station once each during flood tide and ebb tide. Gill nets (25, 51, 76 mm multi-panel monofilament mesh, 1.8 m depth × 15.5 m length), one on each side of the WCS, were used to sample nekton in the canal 10−30 m away from the structure.. Gill nets were set for 3 h once during each flood tide and ebb tide within each tidal cycle.

Environmental and water quality variables were measured once during each tidal cycle in the open marsh channel near the WCS. Temperature, salinity, and dissolved oxygen were measured at the surface with a YSI Model 85 handheld meter. Turbidity samples were collected at the surface once per tidal cycle and analyzed in the laboratory using a MicroTPW Turbidimeter (HF Scientific, Inc.). Center channel water depth (m) was measured every 15 min continuously throughout each sampling period with a HOBO Water Level Logger (Onset Computer Corporation), and these data were used to determine maximum and minimum center channel depths during each tidal cycle. Due to the uniform channel bottom profile (Fig. 1), center channel water depth was representative of the water depth across the channel in front of the WCS openings (on both sides).

Water velocity through the slots may have changed with slot width and affected nekton movement. Velocity (m $s^{-1}$) through the side-channel slot was measured with an Aquadopp acoustic Doppler current profiler (Nortek USA) in June 2009 over four consecutive tidal cycles. Velocity was not measured during DIDSON observations to avoid possible interference with the current profiler (e.g., presence of profiler near the slot, acoustic interference). The profiler (right-angle head) was mounted on the underside of a float on the water surface and positioned in the canal outside the managed marsh with fixed cables approximately 2.5 m directly in front of the slot. In this position, the profiler measured water velocities every 5 min at approximately 20 cm intervals throughout the water column during each tidal cycle. Each slot width was applied to the side channel position for a full tidal cycle (i.e., slack low to the following slack low, approximately 24 h), following the same procedure used for sampling nekton with the DIDSON.

### 2.3. Data analysis

Acoustic imaging data collected with the DIDSON for each tidal cycle was divided into flood tide (i.e., slack low tide to slack high tide) and ebb tide (i.e., slack high tide to slack low tide). Flood tide and ebb tide videos were then each divided into three equal time blocks with the first time block designated as "early," the second as "middle," and the third as "late," resulting in a total of six tide stages: early flood, mid flood, late flood, early ebb, mid ebb, late ebb. To account for variation in tidal duration among these six stages, the video data were sub-sampled by randomly selecting 4 five-minute segments from each stage. Thus, each tidal cycle yielded 6 twenty-minute tide stage video segments or a combined 2 h of DIDSON data for analysis.

Sub-sampled DIDSON data were analyzed using a semi-automated analytical approach to estimate nekton size, abundance, and behavior. Acoustic data were imported, preprocessed, and analyzed in Echoview (version 4.7, Myriax Software Pty Ltd). A detailed description of the analytical approach can be found in Boswell et al. (2008). Because one entire ebb tide (=1 h of sub-sampled data) was not recorded during the December 2008 sampling period, the sub-sampled data total was 31 h rather than a balanced total of 32 h. A limitation in the size of objects that can be resolved from DIDSON data required us to restrict the Echoview analyses to include only targets (nekton) >2 cm in total length. Echoview analyses output data for each tide stage were classified into two categories: migrating individuals and congregating individuals. Migrating individuals were defined as nekton swimming through the slot. Congregating individuals were defined as those observed in front of the WCS, but not swimming through the slot. For each category, we enumerated a total count and estimated the total length of each individual during each tide stage. Migrant abundance was defined as the number of migrants per tide stage. We also calculated the percentage of migrants (i.e., number of migrating individuals/number of congregating individuals) for each tidal stage. In addition, swimming direction (i.e., going into or coming out from the managed marsh) was determined for each migrant.

### 2.4. Statistical analyses

Each acoustic data segment was treated as an independent sample in our analysis, because each segment reflected a unique suite of conditions related to hydrodynamic and biological factors present at the time the data were recorded. Migrant abundance and percentage data were analyzed using a four-factor Analysis of Variance (ANOVA) with slot width, tide stage, diel category (day or night), and month as factors (PROC GLM; SAS, v9.1, 2003). Each tide stage was classified into a diel category based on whether daylight or darkness prevailed (occurred >10 min during the tide stage segment). Two tide stages evenly divided between day and night were excluded from the analyses, and three ebb tide segments were not sampled in December; therefore the actual sample size of $n=91$ tide stages is slightly smaller than the balanced sample size of $n=96$. We also used a five-factor ANOVA with slot width, tide stage, diel category, month, and direction (going inside or coming outside) as factors to analyze the size of migrants. To satisfy the assumptions of ANOVA, we transformed migrant abundance ($\log_{10}[x+1]$), percentage (arcsine), and length ($\log_{10}$) data prior to analyses. For each ANOVA, interaction terms were included using a backward stepwise approach where insignificant interactions were excluded from the model. Differences in treatment means were examined using the Tukey–Kramer test for unequal sample sizes (Dunnett, 1980; Day and Quinn, 1989).

We used logit modeling, preferred when both response and predictor variables are categorical (Floyd, 2001), to independently analyze the effect of tide, season, slot treatment, and diel category on swimming direction (PROC LOGISTIC; SAS, v9.1, 2003). All predictor variables were binary: tide = flood or ebb, season = winter (December and January) or spring (March and May), slot width treatment = control slot width (60 cm) or experimental slot width (10, 15, and 30 cm), diel category = day or night.

Data on the nekton species collected with traditional sampling gears (i.e., cast net and gill net) were for descriptive purposes only and therefore were not statistically analyzed. These data were used to inform the analyses and interpretation of the acoustic imaging data by providing seasonal abundance and size data on the nekton species present at the WCS during field sampling periods.

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**Table 1**
Mean (with standard error) temperature, salinity, dissolved oxygen, turbidity, and center channel water depth for each nekton (December, January, March, and May) and water velocity (June) sampling month. Each variable was measured once per slot treatment, thus $n=4$ per month. Turbidity was not measured in December or May. Inside water depth was not measured in December.

| Environmental variable | December | January | March | May | June |
|---|---|---|---|---|---|
| Temperature (°C) | 15.0 (2.5) | 18.3 (1.4) | 13.8 (1.3) | 28.6 (0.7) | 28.0 (0.6) |
| Salinity | 14.3 (0.4) | 10.7 (1.0) | 10.6 (0.9) | 10.5 (0.1) | 9.0 (0.5) |
| Dissolved oxygen (mg $L^{-1}$) | 7.2 (0.31) | 6.0 (0.40) | 6.9 (0.78) | 5.6 (0.16) | 4.0 (0.30) |
| Turbidity (NTU) | – | 1.5 (0.6) | 0.7 (0.5) | – | 0.7 (0.2) |
| Outside water depth, Max (m) | 2.90 (0.06) | 2.73 (0.11) | 2.66 (0.06) | 2.67 (0.03) | 2.76 (0.05) |
| Outside water depth, Min (m) | 2.25 (0.09) | 2.01 (0.08) | 2.11 (0.08) | 2.24 (0.01) | 2.25 (0.03) |
| Inside water depth, Max (m) | – | 2.38 (0.05) | 2.37 (0.02) | 2.49 (0.03) | 2.45 (0.02) |
| Inside water depth, Min (m) | – | 2.19 (0.06) | 2.25 (0.03) | 2.38 (0.01) | 2.34 (0.02) |

Environmental and water quality data were examined with descriptive statistics. Water velocity data were examined for each of the four slot widths separately. Velocity measurements for each tidal cycle were divided into six tide stages following the same procedure used for DIDSON data. For each tide stage, mean water velocities were calculated using all velocity measurements for each 20 cm depth increment and plotted to create water column velocity profiles (i.e., velocity [m $s^{-1}$]×depth [m]). Thus, tidal cycle water velocity profiles (i.e., all six individual tide stages) were created for each of the four slot widths.

## 3. Results

Most water quality measurements were similar among sampling periods (Table 1). Water temperature, the exception, varied by sampling month, and both the highest (May = 28.6 °C) and lowest (March = 13.8 °C) temperatures were observed during spring. Mesohaline salinities were observed during all sampling months (mean = 11.5, SE = 1.76). Dissolved oxygen was consistently high (mean = 6.4 mg $L^{-1}$, SE = 0.82). Turbidity was low at the WCS (mean = 1.1 NTU, SE = 0.70), although this variable was measured only in January and March. Maximum (mean = 2.7 m, SE = 0.12) and minimum (mean = 2.2 m, SE = 0.12) outside center channel water depths were similar during each sampling period. The outside tidal range (i.e., maximum–minimum center channel depth) observed at the WCS was similar among sampling months (mean = 0.6 m, SE = 0.13). The inside center channel maximum (mean = 2.4 m, SE = 0.06) and minimum (mean = 2.3 m, SE = 0.09) water depths and the inside tidal range (mean = 0.14 m, SE = 0.05) were also similar during each sampling period.

Environmental and hydrological conditions during June water velocity sampling were similar to those during earlier nekton sampling months (Table 1). Mean water velocities were typically low (<0.2 m $s^{-1}$) during most of the tidal cycle for all slot width treatments. Throughout the water column and at all tide stages, water velocities were relatively low at both the 10 cm wide (≤0.19 m $s^{-1}$) and 15 cm wide (≤0.15 m $s^{-1}$) slots. Flood tide water velocities were ≤0.2 m $s^{-1}$ at all depths for the 30 cm wide slot, but ebb tide velocities were greater (0.2–0.3 m $s^{-1}$) in near surface waters (e.g., ≤0.75 m) than in the rest of the water column (≤0.15 m $s^{-1}$). Water velocities for the 60 cm slot width were similar to those of the 30 cm slot width for flood and ebb tide stages. At all depths, flood tide water velocities were ≤0.15 m $s^{-1}$. Near surface water velocities (0.25–0.35 m $s^{-1}$) were greater than those throughout the rest of the water column (≤0.2 m $s^{-1}$) during ebb tide.

### 3.1. Migrant abundance

A total of 746 individuals were observed migrating through the side-channel slot during 31 h of sub-sampled acoustic imaging video recorded over four sampling periods from December 2008 to May 2009. This equates to approximately 24 migrating individuals $h^{-1}$. Migrant abundance was affected by tide stage and was greater during flood tide ($n=596$) than ebb tide ($n=150$) (Table 2, Fig. 2). Significantly more individuals migrated during mid flood tide (mean = 15.9, SE = 4.54) than all ebb tide stages (early, $p=0.0073$; mid, $p=<0.0001$; late, $p=<0.0001$). More individuals migrated during late flood tide (mean = 9.0, SE = 2.37) than mid ebb tide ($p=0.0001$) and late ebb tide ($p=0.0027$). A larger number of migrants also passed through slots during early flood tide (mean = 12.3, SE = 3.25) than mid ebb ($p=<0.0001$) and late ebb ($p=0.0013$). Migrant abundance also varied seasonally (Table 2, Fig. 3). More individuals used the slots in December ($n=362$) than any other sampling month (January, $p=0.0018$; March, $p=<0.0001$; May, $p<0.0001$). The lowest abundance of migrants was observed in March ($n=40$), and migrant abundance also was significantly higher in January than March ($p=0.0011$). Our analysis detected no significant effect in migrant abundance from slot width or diel category (Table 2, Fig. 3), but there was a significant interaction between these two factors (Fig. 4). During the night, more individuals used the 60 cm slot than the 15-cm ($p=0.0453$) slot.

### 3.2. Percentage of migrants

During 31 h of monitoring with acoustic imaging, a total of 310,524 individuals were observed congregating in front of the WCS. Because the numbers of congregating and migrating individuals were recorded for the same discreet time segments, this information was used to determine the proportion of congregating individuals that used the slot (i.e., percentage of migrants) during each tide stage. No significant slot-width or diel effect on the percentage of migrants was detected by our analysis (Table 2, Fig. 3). The percentage of

**Table 2**
Analysis of variance results ($p$-values for $F$ statistics) for effect of slot width, tide stage, diel category, and month on migrant abundance (i.e., migrant total per tide stage), the percentage of migrants (i.e., number migrating/number congregating per tide stage), and individual migrant length observed with DIDSON. A backward stepwise approach was used where insignificant interaction terms were excluded from the model. Swimming direction was only included as a factor in the analysis of migrant length. "na" = not applicable. "ns" = not significant.

| Dependent variable | Error $df$ | Slot ($df=3$) | Tide ($df=5$) | Diel ($df=1$) | Month ($df=3$) | Slot × diel ($df=3$) | Direction ($df=1$) |
|---|---|---|---|---|---|---|---|
| Abundance | 75 | 0.5456 | <0.0001 | 0.7786 | <0.0001 | 0.0066 | na |
| Percentage of migrants | 75 | 0.7307 | 0.0213 | 0.9756 | <0.0001 | 0.0025 | na |
| Length | 732 | 0.0222 | 0.5908 | 0.8596 | <0.0001 | ns | <0.0001 |

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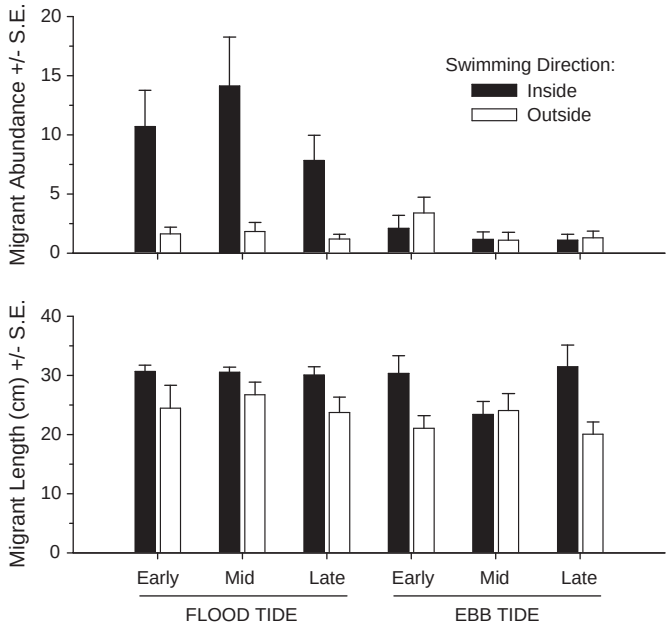


**Fig. 2.** Mean migrant abundance (migrants per tide stage), and mean length of migrants (each with standard error) observed with DIDSON by tide stage and swimming direction ($n = 746$ total). Swimming direction: inside = individuals going into the managed marsh; outside = individuals coming from the managed area.

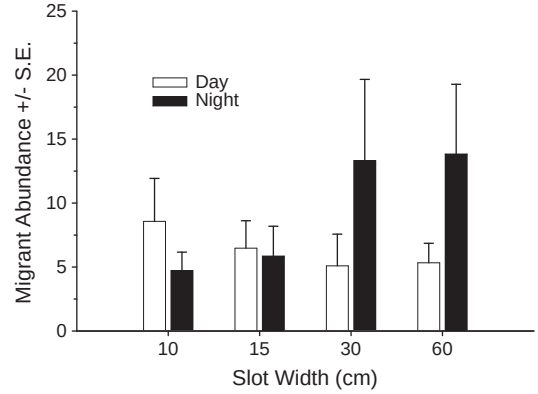


**Fig. 4.** Mean migrant abundance (migrants per tide stage, with standard error) observed with DIDSON by slot width and diel category (day or night) for individuals migrating through the WCS slot ($n = 695$ total; diel category could not be assigned for two tide stages).

migrants varied for the slot-width by diel category interaction, but no significant differences in treatment means were detected (all $p > 0.05$). Tide stage was statistically significant in the analysis (Table 2). A greater percentage of individuals passed through the slot during mid-flood tide than during mid ebb ($p = 0.0456$) and late ebb ($p = 0.0282$). A greater percentage of individuals passed through the slots during December than any other sampling month (all $p < 0.0001$). The percentage of migrants, however, was similar for January, March, and May (all $p > 0.6$).

### 3.3. Migrant length

Migrating individuals ranged in size from 4 to 104 cm, but most individuals (56%) were 15–35 cm in length (Fig. 5). Mean migrant length varied slightly by slot width (smallest to largest: 10<60<15<30) (Table 2, Fig. 3), but our analysis detected no significant differences in treatment means among slot widths (all $p > 0.05$). The size of migrants varied by month (Table 2, Fig. 3), and could be grouped seasonally into winter (December, mean length = 30.3, SE = 0.78; January = 32.8 cm, SE = 0.81) and spring (March, mean length = 14.9 cm, SE = 1.43; May = 20.3 cm, SE = 1.07). Migrants were larger in winter than spring (all $p < 0.0001$), but within seasonal groupings, lengths were not

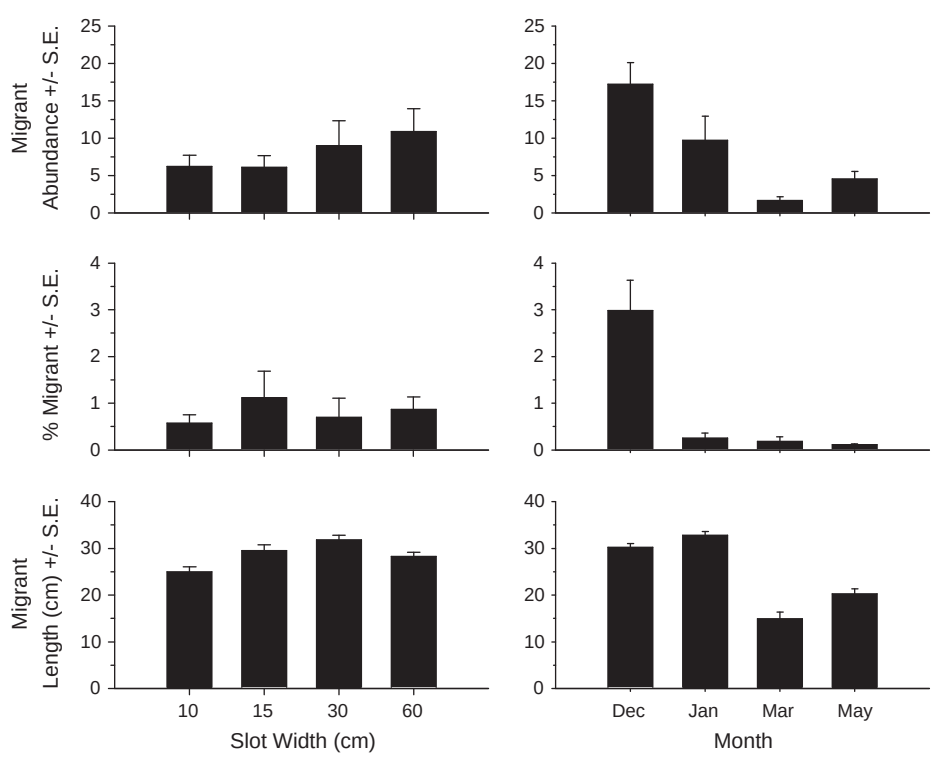


**Fig. 3.** Mean migrant abundance (migrants per tide stage), percentage of migrants (i.e., number migrating/number congregating per tide stage), and migrant length (each with standard error) observed with DIDSON for slot width and sampling month for all individuals migrating through the WCS slot ($n = 746$ total).

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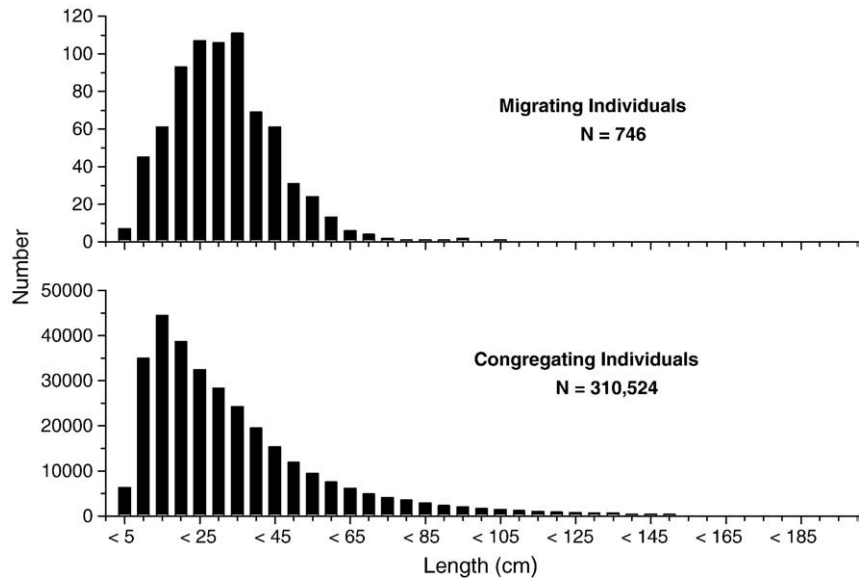


**Fig. 5.** Length-frequency distribution for all individuals observed with DIDSON sorted into 5-cm groups (e.g., <5, <10, <15, … <200 cm). Migrating individuals were observed migrating through the slot and congregating individuals were observed in front of the slot during the same time period. Note, *y*-axes scales differ between graphs.

significantly different (winter, $p = 0.7211$; spring, $p = 0.2266$). Length also varied with swimming direction (Table 2). Migrants observed swimming into the managed marsh (mean length = 30.3 cm, SE = 0.58) were larger than those leaving the managed marsh (mean length = 23.2 cm, SE = 1.11; $p = <0.0001$). Diel category and tide stage did not have an effect on the size of migrants (Table 2, Fig. 2).

### 3.4. Swimming direction

The probability of migrants swimming into the managed marsh (i.e., going inside) was examined for tides, seasons, slot width treatments and diel categories (Table 3). Based on the results of logit modeling, the swimming direction of migrants was influenced by the tidal cycle (Fig. 2). The probability of a migrating individual swimming into the managed area was much greater during flood tide (88%) than ebb tide (43%). The probabilities that individuals migrating into the managed area used the 60 cm slot (85%) or the smaller experimental slot widths (75%) were similar. Swimming direction varied for migrants throughout the diel cycle (Fig. 6). The probability of a migrating individual swimming into the managed area was greater at night (84%) than during the day (68%). Season was not a good predictor of the swimming direction of individuals migrating through the slots (Table 3).

**Table 3**
Logit modeling results for the effect of tide (flood or ebb), season (winter or spring), slot treatment (control or experimental), and diel category (day or night) on the swimming direction (going inside or coming outside) of migrating individuals ($n = 746$). Each predictor variable was analyzed individually. All associated $df = 1$. "na" = not applicable.

| Model information | Predictor variable | | | |
|---|---|---|---|---|
| | Tide | Season | Slot treatment | Diel category |
| Intercept estimate | −0.2953 | 1.0115 | 1.0904 | 1.6935 |
| Wald's $\chi^2$ | 3.2001 | 30.0123 | 108.5630 | 176.8374 |
| *p*-value | 0.0736 | <0.0001 | <0.0001 | <0.0001 |
| Predictor estimate | 2.2489 | 0.3664 | 0.6792 | −0.9176 |
| Wald's $\chi^2$ | 118.4962 | 3.0161 | 11.0491 | 25.5148 |
| *p*-value | <0.0001 | 0.0824 | 0.0009 | <0.0001 |
| Odds ratio estimate | 9.477 | na | 1.972 | 0.399 |

### 3.5. Nekton community

A total of 32 nekton species and 26,621 individuals were collected with cast nets and gill nets during our study (Table 4). More species and individuals were collected in cast nets ($n = 27$ species; 26,481 individuals) than in gill nets ($n = 16$ species; 131 individuals). Cast net samples consisted primarily of small individuals (99.9%<15 cm), whereas a mix of small and large individuals were collected with gill nets (61% 12–20 cm; 39%>20 cm). Gulf menhaden *Brevoortia patronus*, bay anchovy *Anchoa mitchilli*, and striped mullet *Mugil cephalus* were the most abundant small fishes (<20 cm). Decapods crustaceans (grass shrimp *Palaemonetes pugio*; brown shrimp; blue crab *Callinectes sapidus*; length = 3–15 cm) also were frequently collected with these sampling gears. Several species of sciaenids (black drum *Pogonias cromis*; red drum; spotted seatrout) and lepisosteids (alligator gar *Atractosteus spatula*; spotted gar *Lepisosteus oculatus*) were among the large fishes (>20 to 100 cm) collected at the WCS. Although large fishes were less abundant than small individuals in cast net and gill net samples, these species were frequently caught on hook and line in the channel adjacent to the WCS (on both sides) by recreational fisherman during most sampling months. Similarly, on several occasions, river otters *Lutra canadensis* and adult American

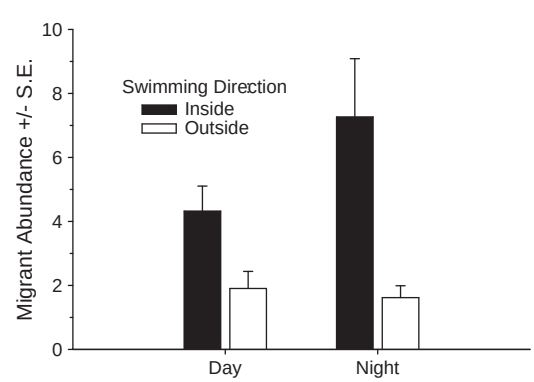


**Fig. 6.** Mean migrant abundance (migrants per tide stage, with standard error) observed with DIDSON by diel category (day or night) and swimming direction for individuals migrating through the WCS slot ($n = 695$ total; diel category could not be assigned for two tide stages).

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**Table 4**
Total number (per month) and mean length (cm) with standard error (all months combined) for each species collected with cast nets and gill nets. Fishes and invertebrates were measured either in total length (*), fork length (§), or carapace width (†).

| Species | Cast net | | | | | | Gill net | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dec | Jan | Mar | May | Length | S.E. | Dec | Jan | Mar | May | Length | S.E. |
| *Adinia xenica** | 7 | 0 | 0 | 0 | 2.7 | 0.15 | – | – | – | – | – | – |
| *Alosa chrysochloris§* | 2 | 0 | 0 | 1 | 8.6 | 1.66 | 0 | 0 | 2 | 0 | 21.4 | 1.55 |
| *Anchoa mitchilli§* | 682 | 244 | 54 | 1750 | 4.7 | 0.02 | – | – | – | – | – | – |
| *Ariopsis felis§* | – | – | – | – | – | – | 0 | 0 | 0 | 2 | 26.6 | 5.75 |
| *Atractosteus spatula** | – | – | – | – | – | – | 0 | 1 | 0 | 3 | 86.8 | 6.56 |
| *Brevoortia patronus§* | 0 | 2 | 93 | 21936 | 5.7 | 0.05 | 0 | 6 | 5 | 3 | 17.5 | 0.53 |
| *Callinectes sapidus†* | 6 | 20 | 6 | 25 | 1.8 | 0.14 | 4 | 2 | 3 | 51 | 14.4 | 0.34 |
| *Cynoscion arenarius** | – | – | – | – | – | – | 0 | 0 | 1 | 0 | 24.2 | – |
| *Cynoscion nebulosus** | 0 | 0 | 0 | 1 | 31.7 | – | 1 | 0 | 1 | 7 | 38.1 | 3.85 |
| *Cyprinodon variegatus* | 49 | 6 | 0 | 1 | 3.9 | 0.11 | – | – | – | – | – | – |
| *Dorosoma cepedianum§* | 4 | 2 | 1 | 16 | 14.4 | 0.49 | 0 | 3 | 1 | 0 | 20.4 | 3.72 |
| *Dorosoma petenense§* | 1 | 0 | 0 | 0 | 8.4 | – | – | – | – | – | – | – |
| *Elops saurus§* | 0 | 0 | 0 | 10 | 8.0 | 0.28 | – | – | – | – | – | – |
| *Farfantepenaeus aztecus** | 0 | 1 | 4 | 131 | 10.3 | 0.15 | 0 | 0 | 0 | 4 | 12.4 | 0.55 |
| *Fundulus grandis** | 8 | 0 | 3 | 1 | 3.9 | 0.43 | – | – | – | – | – | – |
| *Gambusia affinis** | 0 | 0 | 0 | 1 | 4.0 | – | – | – | – | – | – | – |
| *Gobionellus oceanicus** | 1 | 0 | 0 | 0 | 12.5 | – | – | – | – | – | – | – |
| *Lagodon rhomboides§* | 0 | 0 | 0 | 1 | 8.3 | – | – | – | – | – | – | – |
| *Leiostomus xanthurus** | 0 | 0 | 0 | 85 | 12.2 | 0.10 | 0 | 0 | 0 | 1 | 14.9 | – |
| *Lepisosteus oculatus* * | 0 | 2 | 0 | 1 | 50.9 | 6.01 | 0 | 0 | 0 | 1 | 70.2 | – |
| *Litopenaeus setiferus* * | 4 | 1 | 0 | 1 | 8.4 | 1.75 | – | – | – | – | – | – |
| *Menidia beryllina* § | 82 | 5 | 3 | 81 | 5.9 | 0.14 | – | – | – | – | – | – |
| *Micropogonias undulatus* * | 0 | 0 | 35 | 56 | 9.3 | 0.32 | 1 | 1 | 0 | 1 | 20.2 | 1.22 |
| *Mugil cephalus* § | 189 | 226 | 24 | 129 | 14.7 | 0.35 | 1 | 0 | 1 | 0 | 31.8 | 9.05 |
| *Opsanus beta* * | 0 | 0 | 1 | 0 | 9.6 | – | – | – | – | – | – | – |
| *Palaemonetes pugio* * | 11 | 0 | 12 | 447 | 3.5 | 0.03 | – | – | – | – | – | – |
| *Paralichthys lethostigma* * | 0 | 0 | 0 | 1 | 10.1 | – | 0 | 0 | 0 | 1 | 52.8 | – |
| *Poecilia latipinna* * | 12 | 0 | 1 | 0 | 4.0 | 0.18 | – | – | – | – | – | – |
| *Pogonias cromis* * | – | – | – | – | – | – | 1 | 0 | 4 | 3 | 59.0 | 9.65 |
| *Sciaenops ocellatus* * | – | – | – | – | – | – | 11 | 3 | 1 | 0 | 44.5 | 0.64 |
| *Sphoeroides parvus* * | 0 | 0 | 0 | 1 | 2.8 | – | – | – | – | – | – | – |
| *Trinectes maculatus* * | 1 | 0 | 0 | 0 | 2.3 | – | – | – | – | – | – | – |
| Total | 1059 | 509 | 237 | 24676 | | | 19 | 16 | 19 | 77 | | |

alligators *Alligator mississippiensis* were observed swimming in the canal outside the managed area near the WCS.

## 4. Discussion

Few individuals used the WCS slot based on our extensive observations that included all stages of the tidal cycle, both day and night, and multiple seasons. Comparisons with previous research are limited because only two studies have examined nekton passage through slots at WCSs in estuaries: Rogers et al. (1992) examined nekton emigration from a mesohaline coastal Louisiana marsh pond through a 10 cm wide WCS slot and Rulifson and Wall (2006) examined nekton immigration into an oligohaline coastal North Carolina embayment through 4 cm wide slots. Each of these previous studies employed traps to collect individuals migrating in a single direction and compared nekton passage through WCSs with slots and other WCS types (e.g., fixed-crest weir and flap-gated culvert) that lacked slots. Both of these studies concluded that slots enhanced nekton passage through WCSs. Accounting for sampling effort, Rogers et al. (1992) collected approximately 248 individuals $h^{-1}$ migrating through a slotted WCS but only 155 individuals $h^{-1}$ migrating over a fixed-crest WCS (comparison of 1986 data only). Rulifson and Wall (2006) collected approximately 2 individuals $h^{-1}$ migrating through slots compared to 0.5 individuals $h^{-1}$ migrating through flap-gates. In our study, migrants were observed at a rate of 24 individuals $h^{-1}$ with acoustic imaging. Unlike the previous studies, however, in our study, there was always at least one additional opening permitting nekton migration through the WCS. Although it was not possible to monitor both slots and the flap-gates on the WCS in our study, the number of migrating individuals would have likely been greater had all these openings been monitored. Assuming the same number of migrants used the center slot as the side-channel slot and three times more migrants used each of the three flap gates (a flap gate is approximately three times the area of a slot), the number of migrating individuals would have been 265 $h^{-1}$. Nonetheless, considering the individuals observed congregating at the WCS during the study period, the percentage of migrants we observed was extremely low (0.24% overall). Using the same number of congregating individuals and the same assumptions discussed previously regarding the other WCS openings (i.e., the center-channel slot and three flap gates), the percentage of individuals migrating through the WCS would still be very low at only 2.6% of the total individuals observed. Examination of migrants within the context of the associated nekton community may provide a more accurate evaluation of migration patterns through WCSs, and therefore should be incorporated into future nekton passage research.

Despite a six-fold difference in slot width, the number and size of migrating nekton was similar for all four slot sizes examined. A 15 cm slot width was reported to limit upstream migration of large fishes (>100 cm) in a dam fishway (Stuart and Berghuis, 2002). Although present at the WCS in our study, large fishes (>100 cm) were rarely observed migrating through the slots. Presumably, the 30 and 60 cm slot widths examined in our study were large enough to allow the passage of even these large fishes. The congregating nekton observed in our study may have been present at the structure for purposes other than passage (e.g., foraging) or possibly avoided the slots for reasons other than the physical restraint imposed by the slot widths used in our study. A single study on fish migration through dam fishways examined the effect of three slot widths (15, 30, and 45 cm) on the size of migrating individuals (Stuart and Mallen-Cooper, 1999). More large barramundi *Lates calcarifer* passed through a 30 cm wide slot than a 15 or 45 cm slot, but total numbers of migrating individuals

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did not differ significantly among the three slot widths, suggesting the original 15 cm slot size was sufficient for juvenile (<60 cm) barramundi passage. Nekton sizes were not reported in two other studies focused on WCS slots (Rogers et al., 1992; Rulifson and Wall, 2006), and no studies other than ours have examined the effect of slot size on nekton passage through WCSs in salt marshes. The four slot widths examined in our study encompass the range of slot sizes commonly used in nekton passage structures (10 cm, Rogers et al., 1992; 15, 30, 45 cm, Stuart and Mallen-Cooper, 1999; 15 cm, Stuart and Berghuis, 2002; 4 cm, Rulifson and Wall, 2006; 30 cm, Stuart et al., 2008). The similar sizes and numbers of migrants observed for all four slot widths in our study suggests that factors other than slot size may have a greater impact on nekton migration patterns.

Water velocities through and around a WCS may influence nekton migration patterns (Rulifson and Wall, 2006). Fishes can avoid entrainment or swim against currents in openings through WCSs only when water velocities do not exceed critical swimming speeds, which are a good estimate of swimming performance capabilities (Plaut, 2001). The swimming performance of fishes is generally related to fish size (length), and critical swimming speed increases with fish length (Wakeman and Wohlshlag, 1982; Wolter and Arlinghaus, 2003; Fisher et al., 2005). Water velocities measured for each slot width throughout the tidal cycle were typically <0.2 m $s^{-1}$, a consistency likely the result of water movement through other openings in the WCS. A review of the swimming performance of riverine fish species indicates that velocities of 0.2 m $s^{-1}$ would exceed critical swimming speeds for fishes <3 cm total length (TL) and burst swimming speeds for fishes <2 cm TL (Wolter and Arlinghaus, 2003). Assuming a similar relationship for estuarine fishes, all but the smallest size classes of fishes were capable of migrating through the WCS slot during all tide stages. The low water velocities we observed would likely only exceed the critical swimming speeds of larvae and small juvenile fishes (e.g., larval red drum <2 cm total length, Faria et al., 2009). These water velocities would also likely exceed the swimming capabilities of early life history stages of invertebrate nekton species, such as blue crab megalopae (Luckenbach and Orth, 1992). Critical swimming speeds of 1 m $s^{-1}$ for juvenile menhaden *Brevoortia tyrannus* (6 cm TL, Hartwell and Otto, 1978) and 0.47 m $s^{-1}$ for striped mullet *Mugil cephalus* (3 cm TL, Nanami, 2007) suggest that individuals of these species equal or greater in size would not be impeded by the water velocities we measured at the WCS slot. Information on critical swimming speeds for smaller sizes of these and other estuarine species is not available, but individuals with critical swimming speeds less than the water velocities observed in our study would likely be entrained by flows through the slots. Based on the water velocities measured in our study, the slot provided a suitable migration pathway for the majority of size classes of nekton we observed at the WCS.

Few studies have directly examined salt marsh nekton migration through WCSs of any type (Rogers et al., 1994). The difficulties associated with sampling nekton with traps and nets as they transit the structure and the inability to manipulate the design (e.g., change slot width) or operational procedure (e.g., close gates) of most WCSs likely limited research opportunities. Previous studies examining nekton migration through WCS slots used traps and collected only those individuals migrating through the slots in a single direction (Rogers et al., 1992; Rulifson and Wall, 2006). Acoustic imaging with the DIDSON allowed us to examine bi-directional migration through the slots and simultaneously observe migrating and congregating individuals at the WCS. The capability to enumerate the individuals congregating at the WCS provided an estimate of those individuals with the potential to pass through the slot. Similarly, the DIDSON provides accurate estimates of fish size (Burwen et al., 2010). Size differences between migrating and congregating individuals provide information on possible interactions between nekton size and passage rates. It is important to note that the DIDSON is only capable of collecting data in a single two-dimensional plane. In this study, the DIDSON was aimed horizontally, thus all targets identified are collapsed over the vertical domain and determining the vertical position of individuals in the water column was not possible. Continued development of this approach has resulted in the potential to acquire three-dimensional target positions (Boswell, unpublished data).

Nekton migration patterns were influenced by the tidal cycle, with a greater number of migrating individuals during flood tide than ebb tide stages. Peak migration occurred during mid flood tide, and most individuals migrated into the managed marsh during flood tide stages. Individuals were less likely to migrate into the managed marsh during ebb tide. Tidal migration patterns observed at the slot may be explained, at least in part, by the configuration of the WCS examined in our study. During ebb tide, the three flap gates and two slots were open, and water flowed from the managed marsh, whereas during the flood tide, the two slots served as the only avenue for nekton passage. The low numbers of individuals observed migrating from the managed area during ebb tide could be attributed to most individuals using the flap gates for passage. With only the two slots available to migrants during flood tide stages, higher numbers of migrants would be expected to use the slots then. Further, the relative low number of migrants observed coming from the managed area during flood tide may indicate a preference for migration with, rather than against, the current.

Individuals migrating into the managed marsh were larger than individuals coming from the managed area. An opposite pattern has been reported for brown shrimp, where individuals emigrating from managed marsh ponds were larger than those emigrating from similar unmanaged marsh ponds (Herke et al., 1987; Knudsen et al., 1989). Long retention times in managed marshes can lead to larger individuals in managed than unmanaged areas (Knudsen et al., 1989). With the greater degree of connectivity afforded by two continuously open slots and periodically open flap gates at the WCS in our study, large individuals likely were able to emigrate from the managed marsh. Migrants were larger during winter months (December and January) than in spring months (March and May) when juveniles of many species were abundant (e.g., bay anchovy and gulf menhaden). Nearly 75% of all migrants observed during the entire study period were observed in winter months, when migrating individuals were largest, but season was not a good predictor of swimming direction. Size differences between individuals migrating inside and those coming outside were likely somewhat attributable to migrants disproportionately using slots for immigration during flood tide stages and emigrating from the managed marsh through other openings during ebb tide stages.

Migrating individuals had a greater probability of swimming into the managed marsh at night than during the day. During the night, more individuals migrated through the 30 and 60 cm wide slots than narrower slots. Diel differences in nekton migration patterns were likely due to species-specific migration patterns. Common US Atlantic coast salt marsh nekton species including Atlantic silverside *Menidia menidia*, white mullet *Mugil curema*, weakfish *Cynoscion regalis*, and alewife *Alosa pseudoharengus* were more abundant during night than day in subtidal marsh channels (Rountree and Able, 1993). Similarly, Atlantic croaker *Micropogonias undulatus* and brown shrimp migrate primarily at night in US Gulf coast marshes (Rogers and Herke, 1987; Rogers et al., 1993). Most freshwater fish species in a study examining diel fish migration through a vertical-slot fishway exhibited either day or nighttime migration patterns, but not both (Bizzotto et al., 2009).

The large number of individuals observed congregating at the WCS during our study may be the result of nekton behavioral responses. Avoidance behavior associated with fish passage openings has been observed for riverine nekton species (Jansen et al., 2007; Kemp and Williams, 2008). European eels *Anguilla anguilla* altered their behavior when approaching dam turbines and exhibited hesitation or recurrent

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swimming behavior (Jansen et al., 2007). Congregating individuals and schools were often observed circling in front of the WCS, sometimes actively swimming away from the slot opening. These individuals appeared to adopt recurrent swimming behavior (i.e., circling), possibly in response to physical or environmental stimuli associated with the structure (e.g., changes in water flow patterns at openings; Coutant and Whitney, 2000). In our study, juveniles and adults of common estuarine species were collected at the WCS including gulf menhaden, striped mullet, bay anchovy, inland silversides *Menidia beryllina*, red drum, and blue crab. Other types of artificial structures in salt marsh habitats such as bulkheads support less diverse and less abundant nekton communities than natural marsh habitats (Peterson et al., 2000; Bilkovic and Roggero, 2008). Unlike bulkheads, many WCSs permit water exchange through one or more openings (e.g., slots and flap-gates). Mixing from the water exchange through these slots or flap-gates may create favorable water quality and concentrate food for planktivores. The presence of these forage fishes, sometimes in great abundance (e.g., juvenile gulf menhaden in May), in turn may attract piscivorous nekton species to WCSs.

A major limitation of acoustic imaging is species identification. Large fishes such as groupers or tunas and fishes with unique body shapes or swimming types such as eels are easily identified (Mueller et al., 2008; Frias-Torres and Luo, 2009; Han et al., 2009), but most targets cannot be identified to species. Information is unavailable to identify most common salt marsh nekton species, especially smaller size-classes, therefore no attempt was made to identify nekton species from acoustic observations in our study. Image resolution often limits identification and is largely dictated by the experimental set-up. For example, using our sampling methodology, individuals <2 cm were not distinguishable and had to be excluded from analyses. Unlike species-specific fish passage structures (e.g., shad or salmonid fishways), WCS slots were designed to permit migration by the entire species assemblage. Species identification may be less critical when examining the migration patterns of the entire nekton assemblage rather than focusing on a single species, but information on species-specific migration patterns would be necessary for more in-depth analyses. It is important to note that the number of congregating individuals observed in this study is a conservative estimate, meant primarily to provide context for evaluating nekton passage. The experimental set-up was chosen to allow viewing of the entire water column at the WCS slot opening. Nonetheless, only a portion of the water column was located in the view field for most of the distance between the DIDSON mount and the WCS. Therefore, it is possible that more individuals were present, but went undetected. As is the case with many underwater video and acoustic sampling techniques, it is often impossible to determine whether an individual left the view field and then returned, which can result in inflated counts (Ellis and Bell, 2008). Congregating individuals were often observed swimming in a large circular pattern in front of, and parallel to, the WCS, crossing the view field from side to side in a single pass. Sub-sampling the video data by randomly selecting five-minute segments for analysis reduced the likelihood of recounting individuals, but did not eliminate this circumstance entirely. Another limitation of acoustic imaging is that a DIDSON unit is only capable of projecting in one dimension (either horizontally or vertically). Simultaneous horizontal and vertical viewing (three-dimensional observations) can be accomplished by combining two DIDSON units, but this protocol is still under development (Boswell, unpublished data).

## 5. Conclusion

Few individuals used the slots for passage through the structure even though these openings appeared wide enough to accommodate even the largest fishes observed in our study. Moreover, the swimming ability of all but the smallest size-classes of the nekton species likely would be adequate to overcome the current velocities measured at the slots. We could identify no physical restraint imposed by the slots that would explain the low passage rates measured in our study. Nekton used the slots most often on flood tides to access the managed marsh at night. While the majority of migrants were observed during winter months, season did not have an impact on nekton passage in our study. Acoustic imaging allowed a unique and comprehensive evaluation of nekton passage at salt marsh WCSs by permitting the examination of factors such as swimming direction and the proportion of migrants that are unobservable with other nekton sampling techniques.

Because migrants were observed throughout all stages of the tidal cycle, during both day and night, and during multiple seasons, our results suggest that slots can provide a great deal of temporal flexibility for migrants. In contrast to WCS openings such as flap gates that only allow nekton passage in a single direction for a portion of the tidal cycle, slots remain fully open to accommodate various species-specific temporal movement patterns. The rate of nekton passage through the WCS was not related to slot width in our study, indicating that managers have some flexibility when incorporating slots into WCS designs. Incorporating even small-width slots (e.g., 10–15 cm) in WCSs should be beneficial as slots improve nekton passage compared to non-slotted WCSs (Rogers et al., 1992; Rulifson and Wall, 2006). Further, although we only focused on a single side-channel slot, the inclusion of multiple small-width slots at various positions in the WCS spanning the channel (e.g., side-center-side) may facilitate nekton passage by providing multiple access points.

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