

2011

## Spatial ecology of adult spotted seatrout, *Cynoscion nebulosus*, in Louisiana coastal waters

Jody Lynn Callihan

*Louisiana State University and Agricultural and Mechanical College*

Follow this and additional works at: [https://digitalcommons.lsu.edu/gradschool\\_dissertations](https://digitalcommons.lsu.edu/gradschool_dissertations)



Part of the [Oceanography and Atmospheric Sciences and Meteorology Commons](#)

---

### Recommended Citation

Callihan, Jody Lynn, "Spatial ecology of adult spotted seatrout, *Cynoscion nebulosus*, in Louisiana coastal waters" (2011). *LSU Doctoral Dissertations*. 941.

[https://digitalcommons.lsu.edu/gradschool\\_dissertations/941](https://digitalcommons.lsu.edu/gradschool_dissertations/941)

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact [gradetd@lsu.edu](mailto:gradetd@lsu.edu).

**SPATIAL ECOLOGY OF ADULT SPOTTED SEATROUT, *CYNOSCION  
NEBULOSUS*, IN LOUISIANA COASTAL WATERS**

A Dissertation

Submitted to the Graduate Faculty of the  
Louisiana State University and  
Agricultural and Mechanical College  
in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy

in

The Department of Oceanography and Coastal Sciences

by  
Jody Lynn Callihan  
B.S., University of Miami, 2002  
M.S., University of Maryland, 2005  
December 2011

© Copyright 2011  
Jody Lynn Callihan  
All rights reserved

## **DEDICATION**

I dedicate this scholarly work to my parents, Jim and Deb Callihan, and grandparents, John and Charlotte Miller, who sparked my interest and passion for the marine world through visits by us landlubbers to the Virginia coast to go flounder fishing every summer. Through these childhood experiences my interests in the marine environment grew, and most importantly, so did my curiosity in what lies beneath those deep blue waters which undoubtedly hold many important discoveries yet to be made.



## **ACKNOWLEDGEMENTS**

First and foremost, I would like to thank my advisor, Dr. Jim Cowan. He provided all the resources necessary to conduct a cutting edge telemetry study. He also allowed me great freedom and flexibility in designing my study. Through his supervision, I have vastly improved my critical thinking and independent research skills. I am also grateful to Jim for allowing me to complete my dissertation from afar. Furthermore, discussions and correspondence with Jim were instrumental in helping secure my next research endeavor. I also thank my committee members, Drs. Mark Benfield, Jaye Cable, and James Geaghan, for their valuable input and advice on my dissertation research.

I would like to thank the Louisiana Department of Wildlife and Fisheries, particularly the Marine Fisheries staff at the Lake Charles office, for their extensive field support during the Calcasieu Lake telemetry study. Special thanks go to Mike Harbison for his dedication to this project. I spent over 120 days on the water during the course of this study, and on most of those days, Mike was at the helm of our trusty downloading and fish tagging vessels. Mike was a great field partner, hard worker, and conversationist as we often exchanged fishing and hunting stories and discussed sports or fisheries management. We also had several interesting run-ins with the Gulf's famous pop-up thunderstorms, but Mike always brought us to safety in these events. Mike also took many of the photos used in this study and helped design the second generation channel marker receiver mounts. I also thank the following members of the LDWF Lake Charles crew for their field assistance: Rodney Benson, Peyton Cagle, Mandy Courville, Jerry Ferguson, Brad Launey, Amanda Shahan, and Joey Verret.

I extend gratitude to the anglers who volunteered their time to catch the fish used in the Calcasieu Lake telemetry study. Special thanks go to Will Drost, who was pivotal in helping me

recruit and coordinate angler efforts. I also thank the following anglers: Clinton Cox, Chas Drost, Mitch Drost, Cory Duhon, John Dunham, Scott Duplchein, Ellis Dupree, David Fontenot, Moby Goodwin (and sons), Seth Guidry, Ralph Hays, David Hebert, Tom Henning, Bill Hull, Stephen Lucchesi, George Paret, Eric Schram, Gus Schram, Don Scott, Allen Singletary, John Suttle, Tom Turpin, Ross Turpin, Rusty Vincent, Jeremy Waltrip, and Bryan Williams. Also, the following guides from Hackberry Rod & Gun provided study fish: Kevin Augustine, Jason Broussard, Buddy Oakes, and Guy Stansel. I also thank Jerry George, Kevin Savoie, and Mandy Tumlin for their assistance aboard the R/V Ladyfish during tagging events. I believe this study was an excellent example of the co-management concept, whereby collaborative efforts and exchange of ideas among university scientists, management agencies, and fisheries stakeholders can benefit the management of our natural resources.

I am also appreciative of the United States Coast Guard, Cameron Prairie National Wildlife Refuge, and Louisiana Department of Natural Resources for granting me permission to mount receivers onto their existing infrastructure. Thanks also go to Mark Miller who fabricated channel marker mounts; to Marty Heaney and Jeff Enright of Bio-West, who dove and installed those mounts. I would also like to thank Rusty Vincent of the Century Group for donating a truckload of concrete bucket anchors that were used in buoyed receiver riggings. I also thank David Walters of the United States Geological Survey for providing hourly water quality data from the USGS gages in Calcasieu Lake and the Southern Regional Climate Center at LSU for providing meteorological data from the Lake Charles airport.

I would like to thank Dr. Ed Chesney for introducing me to the world of fish husbandry and helping set up my holding experiment at LUMCON. I also thank Jeremy Miller for assisting with daily experimental maintenance and also teaching me how to efficiently use a cast net.

Thanks also to Jeremy Wood for helping catch live menhaden off the LUMCON docks at night to provide prey for my study fish.

I thank the following members of the Cowan lab (past and present) who assisted with my LUMCON study and also helped pull my receiver array with a major hurricane looming in the Gulf: Dr. Kevin Boswell, Andy Fischer, Steve Garner, Dr. Joris van der Ham, Dr. Kim de Mutsert, Kirsten Simonsen, Courtney Nosach, and Michelle Zapp. I also thank Dr. Kevin Boswell for introducing me to the powerful tools of acoustic imaging (DIDSON) and complex data visualization (Eon Fusion). The second chapter of this dissertation benefited greatly through discussions with Dr. Dale Webber of VEMCO, thank you. I would also like to thank Drs. Bill Hopkins and Eric Hallerman for securing office space for me at Virginia Tech, where I completed this dissertation.

Last, but not least, I would to thank those loved ones in my life for their support during this long road. Without their perpetual encouragement, this work would not have been possible. To my fiancée Christine Bergeron, I love you and am looking forward to our big day in September and spending the rest of our lives together. Also, thank you for editing and helping streamline this lengthy prose. To my parents, Jim and Deb Callihan, and grandparents, John and Charlotte Miller, thank you for always being there for me in good times and bad.

This work was funded by the Louisiana Department of Wildlife and Fisheries with Sportfish Restoration dollars provided through the United States Fish and Wildlife Service federal assistance program.

# TABLE OF CONTENTS

DEDICATION.....	iii
ACKNOWLEDGEMENTS.....	iv
ABSTRACT.....	ix
GENERAL INTRODUCTION.....	1
References.....	5
CHAPTER 1: SURVIVAL AND TAG RETENTION IN SPOTTED SEATROUT EQUIPPED WITH ACOUSTIC TRANSMITTERS AND DART TAGS.....	9
Introduction.....	9
Methods.....	12
Results.....	23
Discussion.....	29
References.....	35
CHAPTER 2: THE PERFORMANCE OF ACOUSTIC TELEMETRY RECEIVERS IN A SHALLOW, TURBID ESTUARY.....	41
Introduction.....	41
Methods.....	44
Results.....	79
Discussion.....	119
References.....	129
CHAPTER 3: STOCK STRUCTURE OF SPOTTED SEATROUT IN LOUISIANA INFERRED FROM CONVENTIONAL TAGGING AND ACOUSTIC TELEMETRY DATA.....	134
Introduction.....	134
Methods.....	137
Results.....	152
Discussion.....	167
References.....	183
CHAPTER 4: EFFECTS OF METEOROLOGICAL EVENTS ON THE DISTRIBUTION OF SPOTTED SEATROUT IN A LOUISIANA ESTUARY.....	191
Introduction.....	191
Methods.....	193
Results.....	201
Discussion.....	239
References.....	247

CHAPTER 5: HABITAT USE OF ADULT SPOTTED SEATROUT IN CALCASIEU LAKE, LOUISIANA.....	253
Introduction.....	253
Methods.....	255
Results.....	269
Discussion.....	276
References.....	284
GENERAL SUMMARY AND CONCLUSIONS.....	290
VITA.....	296

## ABSTRACT

Spotted seatrout, *Cynoscion nebulosus*, are common in estuaries and coastal waters of the south Atlantic and Gulf of Mexico and are of considerable recreational and economic importance. Still, the spatial ecology of this species is under-studied and poorly resolved, especially in Louisiana waters. To address this important knowledge gap, I examined the movements, distribution, and habitat use of adult spotted seatrout in coastal Louisiana primarily using high-resolution acoustic telemetry and secondarily, conventional tagging (mark-recapture) data. At the largest spatial scale investigated, I found that adults exhibited a high degree of estuarine fidelity and rarely undertook large-scale movements in excess of 50 km. At smaller (intra-estuarine) spatial scales, abiotic factors had a strong effect on fish distribution. Specifically, fish primarily utilized deeper channel habitats during severe weather events (cold storms and tropical fronts) and females avoided oligohaline waters (0.5-5 psu). Adult spotted seatrout also showed clear habitat preferences, whereby oyster reefs and mud-bottom habitats of the estuary proper were used to a greater extent than channel and marsh regions. Seasonal and size trends in habitat use were also evident, as larger fish (> 400 mm TL) showed a high affinity for structured (reef) habitats and across size classes, artificial reefs were utilized most during spring and summer. My results have direct bearing on the assessment and management of this important species and support the current initiative of an ecosystems-approach to management by informing spatial management options. Finally, the results of my methods validation work on the effects of tagging on spotted seatrout and performance dynamics of telemetry equipment have important implications for future studies. Given the high transmitter retention and survival of telemetered spotted seatrout in my holding experiments, biotelemetry should be a feasible approach for future studies on the movement and behavior of this species. Still, in designing

receiver arrays to study fish movements (of any species), it will be necessary to consider the high variability in receiver detection ranges as revealed by my extensive range testing efforts.

## GENERAL INTRODUCTION

Spotted seatrout, *Cynoscion nebulosus*, are an extremely important recreational species and the most sought after coastal sportfish in the nation. In eight of the past ten years (2000-2009), more spotted seatrout were caught than any other species by recreational anglers in US coastal waters, with the majority of the catch (~85% or 25-35 million fish) coming from state waters (estuaries) along the Gulf of Mexico (GOM) (personal communication from the National Marine Fisheries Service, Fisheries Statistics Division, May 2010). Most of the catch in the GOM is taken in Louisiana (50-60% annually), where a rich fishing heritage exists for this species (Baltz et al. 2003). Fishing for spotted seatrout generates a wealth of economic activity. In Louisiana alone, recreational saltwater fishing activities, a large part of which focus on spotted seatrout, generated a total economic impact of \$757 million in 2006 and supported approximately 7,800 jobs in the state (Southwick Associates 2008). Thus, ensuring healthy populations of spotted seatrout should have positive cultural, social, and economic benefits for the state of Louisiana.

Stock assessments periodically conducted by the Louisiana Department of Wildlife and Fisheries (LDWF), the agency that assesses, manages, and protects the state's fisheries resources, suggest that Louisiana's spotted seatrout population is abundant, in good health, and not overfished (LDWF 1997; Blanchet et al. 2001). Indeed, fishing regulations for the recreational sector have remained unchanged since 1988, except for the recent (2006) implementation of more stringent creel and size limits in the southwestern portion of the state (Cameron and Calcasieu parishes), which was largely due to socio-economic factors rather than compromised productivity of the stock.



While the current status of spotted seatrout in Louisiana appears favorable, it is important to remember that exploited populations can exhibit rapid, dramatic shifts in abundance, especially those inhabiting stressed, complex coastal ecosystems. For instance, multiple anthropogenic stressors (e.g., fishing pressure, habitat degradation, pollution, hydrologic manipulations, and climate change) can have cumulative negative impacts such that a threshold or tipping point is exceeded, resulting in population collapses or changes in community structure that may be irreversible (i.e., hysteresis may result) (Cowan et al. 2008; Thrush and Dayton 2010). The potential for such cumulative, deleterious effects of anthropogenic stressors has amplified in coastal ecosystems as the human population continues to grow exponentially and preferentially settle along and modify coastlines (Peterson and Lowe 2009). Thus, even for those fishery species that currently appear healthy and in good condition (such as spotted seatrout), it is prudent not to: 1) assume that status quo management strategies will simply ensure high stock abundance well into the future or 2) become complacent in furthering our knowledge of the biology and ecology of such species. In fact, attaining a comprehensive understanding of the life history and environmental preferences of these species should be viewed as a priority to promote their continued high productivity. Without such information, fishery and environmental management plans may be inadequately informed, potentially resulting in precipitous declines of once productive stocks due to increased anthropogenic insults in a backdrop of fluctuations associated with natural factors (e.g., winter mortality).

Despite the considerable recreational and economic importance of spotted seatrout, some aspects of their ecology and life history remain poorly resolved or under-studied and warrant further investigation for the purposes of enhancing the assessment and management of this species. One such knowledge gap, especially in Louisiana waters, is the spatial ecology of adult

spotted seatrout, specifically their movement and habitat use patterns. Information on adult movements in Louisiana is restricted to a few historical tagging studies conducted by LDWF that were either limited in their spatial scope (i.e., fish were only tagged in one estuarine system: Rogillio 1980; Rogillio 1982; Arnoldi 1985) or had a low number of tag returns (n=30, Adkins et al. 1979). Moreover, there have been few studies on the habitat use and distribution of adults within Louisiana estuaries (but see Helser et al. 1993; MacRae and Cowan 2010). Given the widely recognized utility of incorporating movement and habitat use information in stock assessments and fishery management plans (e.g., from determining appropriate stock boundaries to protecting critical spawning habitats, Zeller 1998; Begg et al. 1999; Stephenson 1999; Rooker et al. 2007; Starr et al. 2007) there is a clear impetus to advance our knowledge of the spatial ecology of this important species occurring in Louisiana coastal waters.

The evolving tool of remote acoustic telemetry can provide unprecedented high-resolution information on the movement, distribution, and habitat use of coastal fishes. With this technique, stationary underwater receivers are deployed to continuously monitor the presence of tagged fish within the detection range of the unit, only requiring the occasional presence of researchers at study sites for periodic receiver maintenance (Heupel et al. 2006). A major advantage of remote acoustic telemetry is longitudinal data compared to traditional approaches used to assess movement and habitat use (e.g., mark-recapture or point sampling), which provide only cross-sectional data. As such, this technology is well-suited for determining residency patterns within monitored areas over long time periods (e.g., months to years). For instance, numerous studies have used this approach to investigate the degree to which fishes are resident in proposed or existing marine reserve boundaries (Glazer and Delgado 2005; Chateau and Wantiez 2008; Bellquist et al. 2008; Meyer et al. 2010; Parsons et al. 2010) and examine annual

or seasonal patterns of residency within individual estuaries (Able and Grothues 2007; Moser and Lindley 2007; Wingate and Secor 2007; Cowley et al. 2008; Reyier et al. 2010). Migration timing as recorded by telemetry receivers can also be dynamically linked to continuously-recorded environmental variables to better understand which factors (and their values) are important in triggering fish migration (Heupel et al. 2003; Sackett et al. 2007; Childs et al. 2008). In addition, detection magnitudes of tagged fish (i.e., how often fish visit and are detected at receivers) can be compared among receivers deployed in different habitat types or areas to quantify habitat use and distribution patterns (Humston et al. 2005; Dewar et al. 2008; Hindell et al. 2008; Afonso et al. 2009; Carlisle and Starr 2009).

For this dissertation, I employed the emerging technology of remote acoustic telemetry to investigate the movements, distribution, and habitat use of adult spotted seatrout in Louisiana coastal waters to advance our knowledge of the spatial ecology and support the management of this important species. A rather unique aspect of this work was that most study specimens were provided by volunteer recreational anglers. The participation of conservation-minded anglers greatly facilitated this study because without their assistance it would have been much more difficult to meet my fish number and size range targets. The high level of angler participation in this study was due in part to the popularity of spotted seatrout, which is an abundant generalist species in estuaries and nearshore coastal waters along the northern GOM. Still, the ‘co-management’ approach I adopted herein could be used for popular sportfish in other regions globally. The first two chapters of this dissertation focus on methods validation. In chapter 1, I examine tagging effects on spotted seatrout via a laboratory holding experiment. Specifically, I assess the survival of spotted seatrout equipped with acoustic telemetry transmitters and external dart tags and also evaluate the retention of both tag types. In chapter 2, I present results from

extensive range testing of telemetry equipment to aid interpretations of telemetry data acquired from tagged fish. This chapter also provides background information on the operation principles of the telemetry system, the rationale for my receiver array design, and methodological details on the deployment and maintenance of the receiver array. Each of the remaining chapters focuses on a different spatial scale of investigation. At the largest spatial scale (chapter 3), I quantify the degree of estuarine residency (within Calcasieu Lake) and inter-basin movement rates using acoustic telemetry and conventional tagging data, respectively, to delineate the stock structure of spotted seatrout in Louisiana. In chapter 4, I use telemetry to examine how changes in abiotic conditions affect fish distribution in a Louisiana estuary. Finally, at the smallest spatial scale (chapter 5), I investigate the habitat utilization of adult spotted seatrout using remote acoustic telemetry.

## References

- Able, K.W., and T.M. Grothues. 2007. Diversity of estuarine movements of striped bass (*Morone saxatilis*): a synoptic examination of an estuarine system in southern New Jersey. *Fishery Bulletin* 105:426-435.
- Adkins, G.A., P. Bowman, and B. Savoie. 1979. A study of the commercial finfish in coastal Louisiana. Louisiana Department of Wildlife and Fisheries, Technical Bulletin 29, Baton Rouge, Louisiana.
- Afonso, P., J. Fontes, K.N. Holland, and R.S. Santos. 2009. Multi-scale patterns of habitat use in a highly mobile reef fish, the white trevally *Pseudocaranx dentex*, and their implications for marine reserve design. *Marine Ecology Progress Series* 381:273-286.
- Arnoldi, D.C. 1985. Aspects of the biology of spotted seatrout, *Cynoscion nebulosus*, in Calcasieu Lake, Louisiana, with management implications. *Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies* 38(1984):1-18.
- Baltz, D.M., R.G. Thomas, and E.J. Chesney. 2003. Spotted seatrout habitat affinities in Louisiana. Pages 147-175 in S.A. Bortone, editor. *Biology of the spotted seatrout*. CRC Press, Boca Raton, Florida.

- Begg, G.A., K.D. Friedland, and J.B. Pearce. 1999. Stock identification and its role in stock assessment and fisheries management: an overview. *Fisheries Research* 43:1-8.
- Bellquist, L.F., C.G. Lowe, and J.E. Caselle. 2008. Fine-scale movement patterns, site fidelity, and habitat selection of ocean whitefish (*Caulolatilus princeps*). *Fisheries Research* 91:325-335.
- Blanchet, H., M. Van Hoose, L. McEachron, B. Muller, J. Warren, J. Gill, T. Waldrop, G. Waller, C. Adams, R.B. Ditton, D. Shively, and S. VanderKooy. 2001. The spotted seatrout fishery of the Gulf of Mexico, United States: a regional management plan. Gulf States Marine Fisheries Commission, Publication Number 87, Ocean Springs, Mississippi.
- Carlisle, A.B., and R.M. Starr. 2009. Habitat use, residency, and seasonal distribution of female leopard sharks *Triakis semifasciata* in Elkhorn Slough, California. *Marine Ecology Progress Series* 380:213-228.
- Chateau, O., and L. Wantiez. 2008. Movement patterns of four coral reef fish species in a fragmented habitat in New Caledonia: implications for the design of marine protected area networks. *ICES Journal of Marine Science* 66:50-55.
- Childs, A.R., P.D. Cowley, T.F. Naesje, A.J. Booth, W.M. Potts, E.B. Thorstad, and F. Okland. 2008. Do environmental factors influence the movements of estuarine fish? A case study using acoustic telemetry. *Estuarine, Coastal, and Shelf Science* 78:227-236.
- Cowan, Jr., J.H., C.B. Grimes, and R.F. Shaw. 2008. Life history, hysteresis, and habitat changes in Louisiana's coastal ecosystem. *Bulletin of Marine Science* 83(1):197-215.
- Cowley, P.D., S.E. Kerwath, A.R. Childs, E.B. Thorstad, F. Okland, and T.F. Naesje. 2008. Estuarine habitat use by juvenile dusky kob *Argyrosomus japonicus* (Sciaenidae), with implications for management. *African Journal of Marine Science* 30(2):247-253.
- Dewar, H., P. Mous, M. Domeier, A. Muljadi, J. Pet, and J. Whitty. 2008. Movements and site fidelity of the giant manta ray, *Manta birostris*, in the Komodo Marine Park, Indonesia. *Marine Biology* 155(2):121-133.
- Glazer, R.A., and G.A. Delgado. 2005. Designing marine fishery reserves using passive acoustic telemetry. Pages 26-37 in National Oceanic and Atmospheric Administration, editor. *Emerging technologies for reef fisheries research and management*. Professional Paper NMFS 5. NOAA, Seattle, Washington.
- Helser, T.E., R.E. Condrey, and J.P. Geaghan. 1993. Spotted seatrout distribution in four coastal Louisiana estuaries. *Transactions of the American Fisheries Society* 122:99-111.

- Heupel, M.R., Simpfendorfer, C.A., and R.E. Hueter. 2003. Running before the storm: blacktip sharks respond to falling barometric pressure associated with Tropical Storm Gabrielle. *Journal of Fish Biology* 63:1357-1363.
- Heupel, M.R., J.M. Semmens, and A.J. Hobday. 2006. Automated acoustic tracking of aquatic animals: scales, designs, and deployment of listening station arrays. *Marine and Freshwater Research* 57:1-13.
- Hindell, J.S., G.P. Jenkins, and B. Womersley. 2008. Habitat utilization and movement of black bream *Acanthopagrus butcheri* (Sparidae) in an Australian estuary. *Marine Ecology Progress Series* 366:219-229.
- Humston, R., J.S. Ault, M.F. Larkin, and J. Luo. 2005. Movement and site fidelity of bonefish (*Albula vulpes*) in the northern Florida Keys determined by acoustic telemetry. *Marine Ecology Progress Series* 291:237-248.
- LDWF. 1997. 1997 report on the status of spotted seatrout. Louisiana Department of Wildlife and Fisheries, Baton Rouge, Louisiana.
- MacRae, P.S.D., and J.H. Cowan, Jr. 2010. Habitat preferences of spotted seatrout, *Cynoscion nebulosus*, in coastal Louisiana: a step towards informing spatial management in estuarine ecosystems. *The Open Fish Science Journal* 3:154-163.
- Meyer, C.G., Papastamatiou, Y.P., and T.B. Clark. 2010. Differential movement patterns and site fidelity among trophic groups of reef fishes in a Hawaiian marine protected area. *Marine Biology* 157:1499-1511.
- Moser, M., and S. Lindley. 2007. Use of Washington estuaries by subadult and adult green sturgeon. *Environmental Biology of Fishes* 79(3-4):243-253.
- Parsons, D.M., M.A. Morrison, and M.J. Slater. 2010. Responses to marine reserves: decreased dispersion of the sparid *Pagrus auratus* (snapper). *Biological Conservation* 143:2039-2048.
- Peterson, M.S., and M.R. Lowe. 2009. Implications of cumulative impacts to estuarine and marine habitat quality for fish and invertebrate resources. *Reviews in Fisheries Science* 17(4):505-523.
- Reyier, E.A., R.H. Lowers, D.M. Scheidt, and D.H. Adams. 2010. Movement patterns of adult red drum, *Sciaenops ocellatus*, in shallow Florida lagoons as inferred through autonomous acoustic telemetry. *Environmental Biology of Fishes* 90(4):343-360.
- Rogillio, H.E. 1980. Movement and migration of the spotted seatrout in southeast Louisiana. Louisiana Department of Wildlife and Fisheries, Federal Aid in Sportfish Restoration, Project F-33, Final Report, Baton Rouge, Louisiana.

- Rogillio, 1982. Movement study of estuarine sportfish. Louisiana Department of Wildlife and Fisheries, Federal Aid in Sportfish Restoration, Project F-41, Final Report, Baton Rouge, Louisiana.
- Rooker, J.R., J.R. Alvarado Bremer, B.A. Block, H. Dewar, G. De Metrio, A. Corriero, R.T. Kraus, E.D. Prince, E. Rodriguez-Marin, and D.H. Secor. 2007. Life history and stock structure of Atlantic bluefin tuna (*Thunnus thynnus*). *Reviews in Fisheries Science* 15:265-310.
- Sackett, D.K., K.W. Able, and T.M. Grothues. 2007. Dynamics of summer flounder, *Paralichthys dentatus*, seasonal migrations based on ultrasonic telemetry. *Estuarine, Coastal, and Shelf Science* 74:119-130.
- Southwick Associates. 2008. The economic benefits of fisheries, wildlife and boating resources in the state of Louisiana – 2006. Southwick Associates, Fernandina Beach, Florida.
- Starr, R.M., E. Sala, E. Ballesteros, and M. Zabala. 2007. Spatial dynamics of the Nassau grouper *Epinephelus striatus* in a Caribbean atoll. *Marine Ecology Progress Series* 343:239-249.
- Stephenson, R.L. 1999. Stock complexity in fisheries management: a perspective of emerging issues related to population sub-units. *Fisheries Research* 43:247-249.
- Thrush, S.F., and P.K. Dayton. 2010. What can ecology contribute to ecosystem-based management? *Annual Review of Marine Science* 2:419-441.
- Wingate, R.L., and D.H. Secor. 2007. Intercept telemetry of the resident contingent of Hudson River striped bass: migration and homing patterns. *Transactions of the American Fisheries Society* 136:95-104.
- Zeller, D.C. 1998. Spawning aggregations: patterns of movement of the coral trout *Plectropomus leopardus* (Serranidae) as determined by ultrasonic telemetry. *Marine Ecology Progress Series* 162:253-263.

# **CHAPTER 1: SURVIVAL AND TAG RETENTION IN SPOTTED SEATROUT EQUIPPED WITH ACOUSTIC TRANSMITTERS AND DART TAGS**

## **Introduction**

Conventional tagging and biotelemetry are commonly used to investigate movement and habitat use of fishes. A chief criterion for making valid inferences about the large, untagged population of interest based on results from tagged individuals is that the chosen tagging methodology has minimal adverse effects on tagged fish (Jepsen et al. 2002; Mulcahy 2003). Attachment procedures and the presence of tags or biotelemetry transmitters and sensors can have negative impacts on survival, growth, and behavior (Bridger and Booth 2003). In addition, applied tags can be expelled during the course of a study.

The most obvious issue related to high tagging mortality is a reduction in the amount of data collected during a study, which can be especially problematic in telemetry studies that generally use costly electronic transmitters. Also, mortality rates can be overestimated if tagging mortality is assumed to be negligible, when indeed it is high or unknown (Pine et al. 2003). A common cause of tagging mortality is disease due to the cumulative stress associated with capture, handling, and tagging. Another potential source of tagging mortality is predation on tagged fish shortly after their release into the wild (Jepsen et al. 2002).

In addition to tagging mortality, tag loss can occur (more directly) via expulsion. Transmitters are often surgically implanted into the peritoneal cavity of fish and can be expelled through the incision, body wall via pressure necrosis, or possibly trans-intestinally (Chrisholm and Hubert 1985; Marty and Summerfelt 1986; Baras and Westerloppe 1999; Jepsen et al. 2002). Tag expulsion can significantly impact the quantity and quality of data in movement studies. If transmitter retention is poor, but assumed to be 100% (i.e., transmitter loss extraneous to fishing



and natural mortality of telemetered fish is assumed to be zero), the degree of residency and utilization of a study area would be underestimated. For instance, if all disappearances of telemetered fish were assumed to represent permanent emigration from the study area, some fish may have actually expelled their transmitters in areas without receiver coverage and subsequently returned (within the battery life of transmitters) to the study area undetected. Furthermore, tag loss can result in imprecise estimates of migration rates. For example, estimates of movement among two or more water bodies would be biased low if tag loss was substantial and persistent over time, especially if a positive relationship existed between movement distance and time at liberty (Patterson et al. 2001).

Sublethal effects of tagging on fish behavior and performance are possible, but are typically more difficult to measure than survival and tag retention. Implanted transmitters may physically interfere with internal organs such as the stomach and gonads, potentially resulting in altered feeding and spawning behavior (Adams et al. 1998; Berejikian et al. 2007). For example, gonads may become regressed and preclude spawning, or spawning frequency and batch fecundity can be reduced. Consumption rates may be significantly lower for implanted fish, resulting in decreased energy intake and growth. Hence, even speculations that certain movement patterns represent feeding or spawning activity require the assumption that tagged fish spawn and feed ‘normally’. Also, swimming performance of tagged fish may be affected due to the increased weight from implanted transmitters or drag from externally attached tags, especially if the external portion of the tag becomes fouled. For instance, tagged fish may need to expend more energy, via active swimming, to maintain neutral buoyancy or migrate similar distances as their untagged counterparts. The chronic expenditure of extra energy to compensate for the presence of tags can reduce the amount of energy available for somatic and gonadal

growth (Adams et al. 1998; Begout Anras et al. 2003). Finally, tagged fish may experience modified social interactions. Agonistic behavior may be more commonly displayed towards fish with external tags (e.g., nipping of tags), which can increase their vulnerability to predation. Tagged fish may also become subordinate or not school with untagged fish if dominance hierarchies exist (Connors et al. 2002).

Tagging effects should be evaluated on a species-specific basis because the responses of fish to tagging undoubtedly vary among species (Collins et al. 2002; Mulcahy 2003; Fabrizio and Pessutti 2007). Several studies have assessed tagging mortality and retention in spotted seatrout marked with conventional tags such as internal anchor tags (Iversen and Moffett 1962; Hegen et al. 1984; Vogelbein and Overstreet 1987), T-bar anchor tags (Sackett and Hein 1979), and plastic-tipped dart tags (Warren 1998). Yet, only one study to date has evaluated transmitter implantation methodologies in spotted seatrout; this study had some limitations, namely sample size was low (n=4 tagged fish), the author did not examine growth and feeding, and behavioral sedation was used rather than anesthesia (Bradshaw 2006). Clearly, there is a need for a more comprehensive understanding of the effects of tagging on spotted seatrout, for conventional tags and especially biotelemetry transmitters and sensors.

The main objective of this laboratory experiment was to evaluate the effects of surgically implanting acoustic transmitters and inserting dart tags in spotted seatrout to aid in the interpretation of results from the Calcasieu Lake telemetry study (chapters 3-5) and state-wide conventional tagging program (chapter 3). I do not focus on methods development herein, but instead on the effects of the tagging methodology I chose based on a series of pilot telemetry studies conducted in Barataria Bay during 2006. Specific objectives and associated alternative hypotheses are the following:

- Compare acute mortality rates between tagged and untagged (control) fish
  - Ha: Mortality rates will differ between tagged and control fish
- Compare growth (weight change) between tagged and control fish
  - Ha: Weight gain will differ between tagged and control fish
- Compare recent feeding incidence between tagged and control fish
  - Ha: Feeding incidence will differ between tagged and control fish
- Evaluate retention rates of dart tags and acoustic transmitters over two months
- Examine wound healing in tagged spotted seatrout
- Evaluate the success rate of my sex determination methodology

## **Methods**

### Experimental Design

I conducted a preliminary experiment and two main experiments at the Louisiana Universities Marine Consortium (LUMCON) in Cocodrie, Louisiana during 2009. The purpose of the preliminary experiment (April 6-29, 2009) was to determine whether spotted seatrout would survive in the tank system and to practice removing fish from the tanks. I used 15 total fish in the preliminary experiment and placed nine tagged and six control fish in the same tank. The objective of the first main experiment, hereafter referred to as “experiment 1”, was to compare survival, growth, and feeding between tagged and untagged (control) spotted seatrout. I used 48 total fish and two holding tanks in experiment 1, with 24 fish (12 tagged, 12 controls) in each tank. Tagged fish received a surgically implanted dummy acoustic transmitter and were externally tagged with a dart tag, whereas control fish did not receive a transmitter or dart tag. Experiment 1 was three weeks in duration, beginning in May 2009. The objective of the second main experiment, “experiment 2” hereafter, was to evaluate the retention of dart tags and

transmitters over a two month period (May-July, 2009). I used a total of 11 fish in experiment 2 and placed all fish in the same tank; each fish was equipped with a transmitter and dart tag. Thus, three separate tanks were used in the main experiments (two tanks in experiment 1 and one tank in experiment 2), but all three tanks operated on the same re-circulating seawater system.

### Holding Tank System

The tanks used in the main experiments were part of an outdoor re-circulating seawater system comprised of four circular tanks and a sump tank connected to a single biofilter and pump (Figure 1.1). Tank volume was 1,600 L and the flow rate was  $28 \text{ L min}^{-1}$ . Accordingly, the tank turnover time (i.e., the time required to completely filter and “replace” all water in a given tank) was approximately one hour. I used water collected offshore in the Gulf of Mexico by the R/V Pelican to fill the tanks because the bioload of this water was lower than estuarine water. I also subjected water to UV sterilization before it was added to the tanks to eradicate potential pathogens. The tank system was operational for three weeks prior to the start of experiments to ensure that the biofilter was conditioned (i.e., a sufficient colony of beneficial bacteria was present).

I provided supplemental aeration in all tanks during the experiment with an air pump. Only two tank covers were available, and these were placed on the two tanks in experiment 1 (Figure 1.1) to reduce stress and prevent fish from jumping out of the tanks. Sixty watt submersible lights were attached to a timer and operated from 06:00 to 20:00 to simulate a natural photoperiod of 14 hours of daylight and 10 hours of darkness.

### Fish Collection

Fish were collected by angling with live and artificial bait in Timbalier Bay during May 2009 aboard an 8 m research vessel. Only fish greater than 300 mm total length (TL) were



Figure 1.1. Re-circulating seawater system used to hold spotted seatrout during the main experiments.

retained for the experiment. Also, I did not keep fish that were bleeding from their gills, gut-hooked, dropped, or missing fins. Handling of fish was minimized as much as possible and rubber-coated nets were used to net fish and transfer them to a livewell. An oxygenated 300 L livewell was used to hold and transport fish. I added plastic ice bottles to the livewell to control water temperature. No fish were in the livewell for more than four hours, and the maximum transport distance to LUMCON was 25 kilometers.

Fish captured within a few days of each other were placed in the same holding tank upon arrival at LUMCON to ensure that acclimation times were as similar as possible within a tank. Stocking densities did not exceed 24 fish per tank. The acclimation period ranged from nine to thirteen days. Fish were not fed during acclimation so they would be in as similar condition as

possible at the start of the experiment. My rationale was that if fish were fed and only some individuals ate, then those fish may have an advantage at the start of the experiment and exhibit higher post-surgery survival. It was not feasible to track individual feeding histories in the tanks, and if more fish that had fed were assigned to a particular treatment group than the other, treatment effects would be confounded by feeding activity.

#### Tag and Transmitter Specifications

I fabricated dummy transmitters to match the dimensions and weight of VEMCO V9-2H (9 mm diameter, 29 mm length, 5.0 g in air) and V13TP-1H (13 mm diameter, 45 mm length, 12.0 g in air) acoustic transmitters because I deployed these transmitters in the Calcasieu Lake telemetry study. Plastic casings, open on one end, were filled with #7 steel shot and foam, and the open end was capped with quick-setting (15-minute) epoxy (Figure 1.2).

Most telemetry studies only consider the ratio of transmitter weight to body weight when determining the minimum size of fish into which a particular transmitter type can be reliably implanted (Adams et al. 1998; Jepsen et al. 2002; Jadot et al. 2005; Zale et al. 2005), with little regard to fish length. The “2% rule” (ratio of transmitter weight to body weight) developed by Winter (1983) is typically adopted in most studies. However, as Paukert et al. (2001) and Lacroix et al. (2004) argue, fish length and volume of the peritoneal cavity should also be considered when determining minimum fish sizes for transmitter implantation. The pilot telemetry studies I conducted in Barataria Bay demonstrated that some spotted seatrout < 300 mm TL met the 2% rule in terms of weight, but implanted transmitters fit very snugly in their body cavity, and these fish could not maintain proper equilibrium and swimming orientation. Accordingly, I used both length- and weight-based criteria to develop minimum size thresholds for transmitter implantation. Minimum fish sizes for V9-2H and V13TP-1H transmitters were

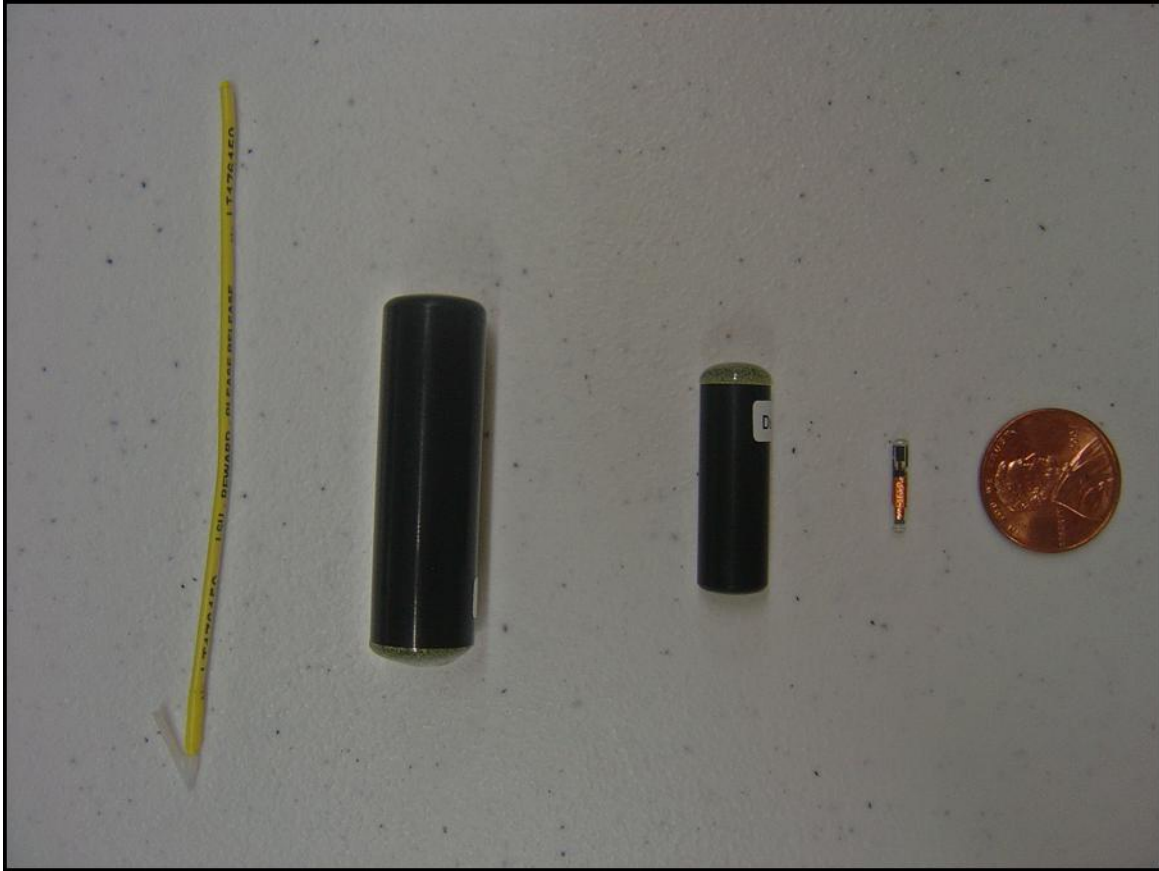


Figure 1.2. Tags and transmitters applied to spotted seatrout. From left: dart tag, V13TP-1H dummy acoustic transmitter, V9-2H dummy acoustic transmitter, and passive integrated transponder (PIT) tag.

300 mm TL and 250 g; 430 mm TL and 700 g, respectively. Thus, a fish had to meet both length and weight minima to be implanted with a given transmitter type. These minimum size criteria were also used for the Calcasieu Lake telemetry study (chapters 3-5).

I used plastic-tipped dart tags with the same specifications as those employed in the state-wide conventional tagging program (HallPrint PDS series, 10 cm length) (Figure 1.2). I also tagged all experimental fish with passive integrated transponder (PIT) tags (BioMark TX1411SSL series, 12.5 mm length, 2 mm diameter) to facilitate identification of individual fish at the end of experiments.

## Tagging and Surgical Procedures

Surgeries were performed in a laboratory adjacent to the outdoor holding tanks. I sterilized all surgical instruments and transmitters in benzalkonium chloride (Benz-All) and rinsed them with sterile saline prior to surgeries. Treatments were administered to all fish from a given holding tank on the same day and only one tank was processed per day. Treatments were assigned systematically, whereby the first fish randomly selected from a tank was not tagged (control), and the next fish was tagged; this process was repeated for all remaining fish.

To remove fish from the holding tanks, I lowered the water level to approximately 20 cm and individually netted fish with rubber-coated nets. Fish were then placed in a 150 L cooler containing a 60 mg L<sup>-1</sup> solution of tricane methanesulfonate (MS-222). I adjusted the temperature and salinity of water in the anesthetic cooler to match conditions in the outdoor holding tanks. Induction times ranged from four to five minutes, after which I removed fish from the anesthetic cooler and measured (standard length (SL) and TL to the nearest mm) and weighed them (nearest gram). A PIT tag was then inserted in the cheek muscle of each fish, between the eye and operculum, using a syringe furnished with a stainless steel applicator needle and plunger (Figure 1.3). Fish in the tagged group received a dart tag inserted between the third and fourth or fourth and fifth pterygiophores of the first dorsal fin via a stainless steel applicator needle with a wooden handle.

All fish were then placed ventral side up in the V-shaped trough of a custom-built surgery cradle constructed from closed-cell foam and housed in a plastic tub (Figure 1.4A). A surgery assistant delivered seawater, containing no anesthetic, at a low flow rate over the gills and occasionally the outer body via plastic tubing (Figure 1.4A). Most fish surgeons administer some level of anesthetic during surgeries (Bridger and Booth 2003), but I have observed the





Figure 1.3. Inserting a passive integrated transponder tag (PIT tag) into a spotted seatrout.

recovery of spotted seatrout is greatly enhanced (especially in regards to recovery time) when no anesthetic is administered during surgery. Typically, fish did not recover until after the surgery was complete; otherwise, a half-strength dose of MS-222 was delivered over the gills with a turkey baster to sedate the fish.

I conducted gonad biopsies to aid in sex determination. If a fish audibly grunted during handling, I assumed it was a male because only male spotted seatrout are soniferous (Gilmore 2003) and these fish did not undergo the biopsy procedure. All other fish received a biopsy. Specifically, a catheter was inserted into the vent (Figure 1.4A) and a small cell sample was extracted for later observation with a dissecting microscope. I constructed the biopsy sampler by attaching 1 mm diameter Teflon tubing (60 cm length) to a 21-gauge needle housed on a 10 mL Luer-Lock syringe (E.J. Chesney, Louisiana Universities Marine Consortium, personal communication).

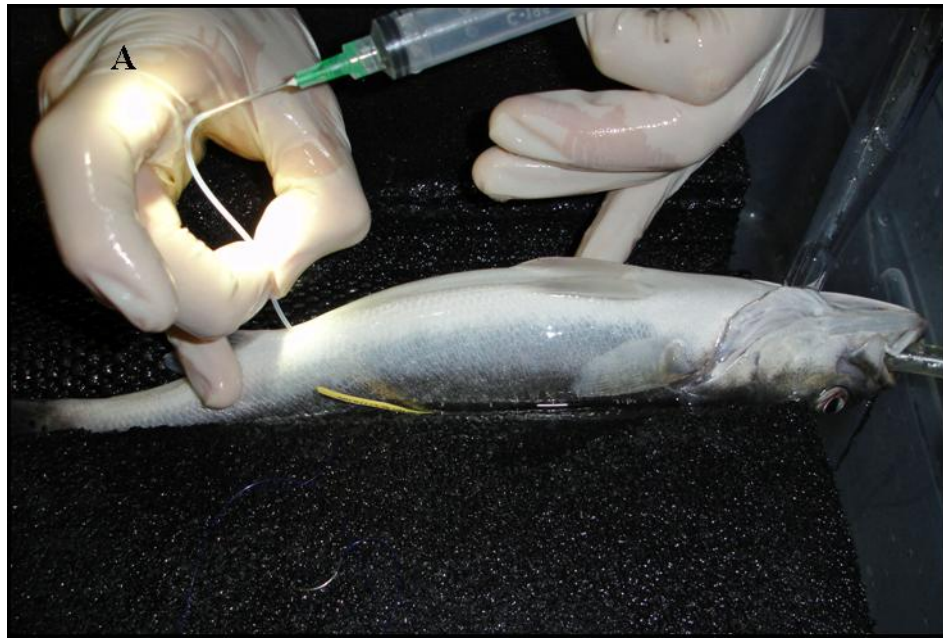


Figure 1.4. **(A)** Gonad biopsy being performed while fish is on the surgery cradle. Also note plastic tubing in the fish's mouth for seawater delivery over the gills. **(B)** Dummy transmitter being inserted into the peritoneal cavity. Note the rust-colored substance on the fish is 10% Povidone-iodine solution and not blood.

I surgically implanted dummy transmitters into fish assigned to the tagged group. Transmitters and surgical instruments were stored in 70% isopropyl alcohol during surgeries, and medical exam gloves were worn by the surgeon and all assistants. I used a dropper bottle to apply 10% Povidone-iodine to the incision site, just offset and parallel to the linea alba between the pelvic and anal fins (Figure 1.4B). I made a 20-30 mm incision through the body wall using a number 11 scalpel and inserted a dummy transmitter into the peritoneal cavity. I used a blunt probe to displace the transmitter posteriorly until the anterior tip of the transmitter was behind the posterior end of the incision to reduce pressure on the incision by the transmitter as suggested by Mulcahy (2003). If the gonads were clearly visible during surgery, I noted the sex of the fish. I closed the incision using three sutures applied in a simple interrupted pattern with surgeon's knots (Wagner et al. 2000). Sutures were made of non-absorbable polypropylene (3-0 Ethicon Prolene, 18 mm length) and outfitted with a FS-2 reverse cutting needle. I topically applied triple antibiotic ointment to the incision and transferred the fish to a 150 L cooler for recovery. Surgery times (i.e., time on the surgery cradle) ranged from five to eight minutes and averaged six minutes and thirty seconds. Control fish remained on the surgery cradle for five minutes, unless they started to recover sooner, in which case they were transferred to the recovery cooler.

I adjusted the temperature and salinity of water in the recovery cooler to closely match that in the outdoor tanks and also added aeration. Fish were held by an assistant until they were able to independently maintain equilibrium and orientation (typically one to two minutes). After ten minutes, fish were transferred to one of the main holding tanks if they were swimming and in apparent good condition. Only two of 59 fish (3.4%) took longer than ten minutes to fully recover and there were no mortalities during the recovery period.

## Experimental Maintenance

Water quality in the holding tanks was monitored daily. Target values for variables were: salinity 25-30, dissolved oxygen  $> 5 \text{ mg L}^{-1}$ , pH = 8.2 and ammonia  $< 0.5 \text{ ppm}$ . The means and ranges of physico-chemical variables during each of the main experiments are provided in Table 1.1. Each tank was also checked daily for fish mortalities and expelled tags.

Experimental fish were fed daily with juvenile *Brevoortia patronus* (20-60 mm TL), from the day after tagging through the day experiments were terminated. I captured live prey using a cast net at the LUMCON dock and held them in a holding tank not harboring experimental fish. In experiment 1, 60 live *B. patronus* were fed daily to each tank; in experiment 2, 30 live *B. patronus* were provided on a daily basis through June 9 and 100 dead prey on each day thereafter. Interestingly, some fish (from both tagged and control groups) fed as soon as one day post-tagging.

At the termination of experiments (21 days for experiment 1, 58 days for experiment 2), I euthanized fish by adding a lethal dose ( $120 \text{ mg L}^{-1}$ ) of MS-222. Fish were netted from the tanks, placed on ice, and immediately weighed and measured. A BioMark Pocket Reader EX was used to glean PIT tag numbers from individual fish.

## Necropsies

I made basic macroscopic observations on the external condition of tagging wounds and incisions (e.g., degree of inflammation) and recorded the number of sutures that remained in tagged fish. Fish were dissected to assess potential damage to internal organs and verify the presence of transmitters and their degree of encapsulation. I also identified and weighed the stomach contents of each fish. Sex was verified by visual inspection of the gonads.

Table 1.1. Values of physico-chemical water variables in the holding tanks during experiments 1 and 2. Ranges of variables are reported and means are given parenthetically. Because all holding tanks were inter-connected in the re-circulating seawater system, daily measurements were only taken for one tank and assumed to be representative of the entire system.

Variable	Experiment 1	Experiment 2
Temperature (°C)	18.1-26.4 (23.3)	18.1-29.5 (26.1)
Salinity (psu)	24-28 (26)	24-28 (26)
Dissolved oxygen (mgL <sup>-1</sup> )	6.3-7.9 (7.0)	6.3-7.9 (7.0)
pH	8.2-8.4 (8.3)	8.0-8.4 (8.3)
Ammonia (ppm)	0-0.75 (0.25)	0-0.75 (0.25)

### Sex Determination

Because the sex of all fish was verified at the end of experiments, it was possible to evaluate the accuracy of the sex classifications I made during surgeries. I calculated classification success rates as the percentage of fish whose sex was correctly determined during surgeries. It was important to assess the accuracy of my sex classification methodology (i.e., determining sex during surgeries via biopsies and visual inspection of the gonads through incisions) because in later chapters I relate movement and habitat use to fish sex as determined by the methods employed herein.

### Data Analyses

The metric I used to assess growth was percent weight change (Knights and Lasee 1996; Sutton and Benson 2003). I calculated this metric for each fish, except those that died, using the following equation:

$$\frac{((W_f - W_t - W_p) - W_i)}{W_i} \times 100 \quad (\text{Equation 1.1})$$

where  $W_f$  = fish weight at the end of experiments,  $W_t$  = transmitter weight,  $W_p$  = weight of stomach contents,  $W_i$  = initial fish weight. I subtracted prey weight from final weight because the purpose of this analysis was to evaluate somatic growth achieved during experiments rather

than recent feeding. To test for differences in growth between treatments I used a two-way mixed model analysis of variance (ANOVA) with treatment (tagged vs. control) as a fixed effect and tank (tank 1 vs. tank 2) as a random effect.

To test for treatment differences in recent feeding, I performed a three-way contingency table analysis with recent feeding incidence as the binary response variable and treatment and tank as the explanatory variables. For this analysis, recent feeding was only scored positive for those fish with partially digested or whole prey items in their stomach. Fish that had empty stomachs or only refractory material (e.g., scales) present were scored negative. As above, fish that died during experiments were excluded from analyses. I performed all statistical tests in Statistical Analysis Software (SAS, version 9.1.3) using an overall alpha value of 0.05.

## **Results**

### **Survival**

One fish died during the preliminary experiment, a 325 mm tagged male at nine days post-tagging. This fish succumbed to a secondary bacterial infection, likely Vibriosis, (J. Hawke, Louisiana State University School of Veterinary Medicine, personal communication) as necrosis was present at the incision site and skin tissue eroded away at the nares.

Only one fish died during experiment 1, a 325 mm control male at five days post-tagging. This fish displayed no signs of infection, but a distinct hand mark was present on its head where the slime coat may have been removed during handling. I considered this single mortality a random, chance event; accordingly, did not statistically compare survival between treatments.

One of eleven fish (9.1%) died during experiment 2, a 491 mm female at 12 days post-tagging. This fish exhibited no obvious signs of infection but lost a considerable amount of weight (6% of its initial weight) and had an empty stomach.

## Growth and Feeding

Fish used in experiments 1 and 2 ranged in size from 305 to 491 mm TL and 278 to 1152 g (Figure 1.5). There were no significant differences in mean initial length or weight between treatments or tanks for experiment 1 ( $p > 0.07$  across all two-way ANOVAs). Fish in the preliminary experiment ranged in size from 278 to 392 mm TL and 207 to 693 g.

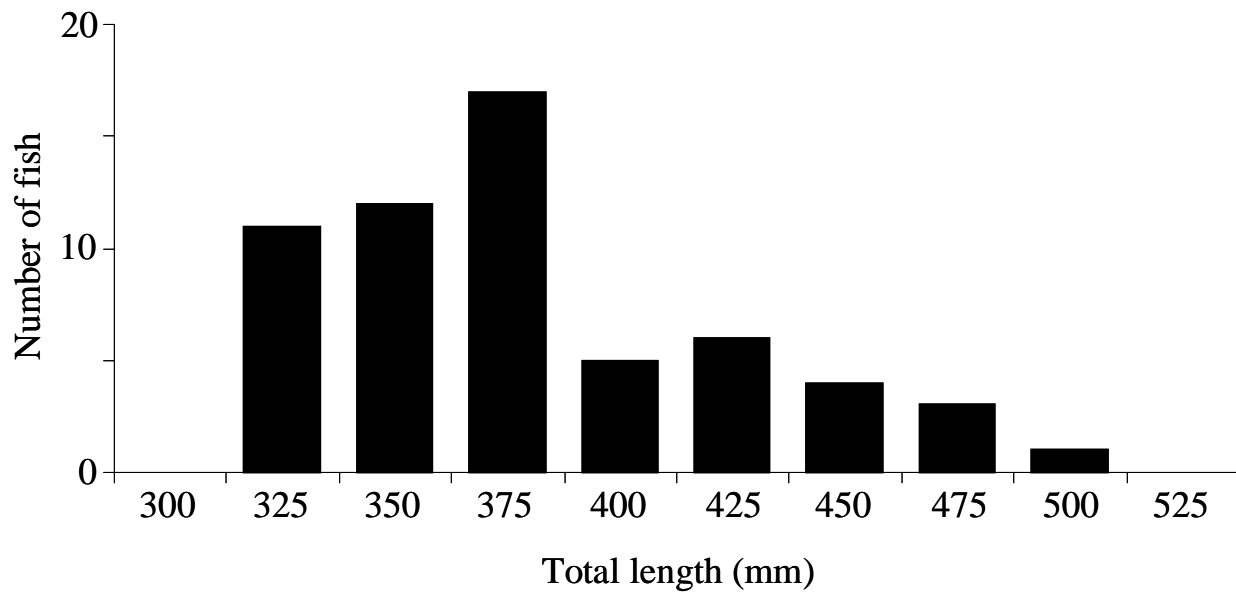


Figure 1.5. Length frequency distribution of all fish ( $n=59$ ) used in experiments 1 and 2. Values along the x-axis are the upper limits of respective 25 mm size bins (e.g., the 325 mm bin corresponds to lengths ranging from 301-325 mm TL).

Most fish (38 of 47 or 81%) lost weight (0.2 to 11.3% of their initial weight) during experiment 1. A significant treatment by tank interaction was present ( $p=0.01$ ), whereby tagged fish lost more weight than control fish in tank 1, but weight change was similar between treatments in tank 2 (Figure 1.6).

Most fish (7 of 10) gained weight (0.2 to 9.0% of initial weight) by the end of experiment 2. The other three fish lost 1.7, 2.6, and 18.2% of their initial weight during the experiment.

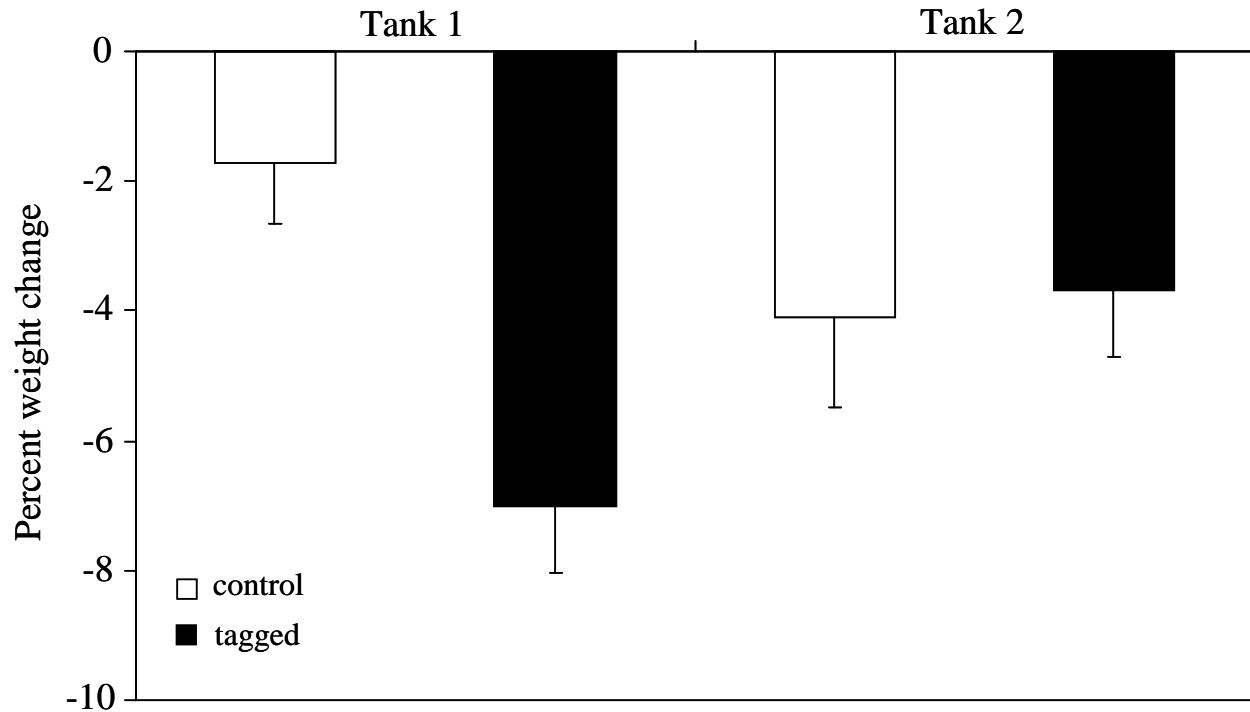


Figure 1.6. Percent weight change for spotted seatrout during experiment 1 (3-week duration). Bars represent mean percent weight change for each tank x treatment combination (n=12 fish per combination, except for the tank 2 tagged group, for which n=11 due to a fish death). White and black bars designate control (untagged) and tagged fish, respectively. Error bars represent standard errors of group means.

In experiment 1, recent feeding incidence was higher for control (75%) than tagged (25%) fish in tank 1, but in tank 2 lower for control (45%) than tagged (75%) fish. Based on the Breslow Day test in the three way contingency table analysis, odds ratios were not homogenous between treatments across tanks ( $p=0.01$ ). Such a result is equivalent to an interaction in a multiple-way ANOVA and precluded a Cochran-Mantel-Haenszel test of conditional independence.

Recent feeding incidence was 90% (9 of 10 fish) in experiment 2. Interestingly, the only fish that did not recently feed had the lone negative outlier value for percent weight change of -18.2%.



### Transmitter Retention and Wound Healing

No dummy transmitters were expelled by the 35 fish tagged in experiments 1 (n=24) and 2 (n=11). Two of nine tagged fish in the preliminary experiment expelled their transmitters through the incision site at eight and eleven days post-surgery, but these fish (281-290 mm TL, 239-243 g) were less than the minimum size thresholds for tagging (300 mm TL, 250 g) I used in the main experiments. Neither fish died after their dummy transmitters were expelled.

At three weeks post-surgery, incisions were healed (closed) in all fish from experiment 1. Scar tissue was present in most fish, along with mild to moderate inflammation, primarily at the suture entry/exit sites and tag ends of sutures (Figure 1.7A). Most fish (88%) still had two or three sutures remaining at the end of experiment 1 (Figure 1.8), but intact sutures were rather loose. Internally, most (92%, 22 of 24) transmitters were covered with a thin, adhesive layer of fibrin emanating from the body wall and gonads (Figure 1.7C). Transmitters generally rested posterior to the stomach and between the gonads (Figure 1.7C), and internal organs were not ruptured or damaged in any fish. Further, only 22% of tagged females had regressed gonads at the end of experiment 1.

At 58 days post-surgery (end of experiment 2), incisions were fully healed with little scar tissue and inflammation (Figure 1.7B); the majority of fish (60%) lost all three sutures (Figure 1.8). Although all fish had fibrin attached to their transmitters, the encapsulation process did not appear to be progressing as there were no dense fibrous capsules observed that completely engulfed transmitters.

### Dart/PIT Tag Retention and Wound Healing

All fish retained their dart tags through experiment 1, but two of ten fish in experiment 2 lost their dart tags at 43 and 45 days post-tagging. Dart tag loss was highest (63%) in the

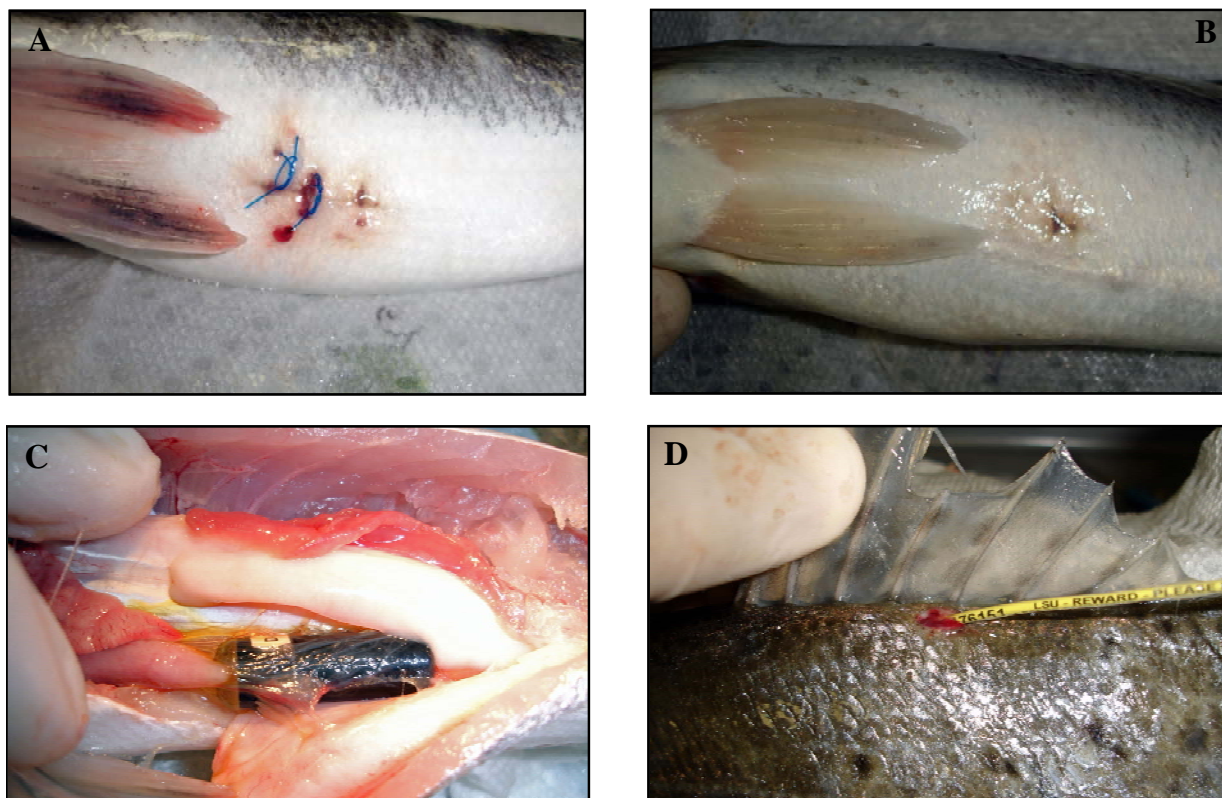


Figure 1.7. Wound healing of tagged spotted seatrout. **(A)** Typical condition of an incision at three weeks post-surgery **(B)** Typical condition of an incision at two months post-surgery **(C)** Encapsulation of a dummy transmitter in the peritoneal cavity **(D)** Dart tagging wound at three weeks post-tagging. Note each image is from a different fish.

preliminary experiment, where five of eight tagged fish shed their tags 14-21 days post-tagging. Four of these five fish were less than 300 mm TL (281-290 mm TL), and two of those four fish also expelled their dummy transmitters.

At the termination of experiments 1 and 2, dart tag insertion sites typically exhibited a moderate degree of inflammation and were not healed (Figure 1.7D). Also, tags were generally very loose and could be pulled out of the fish rather easily.

The overall PIT tag expulsion rate across the main experiments was 5% (3 of 59 fish), and only fish in experiment 1 expelled their PIT tags. The exact timing of PIT tag loss was

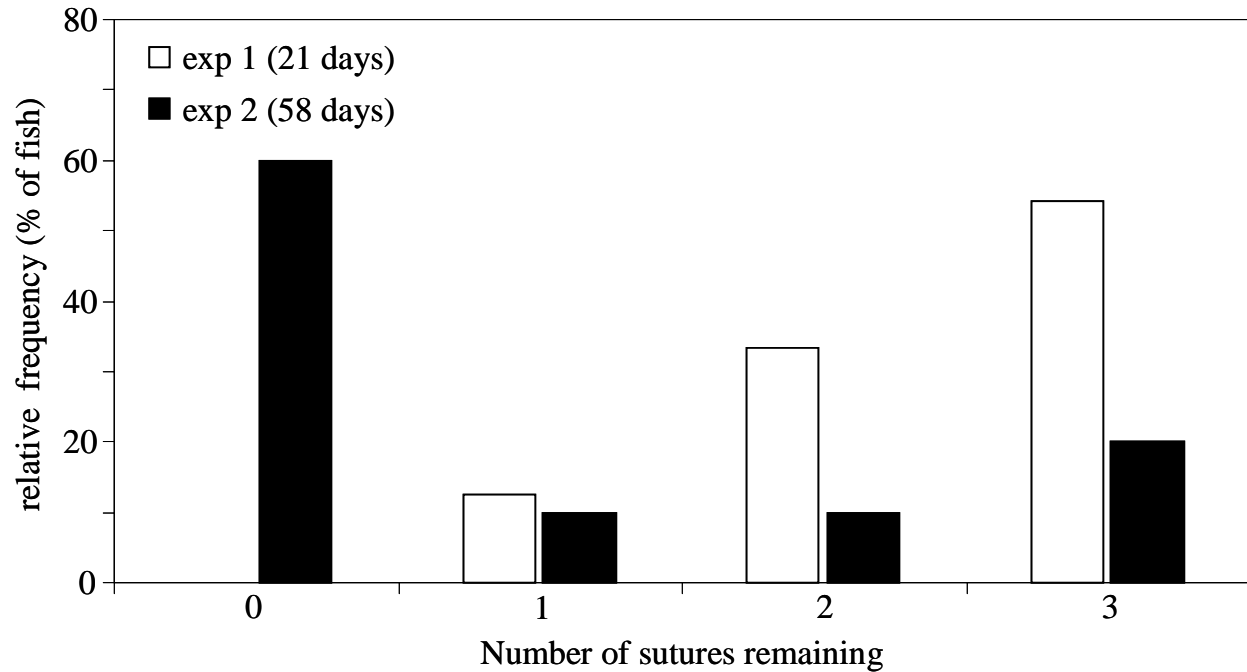


Figure 1.8. Suture loss in tagged spotted seatrout. The bars represent the percentage of fish with respective numbers of sutures remaining at the end of each experiment (e.g., ~50% of the tagged fish alive at the end of experiment 1 still had three intact sutures). Experiment 1 (white bars) was 21 days in duration (n=24 fish) and experiment 2 (black bars) was 58 days in duration (n=10 fish). Three sutures were used to close incisions during the surgical implantation of acoustic transmitters.

unknown because PIT tags were not easily observed lying on the bottom of the tank or floating as were shed dummy transmitters and dart tags, respectively. One fish (7%) lost its PIT tag during the preliminary experiment.

### Sex Determination

Of the 59 fish in experiments 1 and 2, 42 were verified as females and 17 as males during necropsies. No males grunted while being handled, and I was only able to determine the sex of 4 of 17 males (24%) during surgeries by visual inspection of the gonads through the incision site. Biopsy samples were only useful for identifying females (based on the presence of oocytes) because spermatozoa were not detectable in samples. I determined the sex of 20 of 42 females based exclusively on the presence of oocytes and another 10 females from gonad observations

during surgeries. Thus, the sex determination rate for females was 71% (30 of 42 fish) and for all fish (across sexes), was 58%. Most importantly, the success rate for both methods of sex determination (gonad biopsies and visual gonad inspection during surgeries) was 100%.

## **Discussion**

Tagging methodologies and the presence of internal transmitters and external dart tags had minimal deleterious effects on adult spotted seatrout in this study. Acute mortality rates of tagged fish were low (0-9%) and not elevated relative to control fish. Also, despite the fact that most tagged fish (88%) lost weight in experiment 1 (which was likely due to insufficient prey rations, see below), the majority of tagged fish in experiment 2 exhibited positive growth (70%) and recent feeding (90%).

To optimize data collection and analyses in tagging studies, tags must be retained throughout the duration of the study in addition to tagged fish surviving at acceptable rates and displaying normal behavior. The retention of acoustic transmitters in this study was 100% for fish > 300 mm TL, and incision wounds were healed before the majority of suture loss occurred, suggesting the loss of transmitters through surgical incisions is an unlikely mechanism of expulsion under the surgical protocols employed herein. In contrast to transmitter retention, dart tag retention rates were poor (37-80%), and tag loss was delayed at least two to three weeks post-tagging.

### Effects of Surgical Implantation of Acoustic Transmitters

While this laboratory experiment reliably confirmed the surgical procedure itself did not lead to increased mortality, the mortality rates observed in this study are probably conservatively low when considered in a field study context. Most laboratory studies of tagging effects use an acclimation period (~1-2 weeks) to allow fish to recover from capture, handling, and transport

(Knights and Lasee 1996; Wagner et al. 2000; Walsh et al. 2000; Robertson 2003; Jadot et al. 2005). However, in most telemetry studies, fish are generally implanted with transmitters shortly after being captured, and possibly transported to the tagging site (with no acclimation period) (Topping et al. 2005; Lindholm et al. 2007; Ng et al. 2007; Hanson et al. 2008; Abecasis et al. 2009). Thus, the acute compound stress (and presumably tagging mortality) experienced by fish are probably higher in a typical field versus laboratory setting. In my laboratory experiment, 12% of fish (8 of 69) died during the first week of the acclimation period. Similar short-term mortality rates of 11-18% during the first week after capture have been reported in catch-and-release mortality studies for spotted seatrout held in both field enclosures and laboratory tanks (Stunz and McKee 2006; R.G. Thomas, Louisiana Sea Grant, personal communication). Thus, it would be expected the additional stress associated with the surgical implantation of transmitters should only increase mortality relative to these baseline estimates. It is also possible that by using an acclimation period, the weaker individuals are essentially culled from the pool of experimental fish and only those fish in superior condition and possessing a higher chance of surviving the surgery process, are used in experimental trials. This mechanism would also result in conservatively low mortality rates from laboratory studies. More representative estimates of the magnitude of mortality rates associated with surgical implantation of transmitters into spotted seatrout could be obtained by performing surgeries in the field and immediately implanting fish after capture and placing them in field enclosures for one to two weeks.

The prevalent weight loss observed in experiment 1 was due to under-feeding rather than a treatment effect because weight loss was common in both tagged and control fish. Spotted seatrout in experiment 1 were fed less than one percent of their initial body weight per day as the

total prey weight administered per day was only 0.64 to 0.78% of the fish biomass in each tank. This daily ration was obviously not high enough to support somatic growth and probably was inadequate in supplying the requisite total energy for routine metabolic processes, in which case weight loss may have resulted from the utilization of lipid and protein stores as a residual energy source. Upon realizing that most fish lost weight during experiment 1, I increased the daily ration to 3% body weight per day for the remainder of experiment 2; indeed, most fish gained weight by the end of experiment 2. Although there are no published estimates of consumption rates in adult spotted seatrout, values exceeding 1% body weight per day have been reported for many species of warm water piscivores (Palomares and Pauly 1989; Sudekum et al. 1991; Whitledge and Hayward 1997; Olson and Galvan-Magana 2001). To conclusively determine whether growth is higher in tagged versus untagged (control) spotted seatrout, it would be necessary to repeat the experiment with higher prey rations (~3%) and perhaps increased replication (number of tanks).

Transmitter retention was excellent in this study; still, it is possible that transmitters could be expelled beyond the two month period examined here. The functional transmitters I deployed in my field telemetry studies had an approximate battery life of one year. Numerous laboratory studies have reported 100% retention of surgically implanted transmitters over one year for *Paralichthys dentatus* and *Centropristis striata* (Fabrizio and Pessutti 2007), *Caranx malampygus* (Meyer and Honebrink 2005), and *Oreochromis aureus* (Thoreau and Baras 1997). I believe that long-term transmitter retention in spotted seatrout is similarly high. Incisions were healed and closed well before sutures were lost, thus transmitter expulsion through the incision is unlikely in the long-term. Furthermore, transmitters did not exert high pressure on or physically distend any portion of the body wall. Therefore, expulsion through the body wall due to pressure

necrosis is also unlikely. Transmitters encapsulated by a thick fibrous capsule, a foreign body response, may become engulfed by the intestine via myofibroblast contraction and expelled through the anus by peristalsis in a process termed ‘trans-intestinal expulsion’ (Marty and Summerfelt 1986; Baras and Westerloppe 1999). In this study, transmitters were only partially encapsulated, but I can not rule out trans-intestinal expulsion in spotted seatrout beyond two months. Nevertheless, this mechanism of transmitter expulsion appears to be species-specific and most common in siluriform fishes (Baras and Westerloppe 1999). Moreover, my telemetry results (chapters 3-5) confirmed that spotted seatrout can retain transmitters for at least one year based on detection patterns, but the estimation of retention rates from this data is not feasible because the fates of fish that disappear within the battery life of the transmitter are largely unknown.

Results of this study on the effects and retention of surgically implanted transmitters are most applicable to adult spotted seatrout smaller than 500 mm TL because no larger individuals were captured. Only six fish met the minimum size criterion for implantation with the larger V13TP-1H transmitters; three of those fish were tagged (n=2 experiment 1, n=1 in experiment 2), and the remaining three served as controls in experiment 1. Two of three fish implanted with V13s survived and retained their transmitters throughout the experiments. The V13 transmitter burden was maximal in these fish because they were just above the minimum size threshold, but these results are tenuous and inconclusive due to low sample size. Consequently, I was not able to adequately examine the effects of surgically implanting V13 transmitters into large spotted seatrout. The benefits of using the larger V13 transmitters instead of V9s are a shorter delay between transmissions, higher power output, and extended battery life, thus enhancing data collection for larger spotted seatrout that can accommodate these transmitters.

### Dart Tag Loss

Dart tag loss appears to occur earlier in smaller fish (< 300 mm TL). Both the preliminary experiment and experiment 1 were three weeks in duration, yet tag loss (63%) only occurred in the former in which smaller fish were present. Of the eight tagged fish that survived the preliminary experiment, the four fish less than 300 mm shed their tags, and only one of four fish larger than 300 mm shed its tag. Warren (1998) also reported that loss rates of 5 cm dart tags in a short-duration study (< 1 month) were much higher in smaller spotted seatrout (70% tag loss for fish 150-205 mm TL, 0% for fish 206-360 mm TL). These results suggest that tag loss may occur sooner in smaller fish (i.e., < 300 mm TL), which is somewhat counter-intuitive. For a given tag size, the distance between adjacent pterygiophores is reduced which should lead to higher retention as the anterior tip of the tag is more likely to stay lodged behind the pterygiophore anterior to the one on which the barb is actually hooked. One possible explanation for this apparent size effect is that the tag burden (tag length:fish length) is greater in smaller fish and hastens tag loss. While smaller fish may lose their dart tags more quickly than larger fish, results from experiment 2 confirm that larger fish also eventually shed their tags.

Dart tag loss likely persists over time. Beverton and Holt (1957) referred to this type of chronic tag loss as “type II tag shedding” as opposed to type I acute losses. Dart tags that remained in fish at the end of experiments were typically very loose and tagging wounds were not healed. The delayed nature of dart tag loss is likely caused by continual swimming activity which gradually loosens dart tags inserted into the dorsal musculature and results in their loss. Two of ten fish in experiment 2 shed their dart tags during the sixth week after tagging, and had I prolonged the experiment, it is likely that more tags would have been shed. Reported returns of telemetered fish in the Calcasieu Lake telemetry study provide additional evidence for long-term



tag loss in spotted seatrout. Of six recaptured fish: three retained their dart tags 39, 56, and 110 days post-tagging; two fish lost their dart tags up to three and 19 months post-tagging; one fish captured 276 days post-tagging had a cut tag, possibly due to an angler cutting the tag or a predation attempt. The estimate of long-term tag loss based on these returns (33%) is likely an underestimate of true tag loss because anglers are more likely to recognize and report fish that retained their external tags. The two fish that lost their dart tags were only recognized as telemetered fish by accident as internal transmitters were noticed when fish were cleaned. A reasonable model for loss rates of dart tags in spotted seatrout may be 20% per month beginning one month post-tagging, resulting in the loss of about 90% of tags after one year. Tag retention undoubtedly varies by species. Interestingly, long-term (423 days) retention rates (5 cm dart tags) were 90% in confamilial juvenile *Sciaenops ocellatus* (Winner et al. 1998). High tag retention in red drum may be promoted by their robust scales, whereas spotted seatrout are essentially scale-less.

Internal anchor tags are probably better suited for adult spotted seatrout than external dart tags. Short-term (< 1 month) retention rates of 100% have been reported for internal anchor tags in spotted seatrout (Iversen and Moffett 1962; Hegen et al. 1984; Vogelbein and Overstreet 1987), but no longer-term studies have been conducted. Still, results from several movement studies demonstrate that fish tagged with internal anchor tags exhibit higher return rates and days at liberty than dart-tagged fish, implying superior retention. For example, return rates for fish tagged with internal anchor tags ranged from 7.7 to 24.9%, and recaptures of fish at large more than one year were fairly common (~10% of all recaptures) (Iversen and Moffett 1962; Baker et al. 1986; Woodward et al. 1990; Baker and Matlock 1993). Meanwhile, return rates for dart tagged fish were much lower and ranged from 2.2 to 2.7%, with recaptures of fish at large more

than one year virtually non-existent (<0.5% of all recaptures) (chapter 3; also see Hendon et al. 2002). Although retention may be higher for internal anchor tags than dart tags, one disadvantage of internal anchor tags is that they are more difficult and time consuming to apply than dart tags. Conventional tagging programs relying on volunteer anglers commonly use dart tags or T-bar anchor tags (which are also inserted into the dorsal musculature) due to their ease of application, and some of these tags can even be applied *en masse* with tagging guns. Anglers may be less inclined to tag fish if they deem the tagging protocol too difficult, and having a large number of volunteer anglers making incisions in fish (necessary for internal anchor tags) is impractical and could lead to high tagging mortality. Regardless, if reliable quantitative data for the purpose of enhancing fisheries management is to be gleaned from conventional tagging programs, tag retention rates should be high or at least known *a priori* so data can be adjusted accordingly (Gillanders et al. 2001).

In this study I showed that spotted seatrout implanted with acoustic transmitters exhibited high survival, transmitter retention, and feeding incidence, suggesting the surgical implantation methodology employed herein can be reliably used in future telemetry studies of this species. On the contrary, due to the high loss rates of dart tags, I do not recommend their use in studies of migration and mortality of spotted seatrout. In addition to determining the optimal external tag type for spotted seatrout, future research on general tagging effects in this species, for both biotelemetry transmitters and conventional tags, should focus on larger fish (i.e., > 500 mm TL).

## References

Abecasis, D., L. Bentes, and K. Erzini. 2009. Home range, residency and movements of *Diplodus sargus* and *Diplodus vulgaris* in a coastal lagoon: connectivity between nursery and adult habitats. *Estuarine, Coastal, and Shelf Science* 85:525-529.

- Adams, N.S., D.W. Rondorf, S.D. Evans, and J.E. Kelly. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of juvenile chinook salmon. *Transactions of the American Fisheries Society* 127: 128-136.
- Baker, W.B., G.C. Matlock, L.W. McEachron, A.W. Green, and H.E. Hegen. 1986. Movement, growth, and survival of spotted seatrout tagged in Bastrop Bayou, Texas. *Contributions in Marine Science* 29:91-101.
- Baker, W.B., and G.C. Matlock. 1993. Movement of spotted seatrout tagged in Trinity Bay, Texas. *Northeast Gulf Science* 13(1):29-34.
- Baras, E., and L. Westerloppe. 1999. Transintestinal expulsion of surgically implanted tags by African catfish *Heterobranchus longifilis* of variable size and age. *Transactions of the American Fisheries Society* 128:737-746.
- Begout Anras M.L., D. Coves, G. Dutto, P. Laffargue, and F. Lagardere. 2003. Tagging juvenile seabass and sole with telemetry transmitters: medium-term effects on growth. *ICES Journal of Marine Science* 60:1328-1334.
- Berejikian, B.A., R.S. Brown, C.P. Tatara, and S.J. Cooke. 2007. Effects of telemetry transmitter placement on egg retention in naturally spawning, captive reared steelhead. *North American Journal of Fisheries Management* 27:659-664.
- Beverton, R.J.H., and S.J. Holt. 1957. On the dynamics of exploited fish populations. Ministry of Agriculture, Fisheries and Food, London.
- Bradshaw, C.D. 2006. Behavioral ecology of spotted seatrout, *Cynoscion nebulosus*, in Charleston Harbor. Master's thesis. College of Charleston, Charleston, South Carolina.
- Bridger, C.J., and R.K. Booth. 2003. The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. *Reviews in Fisheries Science* 11(1):13-34.
- Chrisholm, I.M., and W.A. Hubert. 1985. Expulsion of dummy transmitter by rainbow trout. *Transactions of the American Fisheries Society* 114:766-767.
- Collins, M.R., D.W. Cooke, T.I.J. Smith, W.C. Post, D.C. Russ, and D.C. Walling. 2002. Evaluation of four methods of transmitter attachment on shortnose sturgeon, *Acipenser brevirostrum*. *Journal of Applied Ichthyology* 18:491-494.
- Connors, K.B., D. Scruton, J.A. Brown, and R.S. McKinley. 2002. The effects of surgically-implanted dummy radio transmitters on the behaviour of wild Atlantic salmon smolts. *Hydrobiologia* 483:231-237.

- Fabrizio, M.C., and J.P. Pessutti. 2007. Long-term effects and recovery from surgical implantation of dummy transmitters in two marine fishes. *Journal of Experimental Marine Biology and Ecology* 351:243-254.
- Gillanders, B.M., D.J. Ferrell, and D.L. Andrew. 2001. Estimates of movement and life-history parameters of yellowtail kingfish (*Seriola lalandi*): how useful are data from a cooperative tagging program? *Marine and Freshwater Research* 52:179-192.
- Gilmore, Jr., R.G. 2003. Sound production and communication in the spotted seatrout. Pages 177-196 in S.A. Bortone, editor. *Biology of the spotted seatrout*. CRC Press, Boca Raton, Florida.
- Hanson, K.C., S. Arrosa, C.T. Hasler, C.D. Suski, D.P. Phillip, G. Niezgoda, and S.J. Cooke. 2008. Effects of lunar cycles on the activity patterns and depth use of a temperate sport fish, the largemouth bass, *Micropterus salmoides*. *Fisheries Management and Ecology* 15:357-364.
- Hegen, H.E., G.E. Saul, and G.C. Matlock. 1984. Survival of handled and tagged spotted seatrout held in wood and wire cages. Texas Parks and Wildlife Department, Coastal Fisheries Branch, Management Data Series 61, Austin, Texas.
- Hendon, J.R., J.R. Warren, J.S. Franks, and M.V. Buchanan. 2002. Movements of spotted seatrout (*Cynoscion nebulosus*) in Mississippi coastal waters based on tag-recapture. *Gulf of Mexico Science* 20(2):91-97.
- Iverson, E.S. and A.W. Moffett. 1962. Estimation of abundance and mortality of a spotted seatrout population. *Transactions of the American Fisheries Society* 91:395-398.
- Jadot, C., A. Donnay, M. Yliff, and P. Poncin. 2005. Impact implantation of a transmitter on *Sarpa salpa* behaviour: study with a computerized video tracking system. *Journal of Fish Biology* 67:589-595.
- Jepsen, N., A. Koed, E.B. Thorstad, and E. Baras. 2002. Surgical implantation of telemetry transmitters in fish: how much have we learned? *Hydrobiologia* 483:239-248.
- Knights, B.C., and B.A. Lasee. 1996. Effects of implanted transmitters on adult bluegills at two temperatures. *Transactions of the American Fisheries Society* 125:440-449.
- Lacroix, G.L., D. Knox, and P. McCurdy. 2004. Effects of implanted dummy acoustic transmitters on juvenile Atlantic salmon. *Transactions of the American Fisheries Society* 133:211-220.
- Lindholm, J., P.J. Auster, and A. Knight. 2007. Site fidelity and movement of adult Atlantic cod *Gadus morhua* at deep boulder reefs in the western Gulf of Maine, USA. *Marine Ecology Progress Series* 342:239-247.

- Marty, G.D., and R.C. Summerfelt. 1986. Pathways and mechanisms for transmitter expulsion of surgically implanted dummy transmitters from channel catfish. *Transactions of the American Fisheries Society* 115:577-589.
- Meyer, C.G. and R.R. Honebrink. 2005. Transintestinal expulsion of surgically implanted dummy transmitters in bluefin trevally – implications for long-term movement studies. *Transactions of the American Fisheries Society* 134:602-606.
- Mulcahy, D.M. 2003. Surgical implantation of transmitters into fish. *ILAR Journal* 44(4):295-306.
- Ng, C.L., K.W. Able, and T.M. Grothues. 2007. Habitat use, site fidelity, and movement of adult striped bass in a southern New Jersey estuary based on mobile acoustic telemetry. *Transactions of the American Fisheries Society* 136:1344-1355.
- Olson, R.J., and F. Galvan-Magana. 2001. Food habits and consumption rates of common dolphinfish (*Coryphaena hippurus*) in the eastern Pacific Ocean. *Fishery Bulletin* 100(2):279-298.
- Palomares, M.L., and D. Pauly. 1989. A multiple regression model for predicting the food consumption of marine fish populations. *Australian Journal of Marine and Freshwater Research* 40:259-273.
- Patterson, W.F., J.C. Watterson, R.L. Shipp, and J.H. Cowan, Jr. 2001. Movement of tagged red snapper in the northern Gulf of Mexico. *Transactions of the American Fisheries Society* 130:533-545.
- Paukert, C.P., P.J. Chvala, B.L. Heikes, and M.L. Brown. 2001. Effects of implanted transmitter size and surgery on survival, growth, and wound healing of bluegill. *Transactions of the American Fisheries Society* 130:975-980.
- Pine, W.E., K.H. Pollock, J.E. Hightower, T.J. Kwak, and J.A. Rice. 2003. A review of tagging methods for estimating population size and components of mortality. *Fisheries* 28(10):10-23.
- Robertson, M.J., D.A. Scruton, and J.A. Brown. 2003. Effects of surgically implanted transmitters on swimming performance, food consumption and growth of wild Atlantic salmon parr. *Journal of Fish Biology* 62:673-678.
- Sackett, S.R., and S.H. Hein. 1979. Results of a floy tag retention study on spotted seatrout (*Cynoscion nebulosus*) in 1/4-acre ponds at the marine laboratory. Louisiana Department of Wildlife and Fisheries, Contributions of the Marine Research Lab, Technical Bulletin 28, Baton Rouge, Louisiana.
- Stunz, G.W. and D.A. McKee. 2006. Catch-and-release mortality of spotted seatrout in Texas. *North American Journal of Fisheries Management* 26:843-848.

- Sudekum, A.E., J.D. Parrish, R.L. Radtke, and S. Ralston. 1991. Life history and ecology of large jacks in undisturbed, shallow, oceanic communities. *Fishery Bulletin* 89:493-513.
- Sutton, T.M, and A.C. Benson. 2003. Influence of external transmitter shape and size on tag retention and growth of juvenile lake sturgeon. *Transactions of the American Fisheries Society* 132:1257-1263.
- Thoreau, X. and E. Baras. 1997. Evaluation of surgery procedures for implanting telemetry transmitters into the body cavity of tilapia *Oreochromis aureus*. *Aquatic Living Resources* 10:207-211.
- Topping, D.T., C.G. Lowe, and J.E. Caselle. 2005. Home range and habitat utilization of adult California sheephead, *Semicossyphus pulcher* (Labridae), in a temperate no-take marine reserve. *Marine Biology* 147:310-311.
- Vogelbein, W.K., and R.M. Overstreet. 1987. Histopathology of the internal anchor tag in spot and spotted seatrout. *Transactions of the American Fisheries Society* 116:745-756.
- Wagner, G.N., E.D. Stevens, and P. Byrne. 2000. Effects of suture type and patterns on surgical wound healing in rainbow trout. *Transactions of the American Fisheries Society* 129:1196-1205.
- Walsh, M.G., K.A. Bjorgo, and J.J. Isley. 2000. Effects of implantation method and temperature on mortality and loss of simulated transmitters in hybrid striped bass. *Transactions of the American Fisheries Society* 129:539-544.
- Warren, J.R. 1998. Spotted seatrout sport fish studies in Mississippi. Mississippi Department of Wildlife, Fisheries, and Parks, Federal Aid in Sport Fish Restoration, Project F-103, Final Report, Jackson.
- Whitledge, G.W., and R.S. Hayward. 1997. Laboratory evaluation of a bioenergetics model for largemouth bass at two temperatures and feeding levels. *Transactions of the American Fisheries Society* 126:1030-1035.
- Winner, B.L., R.H. McMichael, Jr., and L.L. Brant. 1999. Evaluation of small T-anchor and dart tags for use in marking hatchery-reared juvenile red drum, *Sciaenops ocellatus*. *Fishery Bulletin* 97:730-735.
- Winter, J.D. 1983. Underwater biotelemetry. Pages 371-395 in L.A. Nielsen and D.L. Johnson, editors. *Fisheries Techniques*. American Fisheries Society, Bethesda, Maryland.
- Woodward, A.G., J.M. Pafford, and N. Nicholson. 1990. Exploitation, movement, and growth of spotted seatrout in coastal Georgia. Georgia Department of Natural Resources, Federal Aid in Sportfish Restoration, Project F-31, Final Report, Brunswick.

Zale, A.V., C. Brooke, and W.C. Fraser. 2005. Effects of surgically implanted transmitter weights on growth and stamina of small adult westslope cutthroat trout. Transactions of the American Fisheries Society 134:653-660.

## **CHAPTER 2: THE PERFORMANCE OF ACOUSTIC TELEMETRY RECEIVERS IN A SHALLOW, TURBID ESTUARY**

### **Introduction**

All biotelemetry technologies used to study the movement of aquatic organisms have limitations. For example, movement trajectories reconstructed from data storage or pop-up satellite tags are very coarse, with a maximum spatial resolution of 60 to 100 km, thus restricting the use of this technology to highly migratory fishes such as tunas and billfishes (Bradshaw et al. 2007; Evans and Arnold 2009). Radio transmitters are only effective in freshwater habitats because radio waves are rapidly attenuated in seawater due to its high conductivity. A major limitation of acoustic telemetry, the technology employed in this study, is that receiver performance---or the ability of a receiver to detect signals from acoustic transmitters---is highly dependent on environmental conditions (Voegeli and Pincock 1996; Klimley et al. 1998).

Numerous environmental factors control the underwater propagation of acoustic signals, which may ultimately affect receiver performance. Acoustic signals undergo two types of propagation losses, spherical spreading and absorption (Lurton 2002). Significant absorption of acoustic energy can occur when concentrations of suspended particles or air bubbles are high, resulting in reduced detection ranges, the distance from a receiver at which a particular transmitter size or type is reliably detected (Voegeli and Pincock 1996). Spherical spreading causes signals to attenuate (i.e., their decibel level decreases) with increasing distance from their source. Attenuation is important because signals from acoustic transmitters must be at least twelve-fold “louder” than ambient noise levels (i.e., the signal-to-noise-ratio or  $SNR \geq 12$ ) to be electronically detected by receivers (Voegeli and Pincock 1996). Thus, if the environment is noisy in the listening frequency of receivers, a stronger signal is required to meet the SNR detection threshold. Stronger signals occur at shorter source distances because of attenuation;



therefore, in a noisy environment, receiver detection ranges will be lower than in a quiet environment. Interference noise may be physical (e.g., breaking waves, turbulent flow, rainfall), biological (e.g., cetaceans, snapping shrimp), or anthropogenic (e.g., echosounders, engine noise) in origin. Attenuation is also related to sound velocity, whereby faster traveling sound waves experience less attenuation at a fixed source distance, assuming a non-stratified water column. Sound velocity increases with temperature, salinity, and pressure. Hence, receiver performance may vary seasonally, with greater detection ranges during warmer months when sound velocities are higher. In a stratified water column, propagation paths may be refracted or reflected as acoustic signals encounter media with different sound velocities (Voegeli and Pincock 1996). For instance, signals emitted from transmitters below a thermocline may not be detected by receivers in surface waters due to reflection at the temperature gradient (Westmeyer et al. 2007).

Although environmental conditions are highly dynamic in most coastal ecosystems and thus have the capacity to significantly affect receiver performance at multiple temporal scales (hourly to seasonal), few telemetry studies have explicitly considered such effects on their receiver array design and interpretation of results. Most long-term telemetry studies either base detection ranges on a few short-term range tests, each less than 24 hours in duration (Heupel and Hueter 2001; Arendt et al. 2001; Topping et al. 2006; Meyer et al. 2009) or simply report detection ranges with no explanation of the methods used to obtain range estimates (Hartill et al. 2003; Lowe et al. 2003; Mitamura et al. 2005; Dresser and Kneib 2007; Afonso et al. 2008; Hindell et al. 2008). A few hours or days of range testing cannot encompass the full spectrum of environmental conditions that will occur over an entire study. Consequently, short-term range tests underestimate the degree of variation in receiver performance and cannot provide a synoptic understanding of the causes of variation in performance. Furthermore, detection ranges based on

short-term range test data may be overestimates because testing is usually conducted on fair-weather days when acoustic conditions are optimal. Starr et al. (2000) conducted a long-term range test for three months, but receiver performance was not related to environmental conditions. Rather, data were used to estimate the average detection range across the duration of the study and determine the accuracy of depth sensor transmitters. Clearly, there is a need for a better, and more mechanistic, understanding of the effects of environmental conditions on receiver performance to aid interpretation of results from acoustic telemetry studies.

Temporal variability in receiver performance has important implications for the analysis of telemetry data. The type of data collected depends on the receiver system that is employed. Two major types of remote telemetry receivers are available, including those capable of estimating fish position (typically within a few meters) via triangulation and receivers that only record the presence of a telemetered animal when it is within the detection range of the unit (Voegeli et al. 2001; Heupel et al. 2006).

Presence/absence style receivers were used in this study. These receivers are often deployed in 'lines' to study fish migration (Comeau et al. 2002; Finstad et al. 2005; Able and Grothues 2007; Melnychuk et al. 2007). For example, receiver lines may be deployed at an inlet connecting an estuary to the coastal ocean. If receivers on a particular line are spaced too far apart such that their detection ranges do not overlap at certain times, fish may pass through the receiver line undetected and resultant migration rates would be inaccurate. Presence/absence receivers are also widely employed in habitat use studies (Humston et al. 2005; Heupel et al. 2006; Lindholm et al. 2007; Afonso et al. 2009). Knowledge of temporal variability in receiver performance is especially important in these studies because if detection ranges are dynamic and habitat heterogeneity exists within the maximum range, it is impossible to determine which

microhabitat (e.g., reef vs. soft-bottom) telemetered fish are using. Moreover, analyses of habitat use periodicities may be compromised if receiver performance covaries with the same environmental conditions to which fish behavior is being related. For instance, if receiver performance is consistently poor during a given tidal state, lower fish presence during that tidal state could be due to the inability of a receiver to detect fish rather than movement away from the study site (i.e., receiver performance and fish behavior are confounded).

The main goal of this study was to enhance the interpretation of telemetry data by assessing the performance of a remote receiver array that was used to monitor the movements, distribution, and habitat use of spotted seatrout. I focus herein on the causes and consequences of temporal variation in receiver performance based on data from a long-term range test (~one year) at a single site. Several short-term range tests were also performed across multiple sites. Specific objectives and associated hypotheses were to:

- Examine relationships between receiver performance and environmental variables (wind speed/direction, turbidity, water temperature, salinity, dissolved oxygen, and tidal state)

H<sub>a</sub>: Receiver performance is negatively related to turbidity and wind speed; positively related to temperature and salinity

- Determine the ability of acoustic gate receivers to document fish migration
- Verify transmitter operation by determining *in situ* transmitter battery lives and accuracies of sensor transmitters (temperature, depth)

## Methods

### Study Area

Calcasieu Lake is an estuarine system (~300 km<sup>2</sup>) located in the Chenier Plain of southwestern Louisiana (Figure 2.1). This estuary was formed after the last glacial maximum

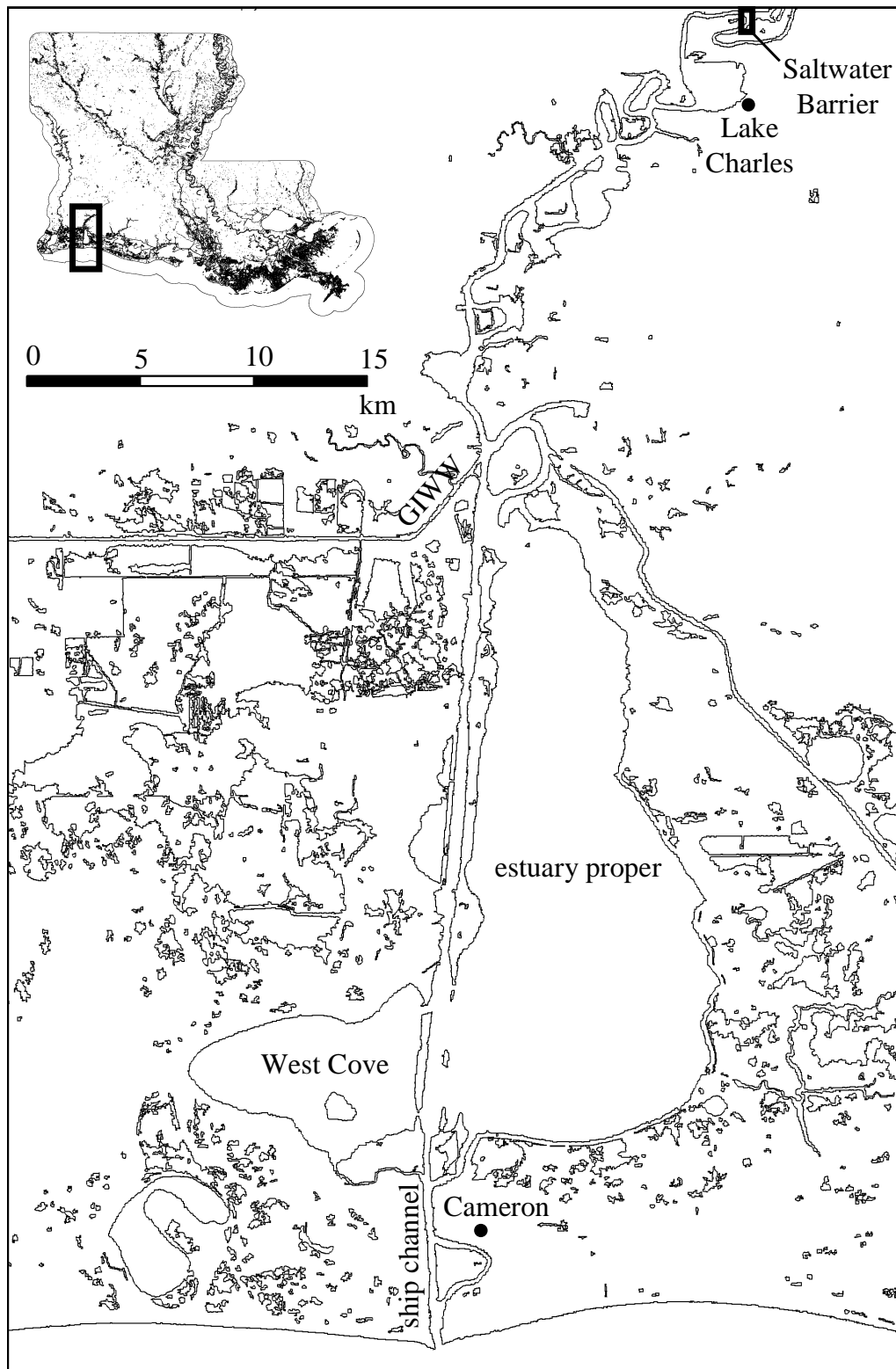


Figure 2.1. Study area, the Calcasieu Lake estuarine system. GIWW = Gulf Intracoastal Waterway. Black box in the upper right corner indicates the location of a water control structure, the Calcasieu River Saltwater Barrier.

when sea level rose and flooded a river-incised coastal valley (Nichol et al. 1996; McBride et al. 2007). Hence, the estuary was not directly formed through the delta cycle as were the large, wide estuaries characteristic of southeastern Louisiana. The main basin of the Calcasieu Lake estuary, referred to hereafter as the “estuary proper,” is 25 km long and widens southward from 5 to 20 km (Figure 2.1). Average and maximum depths of the estuary proper are 1.5 and 2.5 m, respectively. The dominant substrate of the estuary proper is soft to moderately firm mud. Expansive low-relief oyster reefs are present in the several areas of the estuary, and salt marshes fringe the estuary proper.

Like many areas in coastal Louisiana, Calcasieu Lake has experienced substantial modification of its natural hydrologic regime. A relatively deep (~15 m) ship channel was dredged from the main tidal inlet north to Lake Charles (a distance of 60 km) during 1938 to 1941 to provide deep-draft vessels access to the Port of Lake Charles (Figure 2.1). As a result, the tidal inlet connecting the estuary to the nearshore Gulf of Mexico (GOM) was straightened and deepened relative to its natural meandering and shallow state (~4 m) and rock jetties (2 km in length) were installed at the inlet. Additionally, spoil banks of dredged material (~4-5 m high) now separate the estuary proper from the artificial ship channel, except in the southern portion of the estuary where the eastern side of the spoil bank is mostly eroded and along its western side, where two inlets provide entrances to West Cove (Figure 2.1).

Dredging of the ship channel significantly increased the tidal prism in the estuary and altered its natural salinity gradient by allowing saline water to penetrate farther north. Consequently, salt water intrusion threatened the vitality of freshwater wetlands and a thriving rice industry in the Calcasieu River watershed. As a solution to this problem, the U.S. Army Corps of Engineers erected (c. 1968) a water control structure, the Calcasieu River Saltwater

Barrier (hereafter, SW Barrier). This structure is located on the Calcasieu River, 4 km north of Lake Charles (Figure 2.1), and consists of five large flood gates and a navigation gate. The navigation gates are opened to facilitate small vessel passage, and the flood gates remain closed, except when the river stage north of the barrier exceeds 2.5 feet MLLW (a mean lower low water benchmark used by the United States Geological Survey (USGS)), at which time the gates are opened for flood control. Therefore, when the flood gates are closed, the only freshwater input to the estuary is through local rainfall and runoff.

Calcasieu Lake is a well-mixed estuary due to its shallow depth, but vertical stratification may occur sporadically, especially in channel habitats during periods of reduced wind stress and increased river flow (Lee et al. 1990). Similar to other estuaries in the northern GOM, tides in Calcasieu Lake are predominantly diurnal and sometimes semi-diurnal during equatorial tides (Lee et al. 1990). The tidal range in Calcasieu Lake is 0.6 m (Nichol et al. 1992).

Lake Charles is highly industrialized with numerous chemical plants, oil refineries, and liquefied natural gas (LNG) terminals on its shores. The Port of Lake Charles is the 11<sup>th</sup> largest seaport in the USA in terms of tonnage, with 5 million tons of cargo annually (<http://www.portlc.com>). Accordingly, vessel traffic on Calcasieu Lake is high, especially in the ship channel. Cargo ship and tanker traffic is common throughout the entire ship channel. Also, shrimp boats are seasonally active in the channel. The Gulf Intracoastal Waterway horizontally bisects the system just north of the estuary proper and possesses a high volume of tug boat and barge traffic (Figure 2.1). Boat traffic associated with the oil and gas industry is heaviest in the southern extreme of the ship channel, where vessels provide transportation service from Cameron to nearshore oil rigs (Figure 2.1). In the estuary proper, recreational boats are the most common vessel type, and their activity is greatest during prime fishing months, April to

September. High vessel traffic poses special challenges for using remote acoustic telemetry to monitor fish movements, particularly in terms of anthropogenic noise effects on receiver performance and gear loss due to vessel strikes.

### Receiver Array Design

Although this chapter focuses on receiver performance, a description of my receiver array design is warranted here to provide a context for range testing methodologies. I deployed an array of 60 receivers throughout the Calcasieu system (Figure 2.2). This array served a multitude of purposes as it was used to monitor: 1) fish emigration from the estuary (chapter 3); 2) estuarine-scale distribution patterns (chapter 4); and 3) habitat use (chapter 5). To detect fish emigrating from the estuary to the nearshore GOM or vice versa (returning to the estuary), I deployed two receiver lines, with two receivers in each line, in the southern extreme of the ship channel that connects the estuary to the nearshore GOM (Figure 2.2). In this type of design, detection ranges of adjacent receivers within a line must overlap to ensure 100% cross-channel coverage. Also, at least two lines of receivers are required to discern swimming direction. Receiver lines deployed in this configuration are commonly referred to as “acoustic gates” (Grothues et al. 2005; Heupel et al. 2006), and I use the term “inlet gate” hereafter when referring to the receivers in the main tidal inlet that were primarily deployed to monitor fish emigration (Figure 2.2).

To investigate habitat use, I deployed receivers in multiple habitat types (e.g., natural oyster reefs, artificial reefs, mud-bottom, marsh, and channel). A list of potential “hotspots” was generated through meetings with local fishermen and personnel from the Louisiana Department of Wildlife and Fisheries (LDWF). All sites were scouted prior to receiver deployment to choose a set of stations that were representative of the diversity of habitats in the estuary. I also ensured

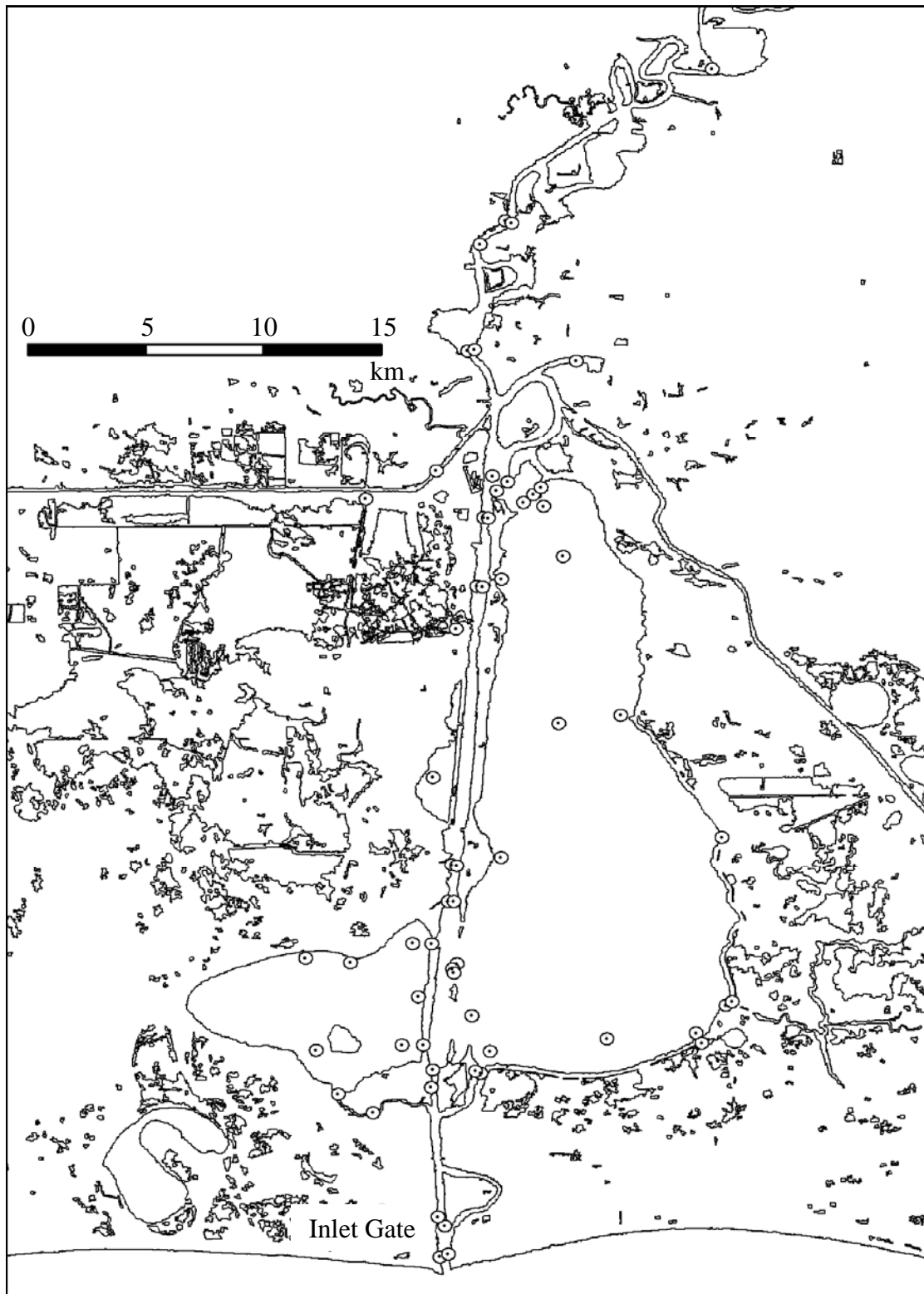


Figure 2.2. Receiver array. Each dot depicts a receiver station ( $n=60$ ). For spatial reference, the radii of circles surrounding dots are 250 m. The four southern-most receivers comprised the inlet gate.



that chosen sites were distributed as equally as possible throughout the system to facilitate the investigation of broad intra-estuary movement and distribution patterns.

All telemetry equipment used in this study was manufactured by VEMCO. Specifically, I used VR2 and VR2W presence/absence receivers and coded pinger (V9-2H) and sensor (V13TP-1H, V13T-1H) transmitters.

### Receiver Mooring and Mounting Designs

Receivers in the ship channel were mounted to channel marker pilings, and all other receivers were moored to buoys. I used two different styles of channel marker mounts. Fiberglass mounts were used in the initial deployment of the array during spring 2007, and aluminum mounts were fabricated midway through the study in summer 2008. Thus, the aluminum mounts were mainly used as replacements for receivers destroyed by vessel strikes.

Fiberglass mounts consisted of two pieces of fiberglass angle, 2.7 and 3.1 m in length. Divers attached the longer fiberglass piece to channel marker pilings with galvanized lag bolts. The shorter piece of fiberglass held the receiver in a Delrin collar (Figure 2.3A). A groove at the bottom of the fiberglass piece bearing the receiver rested on top of a bolt protruding from the bottom of the longer piece of fiberglass. To finish securing the entire mounting system, a lag bolt was driven through the top of both pieces of fiberglass (Figure 2.3B). Divers were only required for the initial installation of this mounting system, as the outer piece containing the receiver could be removed and re-deployed from a small boat with the use of an impact driver.

The aluminum mounting system was fabricated by welding a 2.3 m solid aluminum pole to a flat piece of aluminum intended to sit flush against channel marker pilings (Figure 2.4). Receivers were attached with hose clamps to a bracket welded onto a separate hollow aluminum pole of slightly larger diameter than the solid pole. The hollow pole containing the receiver was



Figure 2.3. Fiberglass mounts used to attach receivers to channel marker pilings. **(A)** Receiver being placed on the mount after downloading, note white Delrin collar holding receiver intact. **(B)** Top-view of mounting system, receiver is underwater and in listening mode. Photo credit: Michael Harbison.

simply slid onto the solid pole already mounted to the piling (Figure 2.4A). The top of the mounting system was secured with cable ties attached to a loop protruding from the flat piece of aluminum (Figure 2.4B). The main advantages of this system were that divers were not required for installation, and the moveable portion of the mount containing the receiver was much easier to re-attach than in fiberglass mounts, especially when currents were strong.

For both fiberglass and aluminum designs, mounts were attached to the mid-channel side of pilings, with a slight diagonal offset to ensure that the piling did not obstruct the reception of acoustic signals emanating between the shoreline and piling. Also, mounts were attached to



Figure 2.4. Aluminum mounts used to attach receivers to channel marker pilings. **(A)** Receiver being placed on the mount after downloading. **(B)** Top-view of mounting system, receiver is underwater and in listening mode. Photo credit: Michael Harbison.

pilings at a height such that receivers were approximately 1 m below MLLW to prevent air exposure during extreme low water events.

Buoy mooring systems consisted of two double-braided nylon ropes (an anchor rope and receiver rope), two anchors (a ballast anchor and main anchor), and galvanized rigging hardware (shackles, swivels, etc.). Main anchors were fabricated by adding an eyebolt to a plastic bucket filled with concrete (~30 kg). I shackled a 1 m piece of chain to the eyebolt, and shackled the anchor rope to the chain. Terminal rope loops were covered with heater hose to reduce abrasion.

Anchor ropes were 1.5 m longer than respective station depths to provide some slack in the rope to: 1) reduce tension on the system during increased sea state; and, 2) allow the receiver to be pulled out of the water and serviced from a small boat. I attached the anchor rope to an eye-eye swivel shackled to a 5 kg mushroom anchor used as a ballast weight (Figure 2.5). Receiver ropes were 0.5 m in length. The bottom end of the receiver rope was connected to the shackle on the mushroom anchor, and the top of the receiver rope was tied onto the swivel on the bottom of the buoy (Figure 2.5). I attached receivers with two hose clamps and six industrial cable ties inserted through the rope. The primary reason for using separate anchor and receiver ropes was to maintain a vertical orientation of the receiver to optimize its performance (Clements et al. 2005). All receivers, including those mounted on channel markers, were deployed with the hydrophone pointing downwards. In an attempt to reduce vessel strikes at night, I equipped all buoys with photo-sensitive strobe lights.

I painted all receivers with anti-fouling paint (TrinidadSR 1277 blue, non-ablative, 70% cuprous oxide) to mitigate biofouling. A series of pilot telemetry studies in Barataria Bay in 2006 revealed that painted receivers performed similarly to unpainted receivers. I also painted the submerged portions of channel marker mounts and receiver ropes of buoy moorings.

### Short-Term Range Tests

The main goal of the short-term range tests was to determine the ability of the inlet gate to detect passing fish (transmitters). Accordingly, I towed transmitters from a small 6 m vessel at two to four knots to simulate fish passage through this acoustic gate. I primarily used fixed delay transmitters with a short delay (30 sec for V9s, 60 sec for V13s) to yield a high number of transmissions, and usually towed only one transmitter at a time to avoid signal collisions. Transmitters were placed in a mesh bag attached to the end of a rope, and an egg sinker (0.4 kg)





Figure 2.5. Mooring system for buoyed receivers. Also note a HOBO temperature logger is connected to the receiver. Photo credit: Michael Harbison.

was added to the terminal end of the bag. The rope was 2 m in length to assure that the transmitters remained below the boat hull during transit. To reduce engine noise, a bow-mounted trolling motor was employed to power and navigate the vessel instead of the outboard motor. During each test, at least one tow was performed through the middle of the ship channel to determine if receivers mounted on shoreward channel marker pilings had a sufficient range to detect mid-channel transmissions.

I also conducted short-term range tests at sites other than the main tidal inlet (Table 2.1, Figure 2.6). Methods were the same as those described above, except for the test in the upper bay (stations 20, 21, 22, and 27; Figure 2.6). For the upper bay test, the vessel remained

Table 2.1. Dates, times, and environmental conditions for short-term range tests. Wind speed, direction, and tidal state were gleaned from the nearest continuously recording instrument (see Figure 2.12). Water temperature and salinities at each site were measured with a handheld YSI (600 series), and reported values are averages of surface and bottom measurements at each station or station group. Station locations are given in Figure 2.6. “L” = low tide.

Date	Time of tests	Station(s)	Wind spd. (ms <sup>-1</sup> )	Wind dir. (deg.)	Tidal state	Water temp. (°C)	Salinity
7-23-07	16:45-17:30	7,7A	2.8	10	Slack L	30.2	10.0
7-23-07	18:00-18:30	10,10A	2.4	30	Slack L	30.4	8.7
7-23-07	18:45-19:30	67,68	1.9	30	Slack L	30.5	8.3
12-5-07	13:00-15:00	47,48	5.1	228	Flood	14.5	18.0
1-14-08	11:30-12:30	47,48	3.5	51	Slack L	13.6	21.4
3-27-08	08:00-10:00	20,21,22,27	4.1	180	Flood	18.8	7.5
5-28-08	17:00-17:45	30,31	5.1	165	Ebb	30.1	13.5
7-14-08	12:30-14:30	Alpha,50	3.2	V	Ebb	31.0	18.6
7-14-08	15:00-16:00	47,48	4.2	235	Ebb	30.1	17.9
1-21-09	14:30-16:00	36	4.1	220	Flood	12.0	12.0
3-11-09	14:30-15:00	85,86	4.6	170	Ebb	21.3	16.4
6-1-09	14:00-16:00	47,48	5.4	155	Ebb	28.5	23.3
6-1-09	16:30-17:00	Alpha,50	5.1	150	Slack L	28.4	22.1
7-27-09	10:00-11:00	14	4.1	200	Ebb	29.8	18.6

stationary at discrete points to allow multiple transmissions to be emitted at the same location instead of the transmitter being continuously towed.

Internal receiver clocks can drift since the time they were last downloaded; therefore, it was necessary to adjust detection data for clock drift. A boat-side VR60 hydrophone was used to determine the actual time of each transmission. Also, ArcPad 6.0 was employed to log the spatial position of the vessel (transmitter) every four seconds. Thus, by cross-referencing times between the VR60 and ArcPad data, it was possible to glean the spatial position of each transmission with no error because both clocks (stopwatch for the VR60, laptop for ArcPad) were synced, within one second, to a GPS that streamed real-time data to a field laptop computer. Nevertheless, to link detection data from stationary receivers with the appropriate

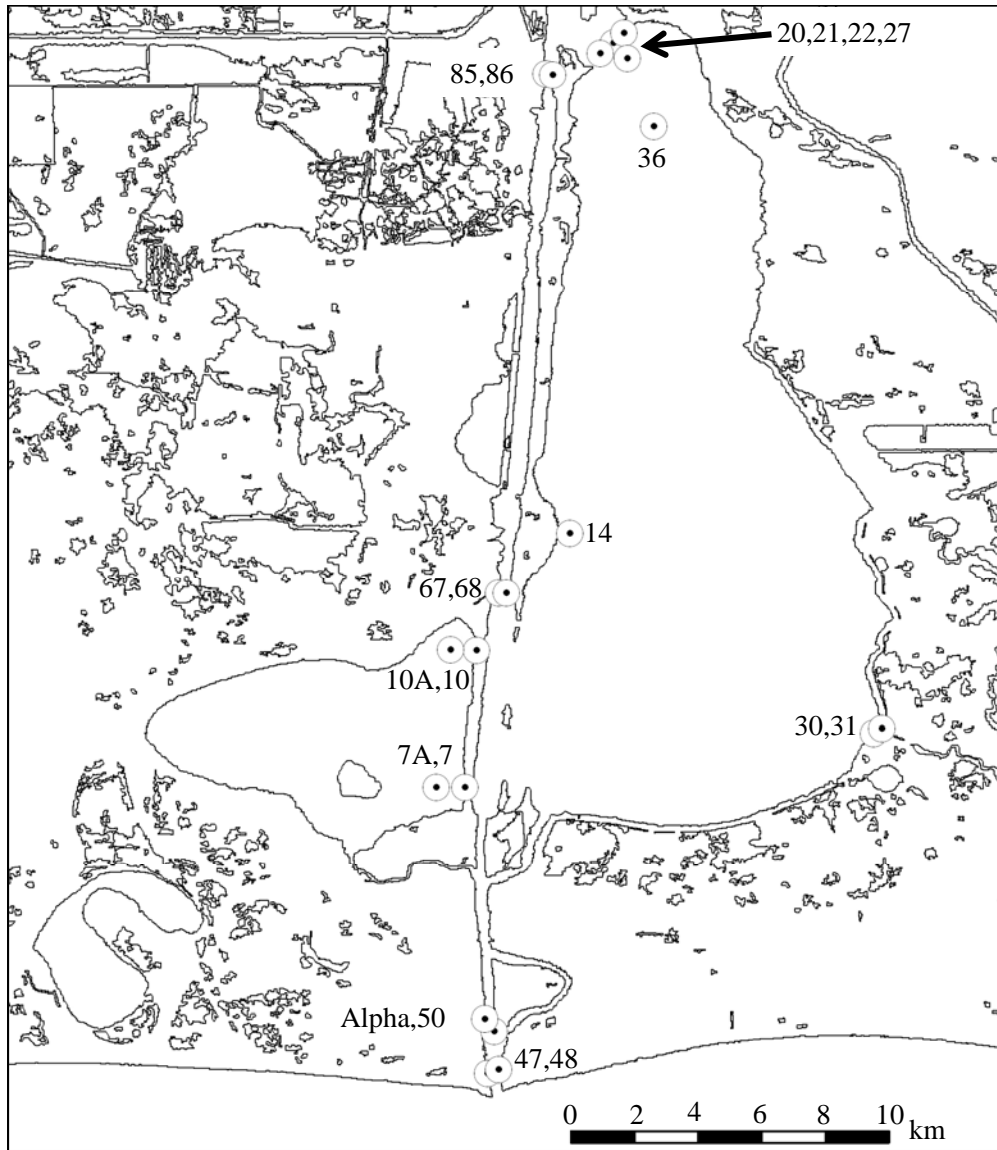


Figure 2.6. Receiver stations where short-term range tests were conducted.

boat-side transmission, it was necessary to account for clock drift. As an example of the effect of receiver clock drift, consider a situation where the transmitter being towed fires every 60 seconds, and transmission times are accurately determined with the VR60, but the clock of the deployed VR2 receiver of interest is running 70 seconds ‘fast’. For a transmission at time  $X$ , the fast VR2 receiver would record the detection time as  $X + 70$  seconds, and if this fast time was

used as the cross-reference time to glean the spatial position of the vessel from the ArcPad log, the position would be 70 seconds “downstream” of where the actual transmission occurred. Moreover, a second transmission (Y) would have occurred within the 70 second clock drift period; thus, the fate of transmission X would be misinterpreted as the fate of transmission Y if the VR2 detection data were not adjusted for receiver clock drift.

Receiver clock drift values were obtained from receiver event files and calculated as the time difference between laptop and receiver clocks at the time of downloading. Receiver clocks were typically fast, and drift values ranged from -7 to +140 seconds, with a median of 68 seconds. To adjust detection times for receiver clock drift, I subtracted drift values from detection times for fast receivers and added drift values to detection times for slow receivers. Receivers were downloaded immediately after each short-term range test. Therefore, the clock drift values I calculated were assumed to be representative of those experienced during the range tests.

To assess the performance of the inlet gate, I calculated the percent of tows in which a given transmitter was detected, referred to hereafter as the “detection rate”. For the other sites, whose main purpose was not determining fish passage, I qualitatively defined detection ranges as the distance within which most (i.e., > 75%) transmissions were detected.

### Long-Term Range Test

I conducted a long-term range test to assess the degree and causes of temporal variation in receiver performance. Three buoyed receivers were deployed at fixed distances (100 m, 250 m, 500 m) from a set of reference transmitters permanently mounted to a piling in the southern portion of the estuary proper (Figure 2.7). Reference transmitters were placed in a mesh bag (dipped in anti-fouling paint) that was attached to the outside of a 3 cm diameter PVC pipe





Figure 2.7. Long-term range test site. The black square shows the location of the piling to which reference transmitters were mounted; circles depict receiver locations, which were 100, 250, and 500 m from the reference transmitters.

mounted to the side of the piling facing towards receivers. Transmitters were mounted 0.8 m below MLLW; the water depth at the piling was 2 m at MLLW. Thus, the transmitters were generally in the middle of the water column. Depths across the site ranged from 1.5 to 2.0 m, and the dominant substrate was moderately firm mud. Scattered oyster shells were present (< 10% coverage) at the 100 m and 250 m receiver stations, and sand comprised a minority of the substrate at the 500 m station.

I utilized two different types of transmitters for the long-term range test, random delay and fixed delay transmitters. The main difference between the two transmitters is that the interval between successive transmissions (delay) oscillates between a minimum and maximum bound (e.g., 60 to 180 seconds) for random delay transmitters, but is constant (e.g., always 60 seconds) for fixed delay transmitters (see below section entitled “Overview of Telemetry System Operation Principles for more detail). I also used two different sizes of reference transmitters, smaller V9s and larger V13s, because these sizes corresponded to those implanted in fish. The power output and delays (only random delay transmitters were used in fish) of reference transmitters matched those implanted in fish. In total, I used three random delay transmitters (one V9 and two V13s) and two fixed delay transmitters (one V9 and one V13) in the long-term range test. Random delays of reference transmitters were 150 to 300 seconds for the V9-2H (expected battery life of 310 days), 60 to 180 seconds for one V13TP-1H (expected battery life of 370 days), and 75 to 225 seconds for the second V13TP-1H (expected battery life of 460 days). Both fixed delay transmitters had a delay of 300 seconds, and expected battery lives were 426 and 844 days for the V9-2H and V13T-1H, respectively. Power outputs were 147 dB re 1µPascal for all V9s and 158 dB re 1µPascal for all V13s.

I activated the random delay reference transmitters on April 13, 2008 and deployed them on April 17, 2008. The original transmitter mount was damaged during the spring of 2008 and had to be modified, which precluded the use of data collected before July 23, 2008. All telemetry equipment was removed from the estuary on August 28, 2008 to prevent gear loss during Hurricanes Gustav and Ike, and re-deployed in late September 2008 (Figure 2.8). Therefore, a one-month gap in range test data is present from August 28, 2008 to September 30, 2008 (Figure 2.8). I did not de-activate reference transmitters during this period; instead, I allowed them to continue operating in the laboratory. Fixed delay reference transmitters were activated on August 24, 2008, but not deployed until after the hurricanes, on October 1, 2008 (Figure 2.8). I temporarily removed all reference transmitters on July 8, 2009 to inspect the spring 2008 transmitters that had expired, and to clean the mount and replace the mesh bag. I re-deployed the reference transmitters (fixed delay only) on July 22, 2009 (Figure 2.8).

I serviced all receivers in the array, including those used in the long-term range test, at roughly six-week intervals. Receiver data were downloaded to a field laptop computer with a serially connected electromagnetic probe (VR2s) or wirelessly via Bluetooth communication (VR2Ws). After downloading, I initialized, cleaned, and re-deployed receivers. Cold seal tape was applied to prevent biofouling of receiver probe holes, and a light coat of anti-fouling paint was applied to receiver hydrophones before re-deployment. Receiver loss was moderate throughout the study, and lost receivers were typically replaced during the same servicing trip in which they were recognized as missing. Two receivers used in the long-term range test were lost, resulting in data gaps from November 17, 2008 to January 23, 2009 for the 250 m station and from September 24, 2009 to October 27, 2009 for the 500 m station (Figure 2.8). During servicing trips, I also measured physicochemical water variables at each receiver station.

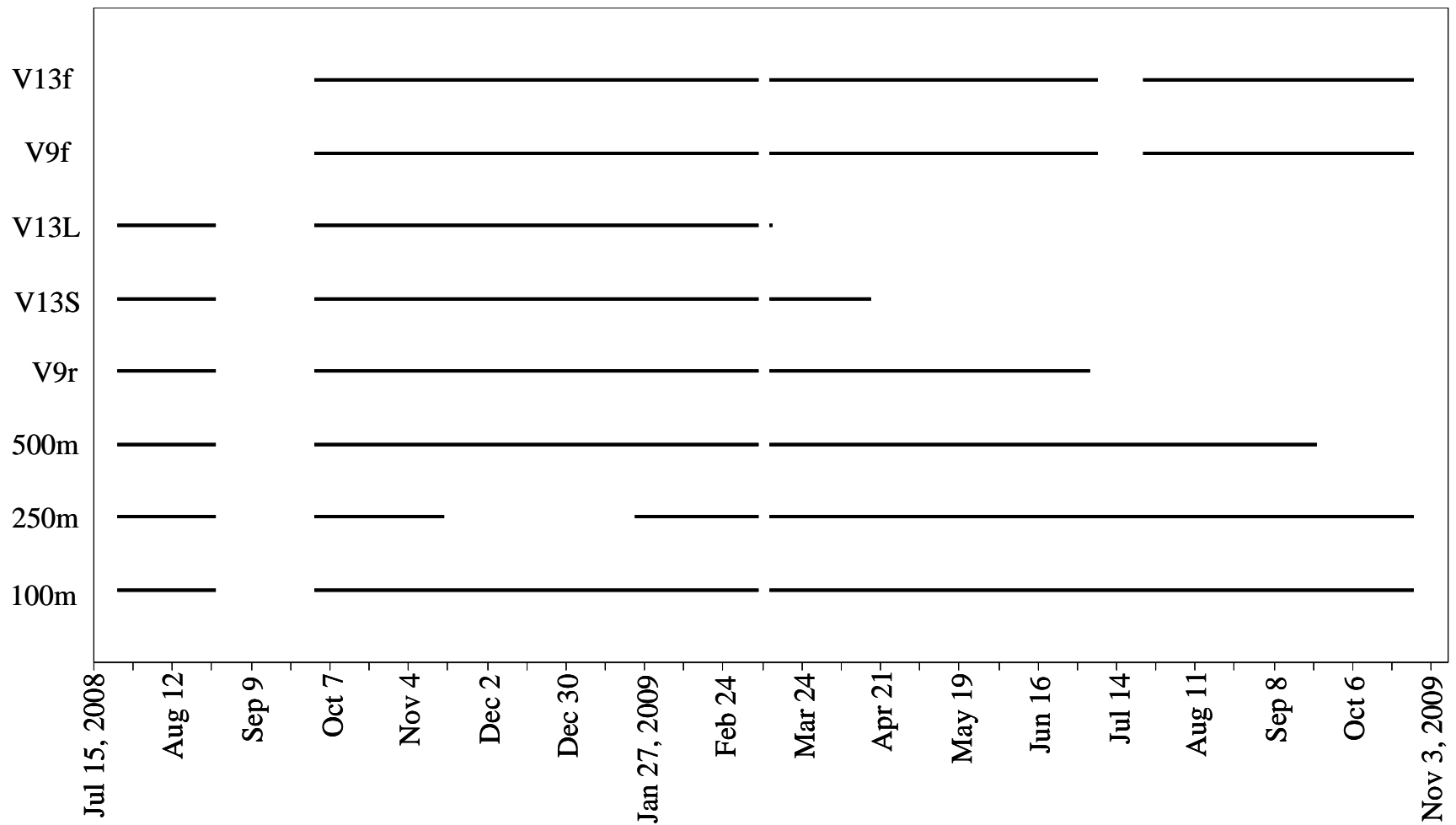


Figure 2.8. Daily operation chronology for receivers and transmitters used in the long-term range test. A gap in the line indicates a given receiver or transmitter was not operational for that period. 100m, 250m, 500m = receivers. V9r = random delay V9 transmitter, V13S = V13 transmitter with average random delay of 120 seconds, V13L = V13 transmitter with average random delay of 150 seconds, V9f = fixed delay V9 transmitter, V13f = fixed delay V13 transmitter. The month-long gap during September 2008 was due to Hurricanes Gustav and Ike, during which time all telemetry equipment was removed from the estuary.

Surface and bottom values of temperature, salinity, and dissolved oxygen were recorded with a 600R YSI sonde attached to a 650 MDS display system; for channel stations, additional surface and bottom measurements were performed in the middle of the channel.

#### Inter-Receiver Performance Test

To determine if receivers had any inherent differences in performance, I conducted two inter-receiver performance tests at the long-term range test site. A preliminary test was conducted for 22 hours from March 19 to 20, 2007, whereby three VR2 receivers were deployed equidistant, 110 m, from two reference transmitters (V9-2H 30 sec fixed delay, V13-1H 60 sec fixed delay). A similar test was performed with the same receivers used in the long-term range test. In this test, I deployed three receivers equidistant (150 m) from one reference transmitter (V13-1H 60 sec fixed delay) for 18 hours during September 29 to 30, 2008. Theoretically, the only performance differences in these tests should be those associated with the inherent variation of individual receivers because all receivers were equidistant from the reference transmitters.

#### Verifying Transmitter Operation

Several secondary objectives regarding transmitter operation were examined as part of the long-term range test. I determined *in situ* transmitter battery lives, the accuracy of transmitter sensors (temperature and depth), and indirectly compared power outputs between a new and previously deployed transmitter. I based *in situ* battery life estimates on two random delay transmitters (one V9, one V13) deployed in spring 2007 (May 11, 2007), and the three random delay transmitters (one V9, two V13s) deployed in spring 2008 for the long-term range test. Random delays for the 2007 transmitters were 150 to 300 seconds for the V9-2H (expected battery life of 230 days) and 60 to 180 seconds for the V13TP-1H (expected battery life of 340 days). A single VR2 receiver was deployed at 250 m from the 2007 transmitters to monitor their

operation and battery lives. Both sets of reference transmitters were deployed during spring tagging events in 2007 in 2008 (see chapter 3) to ensure that reference transmitters experienced as similar environmental conditions as possible to telemetered fish.

For the power output test, I simultaneously deployed a new V9 fixed delay transmitter with a V9 fixed delay transmitter that had been activated for 451 days and deployed 397 days. Detections from the two transmitters were monitored for 18 hours (October 28 to 29, 2009) with receivers at the 100 m and 250 m stations.

Only the larger V13 transmitters contained sensors, for both temperature and pressure (depth). Accuracy estimates provided by the manufacturer (VEMCO) were  $\pm 0.5^{\circ}\text{C}$  for temperature sensors and  $\pm 2.5$  m for depth sensors, with measurement resolutions of  $0.15^{\circ}\text{C}$  and 0.22 m. To verify the reported accuracy of temperature sensors, I compared *in situ* sensor values to temperatures measured by a highly accurate multiparameter YSI 6600 V2 sonde deployed at the same piling complex as the sensor transmitters. The performance of depth sensors was only qualitatively assessed because reference transmitters were static (i.e., attached at a permanent height on the piling).

#### Overview of Telemetry System Operation Principles

To provide a background for the receiver performance metrics I develop below for the long-term range test, an overview of the operation principles for VEMCO telemetry systems is presented here. VEMCO uses a pulse interval coding scheme to convey information on transmitter identification numbers and sensor values. For the transmitters I used, each transmission consisted of a sequence of eight pings. The time intervals between pings, on the order of 100s of milliseconds, are used to code information. The first of the seven ping intervals, referred to as the sync period, is the shortest (~320-360 milliseconds) and values are unique for

each transmitter family or code space. For transmitters that only convey information on identification numbers, termed pingers, four intervals are used to code identification numbers, and two intervals are used for error-checking. Each transmitter identification number has a unique set of time intervals between pings. The total number of unique identifications (IDs) for the pingers I employed (V9-2Hs) was 64,000. Transmitters that convey information on both IDs and sensor values alternate their transmissions, whereby one transmission is a pinger transmission and the next is a sensor transmission. For sensor transmissions, two ping intervals code IDs, two intervals code sensor values, and the remaining two intervals are used for error-checking. Time intervals used to code sensor values vary in length as a function of the variable they are measuring. For example, longer ping intervals are used to indicate cooler water temperatures and vice versa. The length of time required for a complete transmission sequence of eight pings is termed the burst length, which is typically three to four seconds. The time between successive transmissions is referred to as the delay period. Random delay transmitters are programmed to randomly “select” a delay period between a minimum and maximum length to ensure that delay periods are constantly changing to reduce collisions when multiple transmitters are present within the detection range of a receiver. For example, if minimum and maximum delays are 60 and 180 seconds, respectively, the delay between transmissions X and Y may be 70 seconds, with the delay between transmissions Y and Z 160 seconds. On the contrary, the delay period for fixed delay transmitters is constant (e.g., always 300 seconds).

For successful electronic detection and storage of transmitter information, a receiver must “hear” all eight pings of a transmission sequence, and the sequence must pass the receiver’s error-checking algorithm. For each detection, receivers store date and time stamps, transmitter IDs, and sensor values. The VR2 and VR2W receivers both operate at 69 kHz, but the

bandwidth of their preamplifier is 20-100 kHz. Therefore, receivers are sensitive to noise in the range of 20-100 kHz, which encompasses the frequencies of sea state, biological, and anthropogenic (e.g., echosounder, vessel engine) noise.

#### Development of Receiver Performance Metrics for the Long-Term Range Test

To assess receiver performance it was necessary to develop a metric, hereafter referred to as detection efficiency (DE) that related the number of transmissions electronically recorded by a receiver to the total number of transmissions expected during a given time period. Calculation of the total number of expected transmissions is rather straightforward, especially for fixed delay transmitters; however, when multiple transmitters are simultaneously deployed at the same site, collisions can complicate interpretations of the number of transmissions recorded by a receiver. For example, if two transmitters were concurrently deployed at the same site, the total number of transmissions from each transmitter during a given time period would be the same as if they were deployed separately at distant locations. Yet, the number of recorded detections would probably be lower, due to collisions, for the situation where the two transmitters were deployed simultaneously at the same site.

Collisions occur when the bursts of two or more transmitters overlap in time. Generally, one transmitter will fire simultaneously or shortly after (i.e., within 3 seconds) another transmitter, resulting in a ping interval shorter than the sync. When this occurs, the receiver recognizes the ping sequence as invalid and neither transmission is electronically recorded. Occasionally, transmissions from two or more transmitters will collide to create a hybrid sequence with valid ping intervals; however, in all but one of every 256 such cases, the error-checking algorithm is able to recognize that the ping sequence originated from different transmitters, and a rejection is logged in the receiver event file. When the error-checking



algorithm fails (one of every 256 hybrid sequences), a false detection is recorded by the receiver (i.e., detection of a transmitter with a valid identification number that is not actually present at the receiver site). In both of these collision mechanisms, the number of syncs is largely unaffected, but detections decrease when collisions occur. For the latter (non-hybrid) mechanism, recorded rejections increase when collisions occur.

I simultaneously deployed up to five transmitters (three random delay, two fixed delay) in the long-term range test; therefore, it was necessary that receiver performance metrics appropriately accounted for collision effects. My original intent was to only calculate detection efficiencies for the fixed delay reference transmitters because it was possible to determine the exact number of expected transmissions from these transmitters. Nevertheless, the different burst times of the two fixed delay transmitters I used led to frequent collisions. As a hypothetical example of how this occurs: consider two fixed delay transmitters (X and Y) with equal delays (e.g., 300 sec) that are activated 150 seconds apart, but whose burst times differ (burst is one second longer for transmitter Y than X). The original 150 second gap between successive transmissions from different transmitters will “close” by 1 second per transmission due to the longer burst of transmitter Y, and the transmitters will collide every 12.5 hours (Figure 2.9). These collisions will persist (~one hour) until the transmitters are no longer synchronously firing. The burst time of the fixed delay V9-2H transmitter was constant, but the burst of the V13T-1H was variable because it also coded temperature information in its transmissions. Thus, depending on temperature (longer bursts at cooler temperatures), the burst length of the V13 was up to 0.7 seconds longer than that of the V9-2H, which resulted in collisions every four to eight days (see below). Consequently, it was not feasible to calculate detection efficiencies for extended periods (i.e., one year) based upon data from fixed delay transmitters. Instead, I

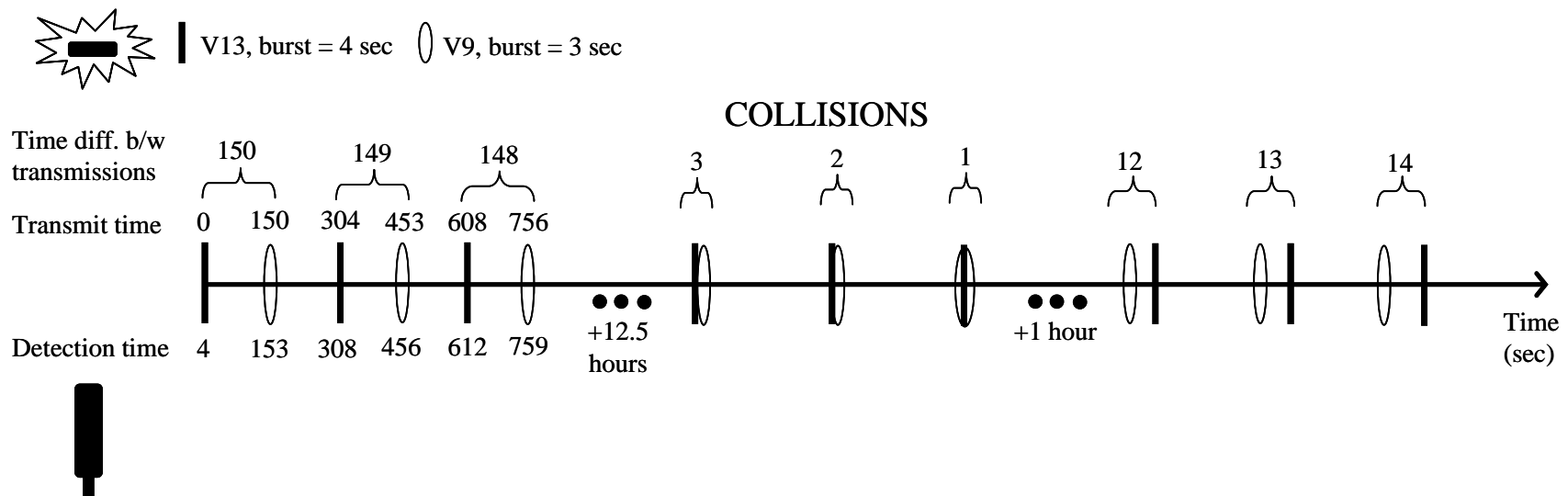


Figure 2.9. Conceptual diagram illustrating how collision periods arise when two fixed delay transmitters with equal delays, but different burst times, are deployed simultaneously. Black bars depict transmissions from a hypothetical V13T-1H transmitter with a burst of four seconds, and ovals depict transmissions from a V9-2H with a three second burst.

calculated daily DEs using data from the random delay reference transmitters for the period July 23, 2008 to June 30, 2009.

I used the following equation to calculate daily DEs for random delay transmitters:

$$DE = \frac{Nr_{(t,d)}}{Ne_{(t,d)}} \times 100 \quad (\text{Equation 2.1})$$

where  $Nr$  = the number of detections of a particular transmitter ( $t$ ) recorded by a receiver during a given time period (e.g., one day),  $Ne$  = the number of expected transmissions from a particular transmitter ( $t$ ) during a given time period (e.g., 24 hours), and  $d$  = receiver distance (100 m, 250 m, or 500 m). Daily DEs were calculated for each receiver distance (100 m, 250 m, 500 m) x transmitter combination (V9-2H, V13TP-1H). I excluded all data from the V13TP-1H random delay transmitter with a delay of 75 to 225 seconds because it prematurely expired (see below). For the other two random delay transmitters, I determined the expected number of daily transmissions ( $Ne$ ) by dividing the total number of seconds in one day by the sum of the burst length and average delay. As an example, the V9-2H transmitter had an average delay of 225 seconds and burst length of 3.2 seconds. Hence,  $Ne$  was 378 or  $(86400/(225+3.2))$  for the V9 2H. For the V13TP-1H random delay transmitter,  $Ne$  was 699.

Due to the randomization of delay periods, the actual number of daily transmissions from each transmitter may deviate slightly from the expected number. I based DEs on a relatively long time period (24 hours) over which 400 to 700 transmissions occurred. It is highly unlikely that a transmitter would select all short or all long delays over this period; instead to reduce collisions, the transmitter would more likely select a range of delays oscillating about the average (D.M. Webber, VEMCO, personal communication). Moreover, from this perspective of transmission schedules, it is illogical that the number of collisions would exhibit significant inter-daily variation (i.e., temporal variation in daily DEs would not be confounded by

collisions). Still, collisions may cause the magnitude of detection efficiencies to be consistently underestimated with the metric I employed, but this bias is probably small because the transmitters I used had long delay periods (60 to 300 sec), which reduces collision potential. To demonstrate that collisions did not cause the observed temporal variation in daily detection efficiencies, I analyzed receiver diagnostic data for the period July 23, 2008 to August 27, 2008, when only random delay transmitters were active at the long-term range test site (Figure 2.8).

Downloaded receiver data include diagnostic information in addition to detections of telemetered fish. Data summaries in event files provide the total number of rejections, pings, syncs, and detections on each code space during a particular time period, daily for VR2Ws and summed across the entire deployment period for VR2s. If collisions were inducing temporal variability in the number of daily detections, this would be indicated in diagnostic data by an increase in the number of rejections on days with lower detections, with the number of syncs remaining fairly constant. To explore these relationships, I utilized data from the VR2W receiver at 100 m because collision effects should be greatest for this receiver as it was nearest the reference transmitters and thus had the highest detection probability. The number of daily detections exhibited a strong positive correlation with the daily number of syncs (Spearman  $\rho = 0.78$ ,  $p < 0.0001$ ), but no significant correlation with the daily number of rejections. The positive correlation between syncs and detections and lack of relationship between the number of rejections and detections suggests that temporal variation in the number of daily detections was due to environmental variation, not collisions. For instance, the lowest number of detections and syncs occurred on August 5, 2008 when a strong tropical storm (Edouard) passed over the study area (Figure 2.10).

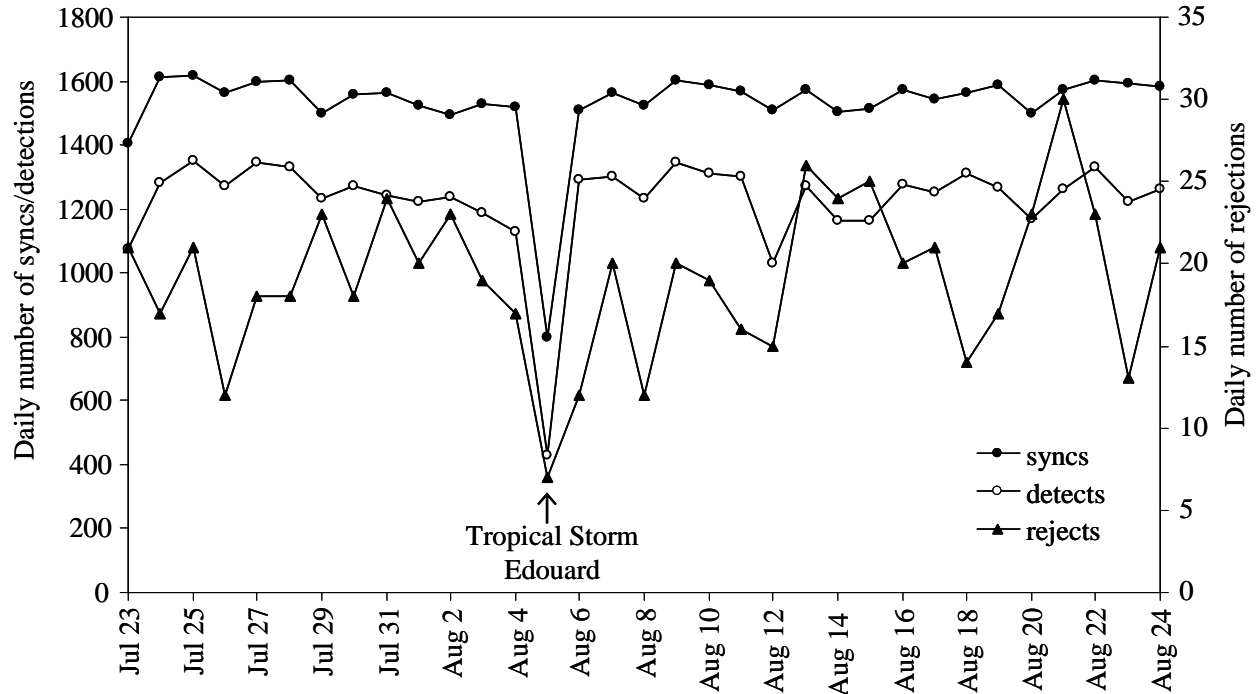


Figure 2.10. Diagnostic data from the VR2W receiver deployed at 100 m at the long-term range test site. Three random delay transmitters were simultaneous deployed; the number of syncs, rejections, and detections were summed over all transmitters for each day from July 23 to August 24, 2008. Tropical Storm Edouard passed over the study site on August 5, 2008.

Despite the periodic collisions between fixed delay reference transmitters (via the burst length mechanism described above), data from these tags were still useful, particularly for evaluating DEs at finer temporal scales (i.e., hours). First, to eliminate the potential for collisions between fixed and random delay transmitters, I only used fixed delay transmitter data for the time period after which random delay transmitters expired (July 23, 2009 to October 27, 2009). Secondly, for this time frame, I conducted a collision analysis to identify periods during which fixed delay transmitters were colliding with one another. For this analysis, I calculated the mean time difference between successive detections (of the two different transmitters) for hours during which both transmitters were detected by the VR2W receiver at 100 m. Collision periods were easily recognized due to their cyclic nature (Figure 2.11), as expected with

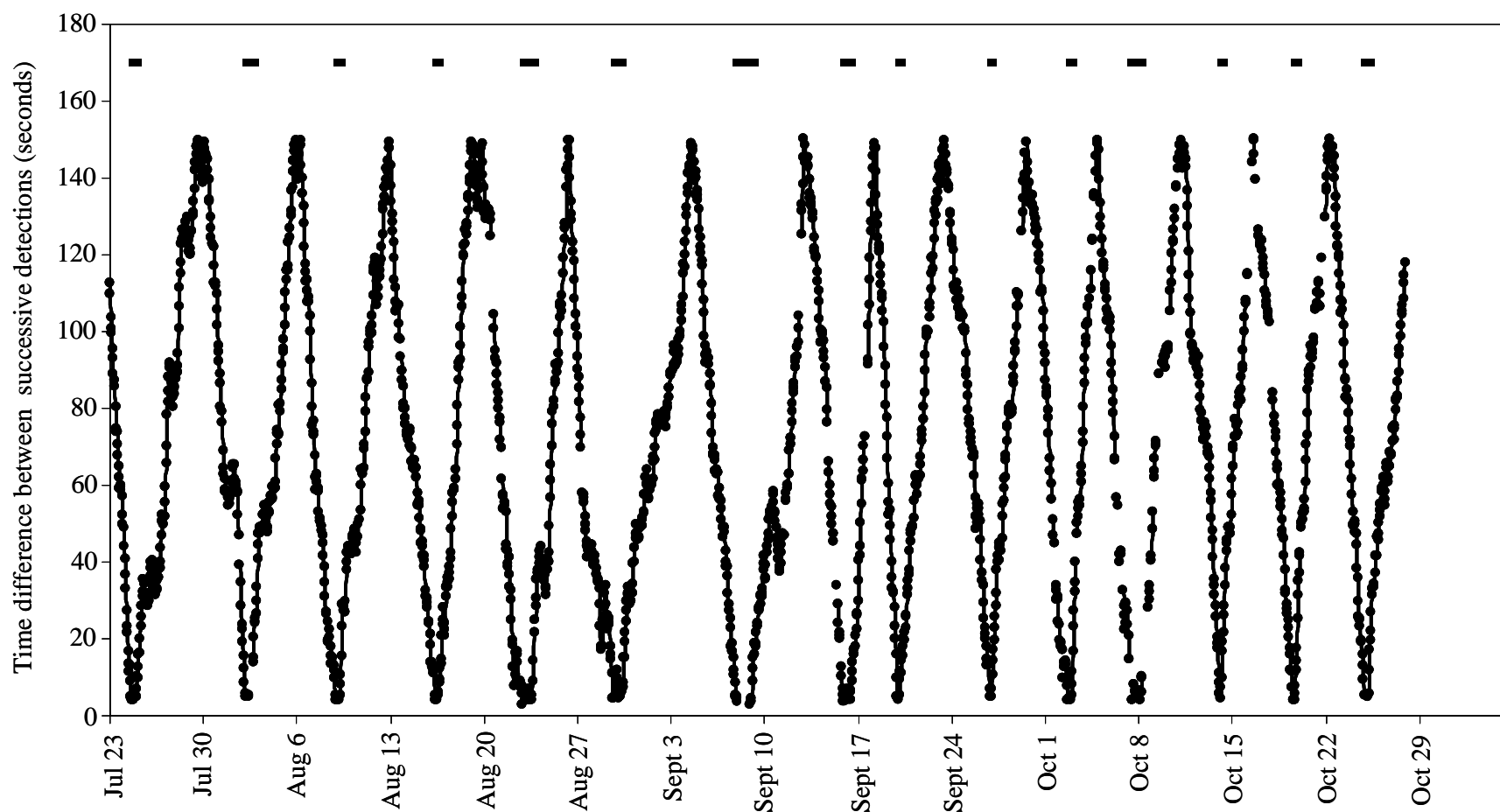


Figure 2.11. Results from the collision analysis of the two fixed delay reference transmitters (V9, V13) for the period July 23, 2009 to October 27, 2009. For each hour that transmitters were detected at the 100 m receiver, I calculated the mean time difference between successive detections of the two different transmitters; this metric is depicted by the black dots. Breaks in the line connecting the dots indicate hours during which only one or neither transmitter was detected. Black bars designate collision periods (i.e., when collisions were assumed to be occurring because the time difference between successive detections of the two different transmitters was less than five seconds and transmitters were presumably firing simultaneously).

transmitters possessing equal delays but different burst lengths (Figure 2.9). As the time interval between successive detections of the two different transmitters decreased to around five seconds, there were typically periods of no detections (which I assumed represented collision periods), followed by increased intervals between successive detections of the two transmitters (Figure 2.11). Accordingly, I assumed those periods in which the time between successive detections of the two different transmitters was less than five seconds constituted collision periods; indeed, if two transmitters fired less than five seconds apart, their bursts would overlap and likely result in a collision (i.e, no detections). I excluded data from collision periods from all analyses.

I calculated DEs for collision-free periods of fixed delay transmitter data using Equation 2.1 (see above). Both hourly and daily DEs were calculated. I only calculated daily DEs for those days on which collisions did not occur. For daily DEs,  $N_e$  (in Equation 2.1) was 284 for both transmitters (V9-2H, V13T-1H); for hourly DEs,  $N_e$  was 12 for both transmitters.

### Environmental Data

Environmental data measured with continuously recording instruments deployed by various agencies were used to examine the effects of environmental conditions on receiver performance (Figure 2.12, Table 2.2). I deployed a multiparameter YSI sonde (6600 V2) at the long-term range test site for high resolution (10-minute) measurements of water temperature, salinity, turbidity, and dissolved oxygen. The sonde was shackled to a chain and placed inside a PVC pipe (2.5 m long, 15 cm diameter) mounted to a piling. To promote water flow, numerous holes were drilled into the sides of the PVC pipe, and the top and bottom of the pipe were left open, with the exception of two safety bolts across the bottom. The optical probes of the sonde (turbidity, dissolved oxygen) were equipped with mechanical wipers that periodically cleaned probe surfaces to mitigate biofouling. I also installed an antifouling kit on the sonde (copper

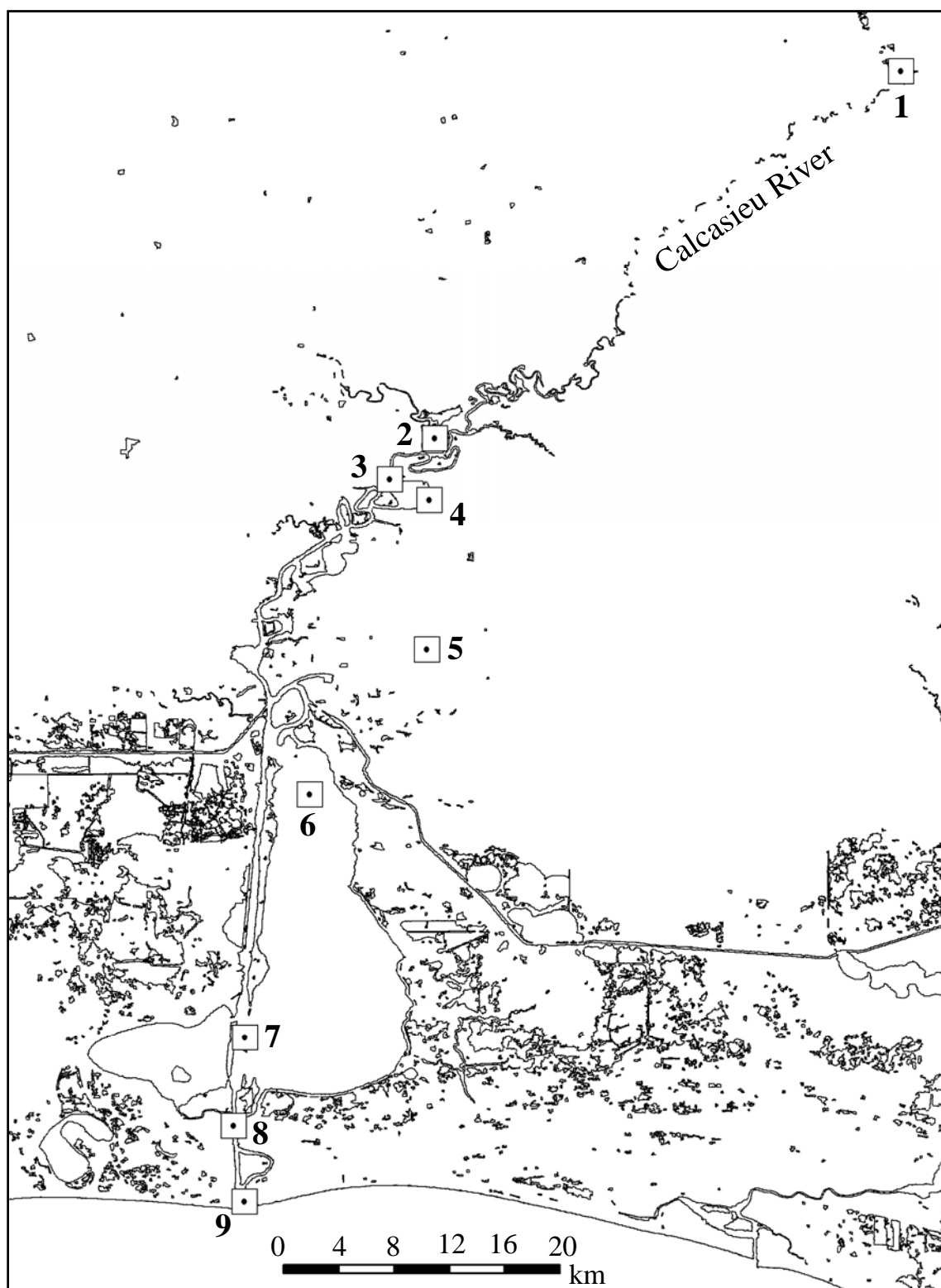


Figure 2.12. Locations of continuously recording instruments from which environmental data were gleaned. Station numbers are linked to Table 2.2, which provides a list of variables measured at each station and their recording frequencies.



Table 2.2. Summary of environmental data collected by continuously recording instruments. See Figure 2.12 for station locations.

Station	Name	Agency	Measured variables and recording frequency
1	Kinder	USGS	Water height, streamflow, wind speed/direction, 30 minute intervals
2	SW Barrier	US ACOE	Number of hours flood gates and navigation gates are open each day
3	Lake Charles	USGS	Water height, water temperature, salinity, 60 minute intervals
4	Lake Charles	NOAA	Water height, 60 minute intervals
5	LCH Airport	FAA	Air temperature, relative humidity, wind speed/direction, barometric pressure, precipitation, 60 minute intervals
6	Hackberry	USGS	Water height, water temperature, salinity, 60 minute intervals
7	9Mile	LSU	Water temperature, salinity, dissolved oxygen, turbidity, 10 minute intervals
8	Cameron	USGS	Water height, water temperature, salinity, wind speed/direction, 60 minute intervals
9	Cameron	NOAA	Water height at 60 minute intervals; water temperature, wind speed/direction, air temperature, barometric pressure at 6 minute intervals

probe guard, copper probe tape, and copper wipers for optical probes), and LDWF personnel cleaned the sonde monthly. Still, biofouling occasionally compromised the quality of sonde data, particularly salinity and turbidity measurements. Biofouling effects were easily recognized in sonde data and mostly occurred near the end of given deployment periods. After optical probes became fouled, turbidity values remained high and salinity steadily declined. Furthermore, occasional spikes (~1000 NTU) were present in the turbidity data that resulted from either the wiper mechanism parking over the optical probe or large particles passing through the water column when a measurement was taken. I filtered all turbidity outliers (spikes) from the sonde data, and also excluded all turbidity and salinity data I deemed to be compromised by biofouling.

I used wind data from the National Oceanographic and Atmospheric Administration (NOAA) and USGS stations near Cameron (Figure 2.12 stations 8 and 9, Table 2.2). Data from the NOAA station was used for most of the period during which the long-term range test was conducted, except from August 1 to 27, 2008 and October 1 to 17, 2008, when data from the USGS station were used because the NOAA station was not operational. I only calculated daily mean wind speed and direction for days on which at least 90% of the total possible number of observations were available. I used Rose diagrams to determine daily wind directions. If more than 75% of daily wind direction values were within 45° of each other, I assigned a dominant wind direction (angle) for that day; otherwise, only the daily mean wind speed was calculated.

The nearest tidal gauge to the long-term range test site was the USGS station at Cameron (7 km) (Figure 2.12 station 8). The typical tidal lag between the main tidal inlet at Cameron and Lake Charles, a distance of 60 km, is only four hours. Therefore, I assumed the tidal lag between

sites only 7 km apart was negligible, and that the tidal state at Cameron was representative of the long-term range test site.

I utilized meteorological data to determine when strong cold fronts passed over the study area. Cold fronts are fairly common in coastal Louisiana from fall to spring (October to April), with an average frequency of about seven days (Moeller et al. 1993). Frontal passages are characterized by a sharp decline in air temperature, rise in barometric pressure, and a sudden shift from southerly to strong north-northwesterly winds (Moeller et al. 1993).

### Data Analyses

I used least-squares linear regression to explore relationships between daily DEs and environmental variables (wind speed, turbidity, water temperature, salinity, and dissolved oxygen). Multiple regression was not appropriate due to multicollinearity of independent variables; therefore, separate regressions were conducted for each environmental variable. I based regression analyses on data from random delay transmitters deployed at the long-term range test site because they afforded examination of a longer time period (10 months) and thus encompassed a greater range of values for respective environmental variables than fixed delay transmitters (three months). Furthermore, I only used data from receiver distances at which detection efficiencies were intermediate and most variable for each transmitter (100 m for the V9, 250 m for the V13) because receivers at these distances were presumably the most sensitive to changes in environmental conditions. Finally, I excluded data from the last four days of operation of each transmitter because detection efficiencies consistently declined over the last few days transmitters were operational. Therefore, excluding this data avoids confounding between receiver performance and transmitter power output.

I also examined plots of daily DEs by month for a more temporally-continuous approach than regression analyses. I based these plots upon data from the 100 m receiver for the V9 transmitter because it had the longest operation period of all random delay transmitters.

Regression analyses also were performed to evaluate potential effects of biofouling on receiver performance. A steady decline in performance over the entire deployment period (one year) could be due to fouling of the mesh bag harboring reference transmitters, a decline in transmitter power output over time, or fouling of receiver mooring gear (e.g., barnacle growth on the submerged portions of buoys and ropes). To analyze these relationships, I regressed daily DEs for each receiver distance x transmitter combination against the cumulative number of days each receiver was operational after October 1, 2008, the date receivers were re-deployed after the hurricanes. I based these analyses on data from random delay transmitters (October 1, 2008 to June 30, 2009).

I also examined the potential for biofouling of receiver hydrophones to reduce detection efficiencies between servicing (i.e., cleaning) trips. If biofouling compromised receiver performance, detection efficiencies should display a constant decline over the time period between which receivers were cleaned (Heupel et al. 2008). I assumed that a significant decline in receiver detection efficiencies, across transmitters, was attributed in part to biofouling of receiver hydrophones. I used data from both random and fixed delay transmitters to assess fouling effects during inter-downloading periods. Collision days were excluded from fixed delay transmitter data.

I conducted Fast-Fourier Transform (FFT) analyses to determine if receiver performance exhibited significant periodicities. I based this analysis on hourly DE data from the fixed delay transmitters from July 23, 2009 to October 16, 2009, including collision periods. I assumed that

collisions had a negligible effect on FFT analyses for multiple reasons. First, the principal temporal scales of interest were diurnal and diel (12-24 hours), yet collisions occurred at a much lower frequency (~150 hours). Therefore, it is highly unlikely that collisions could artificially ‘create’ a 12-24 hour cycle in DEs. Secondly, if collisions are driving the temporal dynamics of hourly DEs, this should be evident in the FFT results because of the cyclic and predictable nature of collisions. Finally, the resolution of collision-free data, 150 continuous hours, was too low to investigate diel and diurnal periodicities in receiver performance. I employed a triangular spectral window to smooth periodogram and spectral density estimates. Also, Bartlett’s Kolmogorov-Smirnov statistic was used to test if temporal patterns in the data could be attributed to white noise.

To complement FFT analyses, I also determined overall hourly DEs for the period July 23 to October 16, 2009. To obtain the total number of expected transmissions for each hour (e.g., hour X) over this period, I multiplied the total number of collision-free hours (for each hour) by 12. Overall DEs were then calculated by dividing the total number of recorded detections for a given hour (summed across the entire deployment period) by the total number of expected transmissions. Theoretically, if no diel pattern exists, overall DEs should be equal across hours. I employed chi-square tests of independence to determine if detection efficiencies differed among hours for each fixed delay transmitter x receiver distance combination. Because six separate tests were conducted (one for each combination), I evaluated statistical significance of each test using a Bonferroni-adjusted alpha value of 0.008.

Hourly detection efficiency data from fixed delay transmitters also were used to determine the effect of tidal state on receiver performance by examining plots of hourly DEs

(collision-free periods only) and water height. I also used hourly DE data to provide a detailed chronology of the response of receiver performance to the passages of cold fronts.

Finally, to validate the accuracy of transmitter temperature sensors, I used paired t-tests to compare matched hourly temperature measurements from sensor transmitters and the sonde deployed at the long-term range test site. I chose four total days of data for this analysis, one day at the beginning and end of respective operation periods for each V13TP-1H random delay reference transmitter deployed in 2007 and 2008. Selected dates were May 14, 2007; December 30, 2007; July 30, 2008; April 7, 2009. Paired t-tests were conducted separately for each day ( $n=24$  matched measurements per day). I performed all statistical analyses in Statistical Analysis Software (SAS, version 9.1.3) using an overall alpha value of 0.05.

## **Results**

### Overall Detection Efficiencies for the Long-Term Range Test

For each transmitter, DEs decreased with increasing receiver distance (Figures 2.13, 2.14). At each distance, DEs were higher for V13s than V9s (Figures 2.13, 2.14). For the V9, DEs were very low (medians  $< 8\%$ ) at the 250 and 500 m stations. Across respective transmitter size x distance combinations (e.g., the V9 at 100 m), median detection efficiencies were consistently higher (5-10%) for fixed compared to random delay transmitters (Figures 2.13, 2.14). Finally, daily DEs within each transmitter size/type (e.g., V9 random delay) exhibited strong positive correlations among distances (100, 250, 500 m) for the entire deployment period (Figure 2.15, Table 2.3).

### Effects of Environmental Conditions on Receiver Performance

Daily DEs exhibited a significant negative relationship with wind speed (all directions), for both V9 ( $p < 0.0001$ ) and V13 ( $p < 0.0001$ ) transmitters. Interestingly, when wind direction

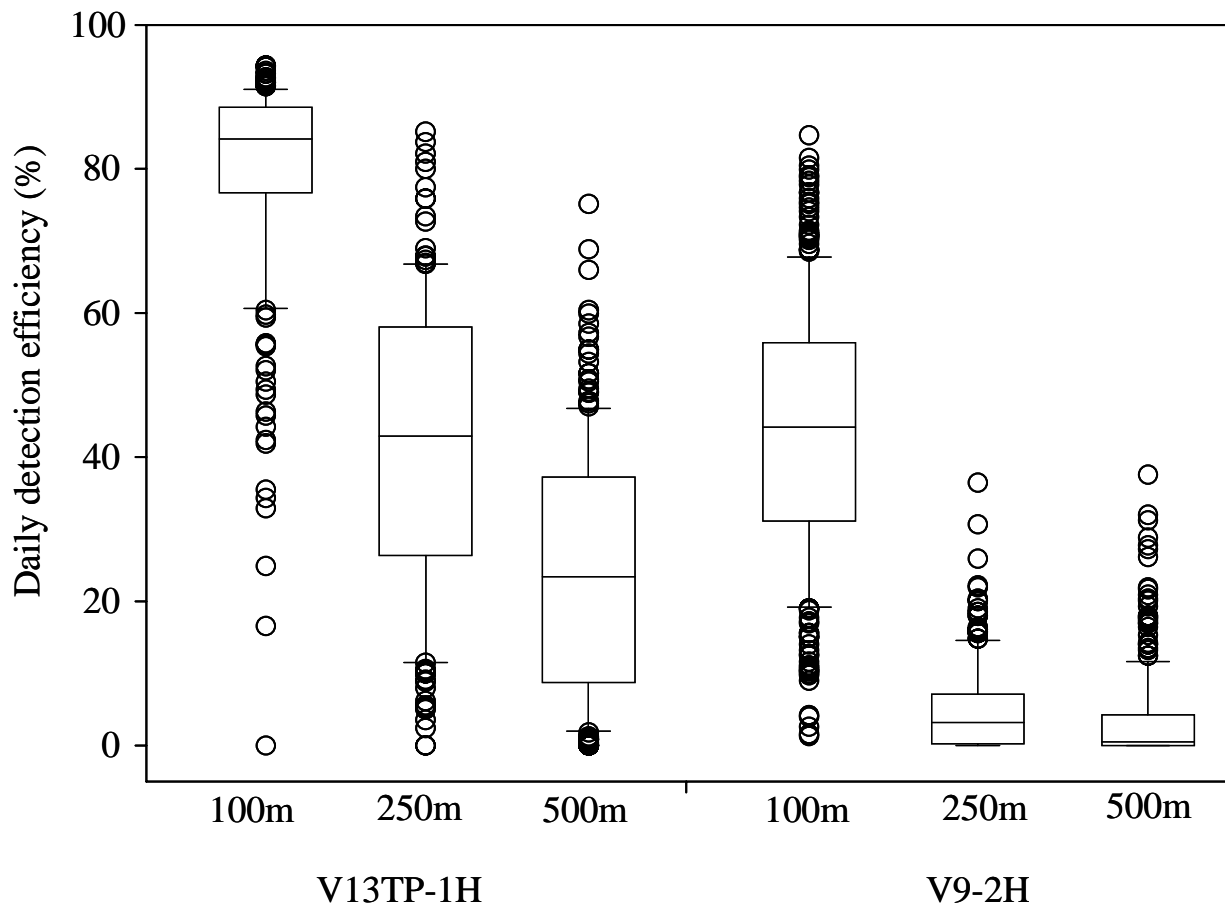


Figure 2.13. Distribution of daily detection efficiencies for each receiver distance x transmitter combination (random delay transmitters). For each day, detection efficiencies were calculated by dividing the daily number of recorded detections (of a given transmitter at a particular receiver) by the number of expected transmissions from respective transmitters during a 24-hour period; this ratio was then converted to a percentage. The V9-2H transmitter was deployed for 306 days, and the V13TP-1H transmitter 228 days. Data from the last four days of operation of each transmitter were excluded from calculations. The receiver at 250 m was not operational for 68 days.

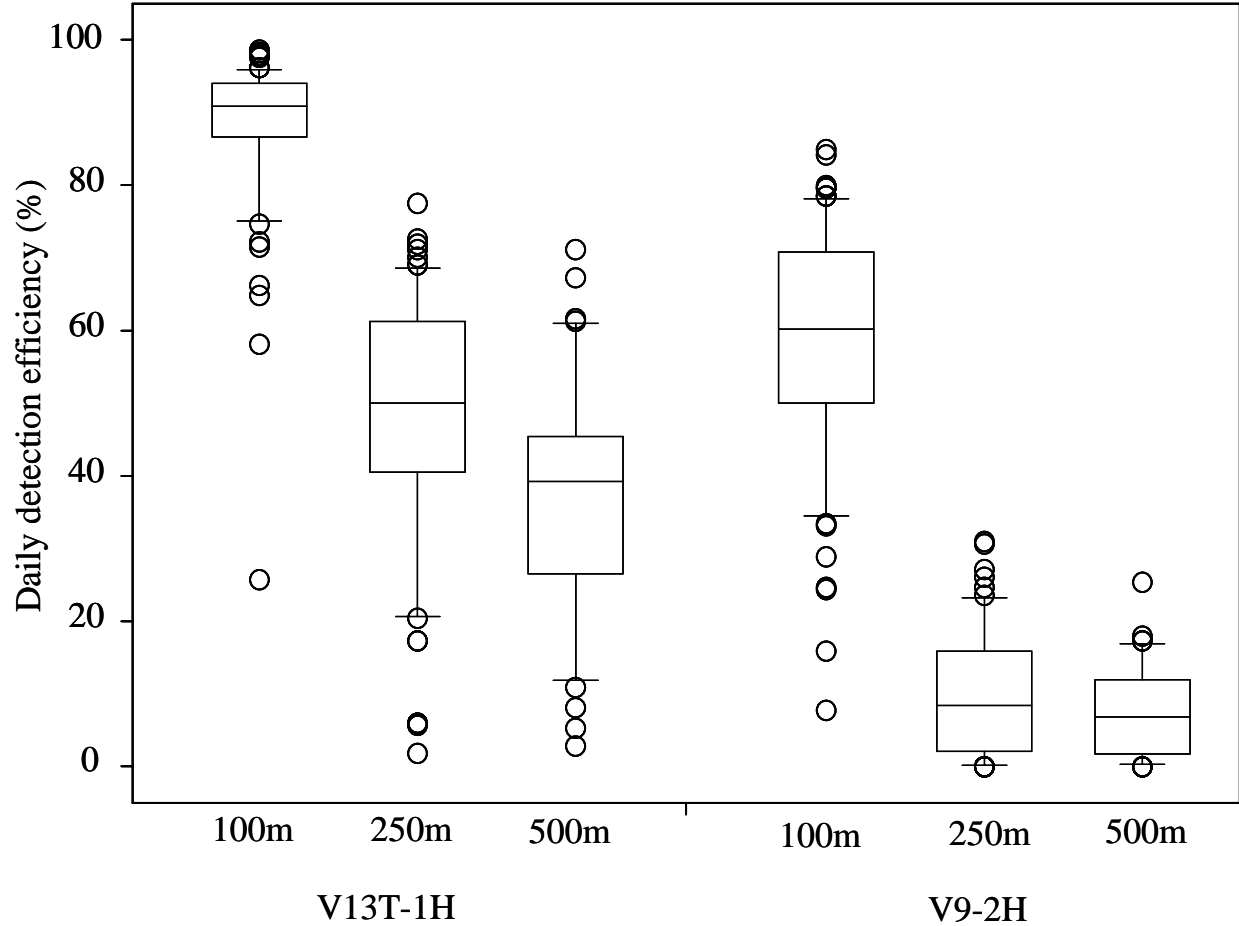


Figure 2.14. Daily detection efficiencies for each receiver distance x transmitter combination (fixed delay transmitters). For each day, detection efficiencies were calculated by dividing the daily number of recorded detections (of a given transmitter at a particular receiver) by the number of expected transmissions from respective transmitters during a 24-hour period; this ratio was then converted to a percentage. The V9-2H and V13T-1H transmitters were deployed 97 days, but detection efficiencies were only calculated for days on which no transmitter collisions occurred ( $n=75$ ). The receiver at 500 m was not operational for the last 34 days of the study. Data from the last four days of operation of each transmitter were excluded from calculations.



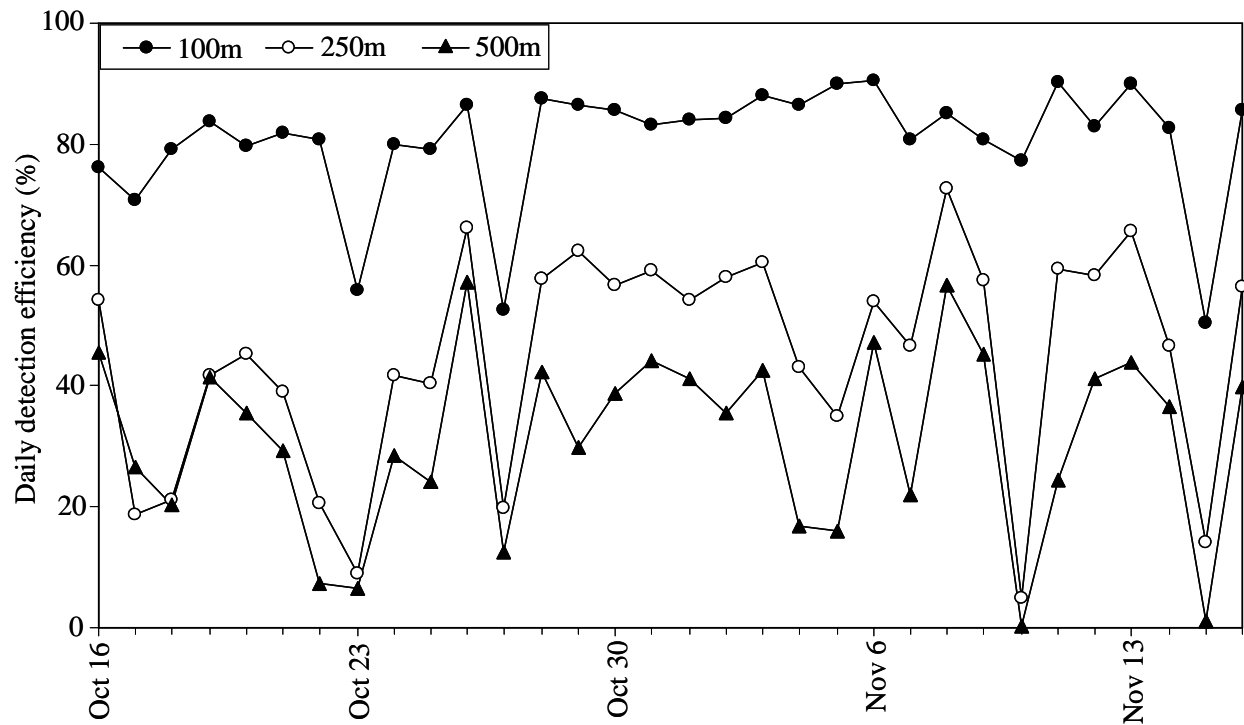


Figure 2.15. Daily detection efficiencies for each receiver distance (100, 250, 500 m) for the period October 16 to November 16, 2008. Data are shown for the V13TP-1H random delay transmitter. Detection efficiencies were calculated by dividing the daily number of recorded detections (at each receiver) by the number of expected transmissions from the V13 transmitter during a 24-hour period; this ratio was then converted to a percentage by multiplying by 100.

Table 2.3. Spearman rho correlation coefficients of daily detection efficiencies among receiver distances for each transmitter size/type (e.g., the V9 random delay transmitter). Cross-correlations were based on data from days (n) during which both receivers were operational for each comparison. Daily detection efficiencies for fixed delay transmitters were only calculated for days during which collisions did not occur.

	Spearman rho	p-value	n
Random delay V13			
100 vs. 250m	0.72	<0.01	160
100 vs. 500m	0.52	<0.01	228
250 vs. 500m	0.75	<0.01	160
Random delay V9			
100 vs. 250m	0.63	<0.01	238
100 vs. 500m	0.62	<0.01	306
250 vs. 500m	0.71	<0.01	238
Fixed delay V13			
100 vs. 250m	0.66	<0.01	75
100 vs. 500m	0.45	<0.01	48
250 vs. 500m	0.82	<0.01	48
Fixed delay V9			
100 vs. 250m	0.53	<0.01	75
100 vs. 500m	0.41	<0.01	48
250 vs. 500m	0.74	<0.01	48

was considered, wind speed explained 30 to 35% more variation in daily DEs when winds were north versus south (Figures 2.16, 2.17). All direction-specific regressions were statistically significant ( $p < 0.0001$  north wind,  $p < 0.05$  south wind). Daily DEs also exhibited a significant negative relationship with turbidity, for both V9 ( $p < 0.0001$ ) and V13 ( $p = 0.0014$ ) transmitters (Figure 2.18).

Daily DEs for the V13 transmitter were not significantly related to daily water temperature, salinity, or dissolved oxygen. For the V9 transmitter, daily DEs displayed a significant negative relationship with water temperature ( $p < 0.0001$ ) and significant positive

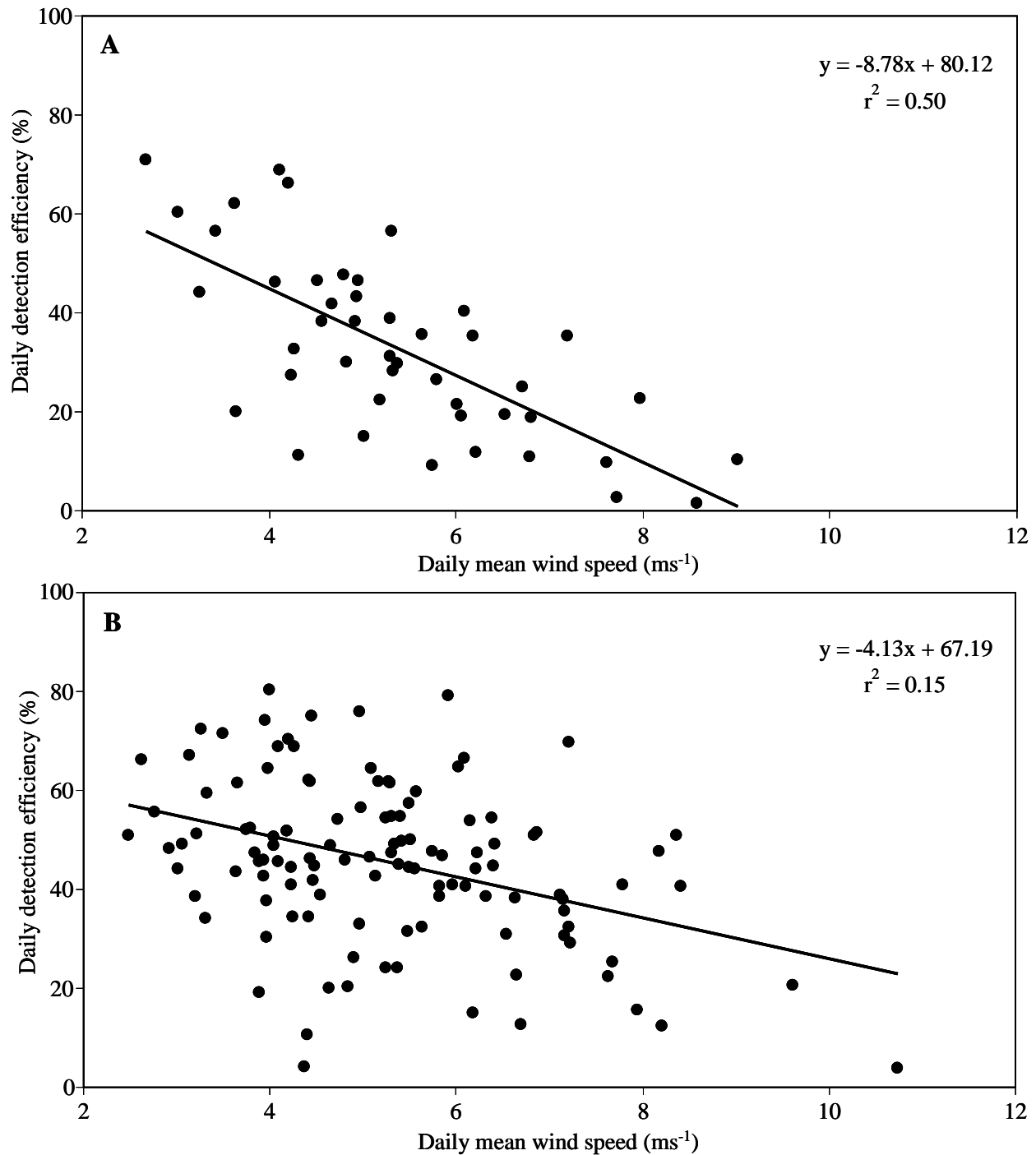


Figure 2.16. Relationship between daily detection efficiencies and wind speed for the V9-2H random delay transmitter at the 100 m receiver for days when (A) winds were predominantly north ( $345\text{--}45^\circ$ ) ( $n=45$  days) and (B) days when winds were predominantly south ( $120\text{--}225^\circ$ ) ( $n=119$  days). Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V9 transmitter by the number of expected transmissions from the V9 during a 24-hour period; this ratio was then converted to a percentage. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9).

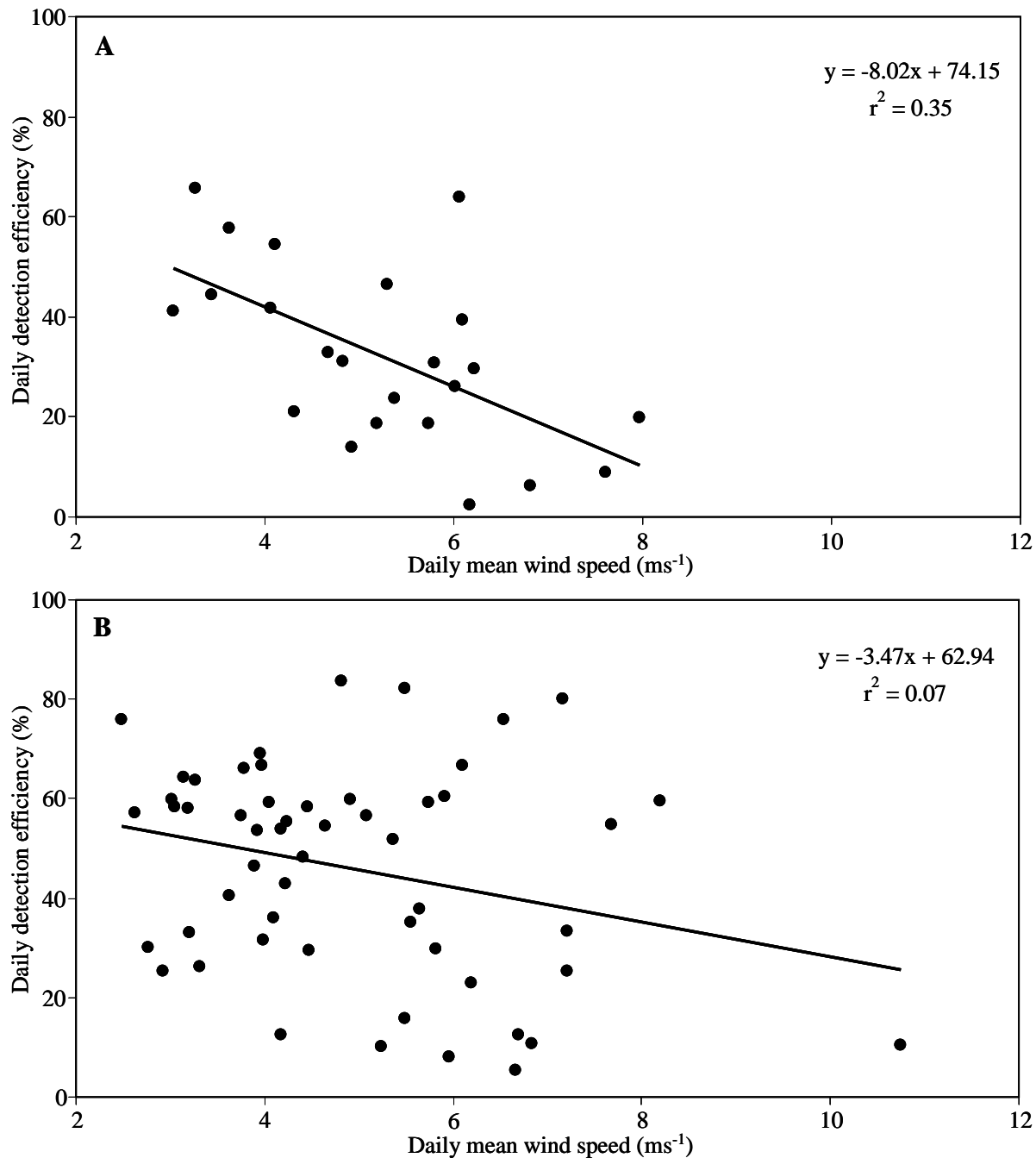


Figure 2.17. Relationship between daily detection efficiencies and wind speed for the V13TP-1H random delay transmitter at the 250 m receiver for days when (A) winds were predominantly north (345-45°) (n=23 days) and (B) days when winds were predominantly south (120-225°) (n=54 days). Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V13 transmitter by the number of expected transmissions from the V13 during a 24-hour period; this ratio was then converted to a percentage. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9).

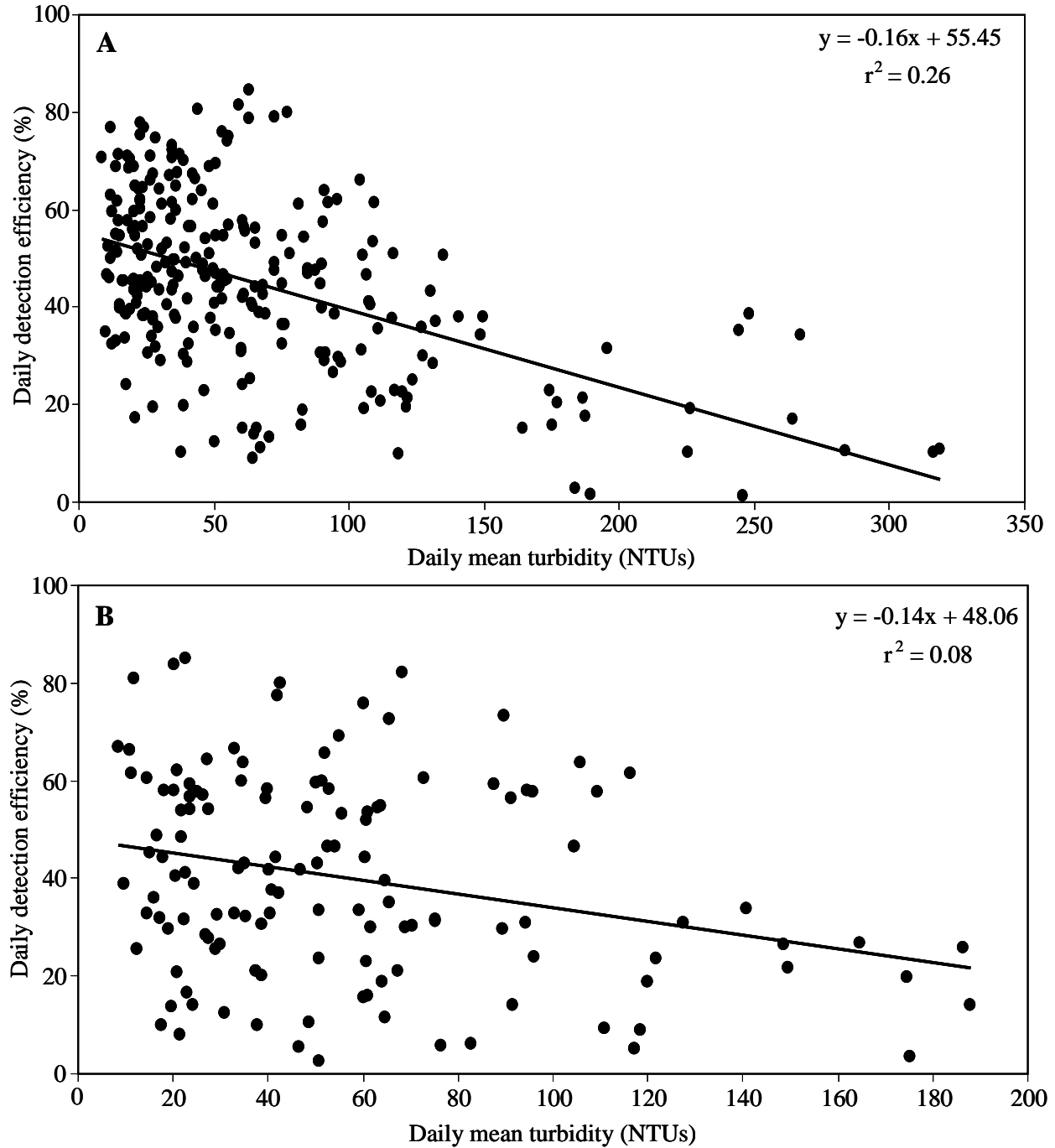


Figure 2.18. Relationship between daily detection efficiencies and turbidity for (A) the V9-2H random delay transmitter at the 100 m receiver (n=257 days) and (B) the V13TP-1H random delay transmitter at the 250 m receiver (n=132 days). Daily detection efficiencies were calculated by dividing the daily number of recorded detections (of a given transmitter at a particular receiver) by the number of expected transmissions from respective transmitters during a 24-hour period; this ratio was then converted to a percentage. Turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).

relationship with dissolved oxygen ( $p = 0.0002$ ); still, these relationships were very weak as indicated by the low coefficients of determination ( $< 0.07$ ) (Figure 2.19).

Detection efficiencies were extremely low on days that cold fronts passed over the study area. For instance, the three nadirs in daily DEs ( $< 10\%$ ) during December 2008 occurred on days of strong frontal passages when wind speeds and turbidity were accordingly high (Figure 2.20). Moreover, for a cold front on October 16-17, 2009, DEs decreased precipitously as the leading edge of the front crossed the study area (Figures 2.21, 2.22). Detection efficiencies at the 100 m receiver were low for both the V9 (DEs  $< 20\%$ ) and the more powerful V13 (DEs  $< 40\%$ ) during peak frontal conditions (Figures 2.21, 2.22). Detection efficiencies remained depressed for both V13 and V9 transmitters for about 24 hours, except for a three to six hour period when turbidity was reduced during mid-flood to slack high tide (Figures 2.21-2.23).

During spring 2009, daily DEs were tightly coupled with turbidity. For example, the lowest detection efficiencies in April 2009 occurred on days with the highest turbidity (Figure 2.24). Interestingly, two of these large turbidity shifts in late April occurred under a fairly stable wind regime (Figure 2.24). These late April turbidity spikes were likely due to increased sediment loads associated with spring freshets. During summer 2009, daily DEs were more stable (40-60%) than in other months (i.e., fall to spring); winds were moderate and southerly, and turbidity relatively low (Figure 2.25).

Hourly DEs exhibited a strong diel periodicity, as peak spectral densities occurred at a period of approximately 24 hours for all transmitter x receiver distance combinations except the V13 at 100 m (Figures 2.26, 2.27). This diel periodicity was not related to tidal dynamics, as DEs were not consistently higher or lower during a given tidal state. Instead, the periodicity appeared to be driven by a day-night cycle, whereby DEs were higher at night than during the

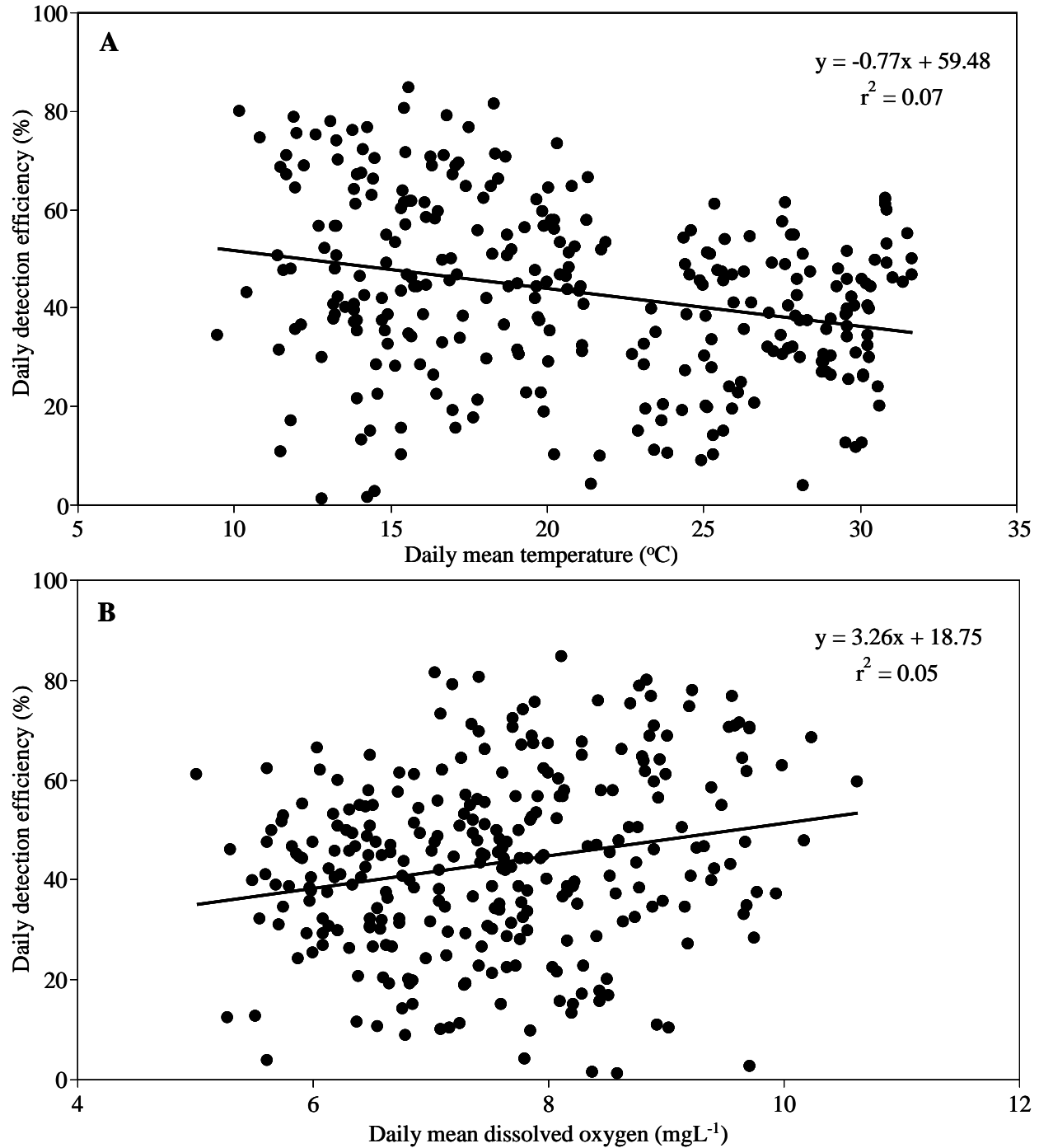


Figure 2.19. Relationship between daily detection efficiencies and (A) water temperature and (B) dissolved oxygen for the V9-2H random delay transmitter at the 100 m receiver (n=294 days). Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V9 transmitter by the number of expected transmissions from the V9 during a 24-hour period; this ratio was then converted to a percentage. Water temperature and dissolved oxygen were measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).

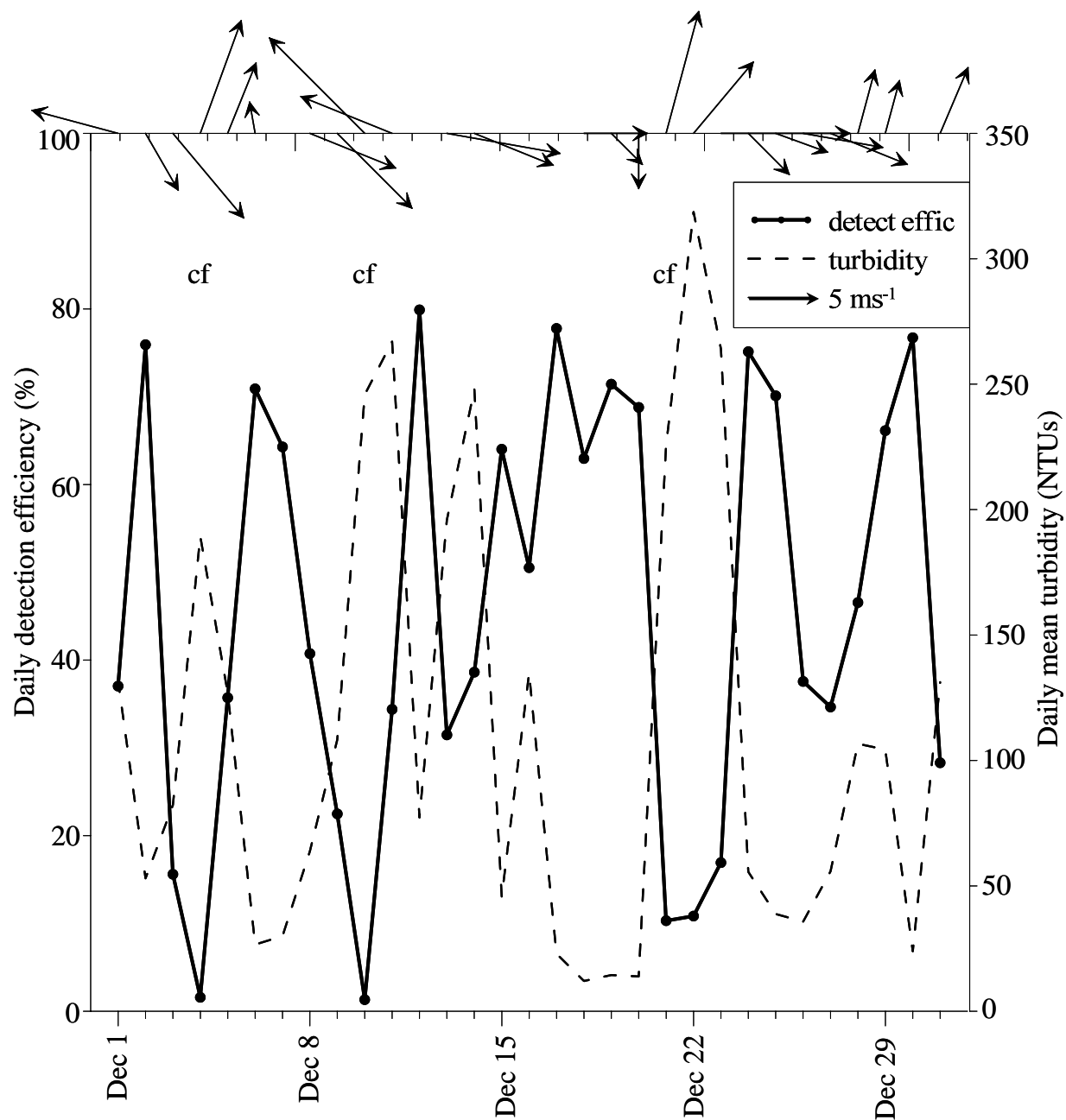


Figure 2.20. Relationship between daily detection efficiencies and turbidity/wind velocity during December 2008 for the 100 m receiver and V9-2H random delay transmitter. Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V9 transmitter by the number of expected transmissions from the V9 during a 24-hour period; this ratio was then converted to a percentage. For the wind plot along the top x-axis, vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7). “cf” indicates days on which cold fronts passed over the study area.



Figure 2.21. Receiver performance during the passage of a cold front (V9-2H fixed delay transmitter, 100 m receiver). Ninety consecutive hours of data are shown (October 14-17, 2009), and “cf” indicates when the leading edge of the cold front crossed the study area. Hourly detection efficiencies (solid black line with dots) were calculated by dividing the hourly number of recorded detections of the V9 transmitter by the number of expected transmissions from the V9 during a one-hour period; this ratio was then converted to a percentage. For the wind plot along the top x-axis, vector lengths are positively scaled to wind speed as indicated in the previous figure (Figure 2.20); arrows point towards the direction from which the wind was blowing. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity (represented by the dashed line) was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).

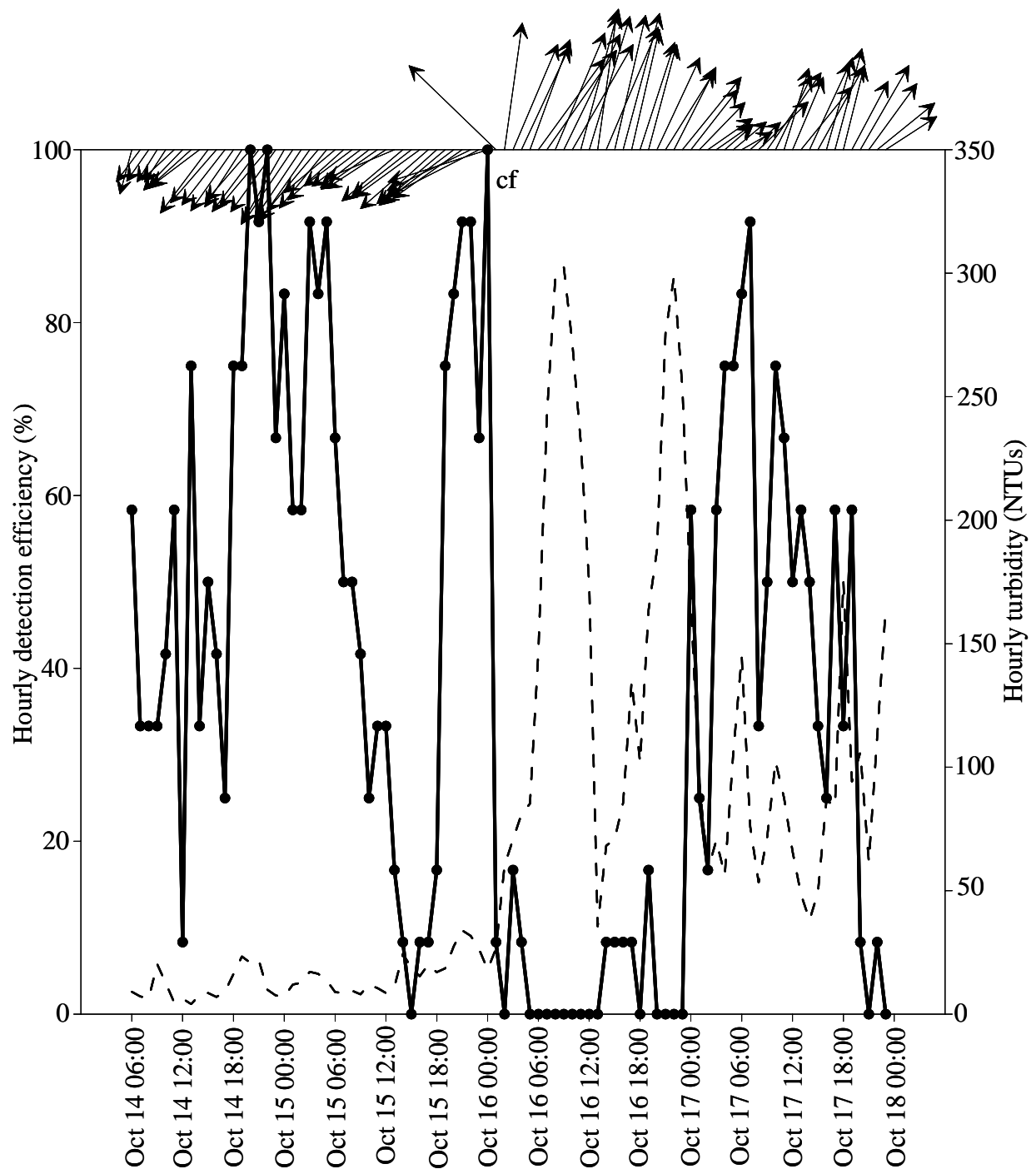
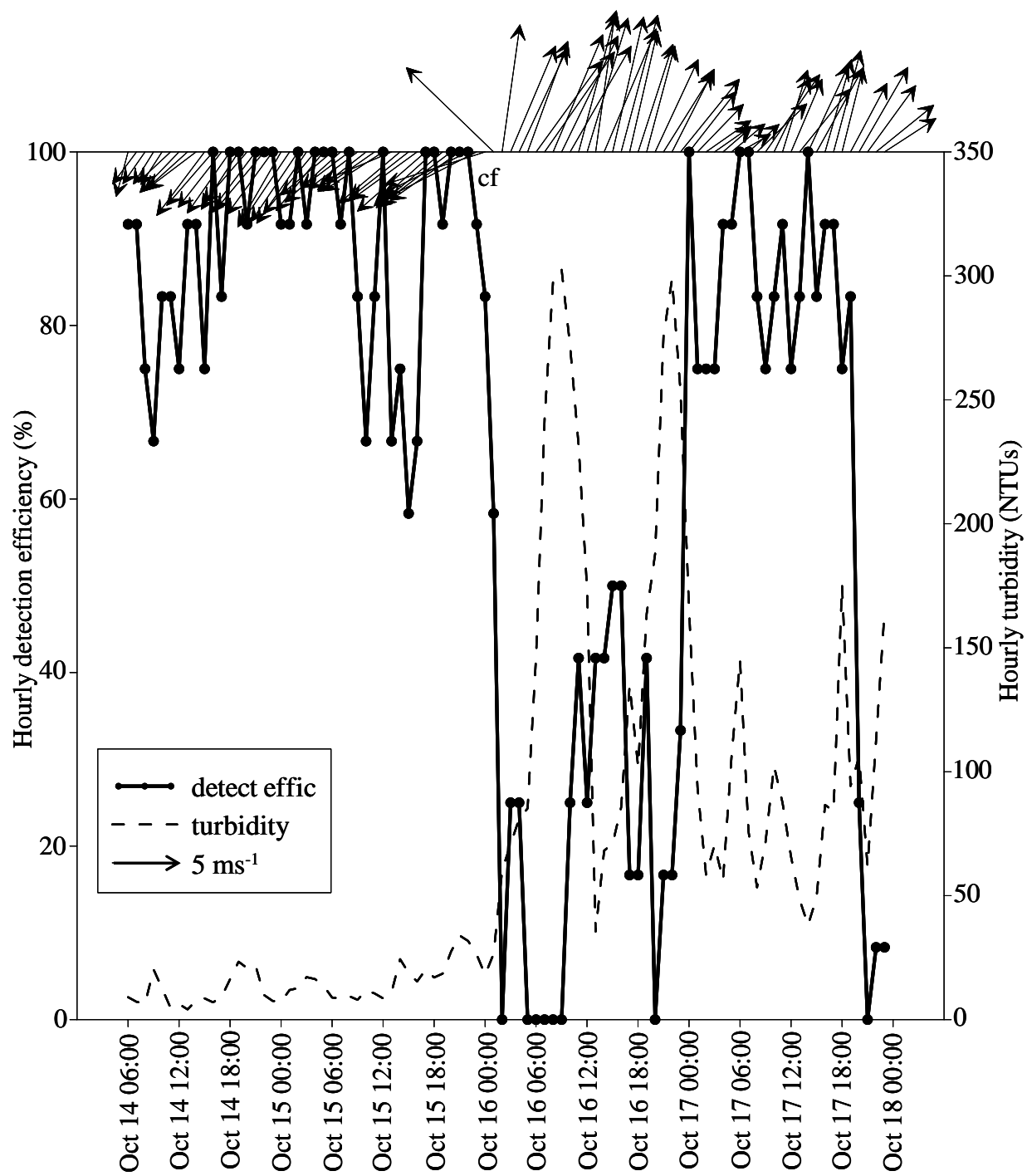


Figure 2.22. Receiver performance during the passage of a cold front (V13T-1H fixed delay transmitter, 100 m receiver). Ninety consecutive hours of data are shown (October 14-17, 2009), and “cf” indicates when the leading edge of the cold front crossed the study area. Hourly detection efficiencies were calculated by dividing the hourly number of recorded detections of the V13 transmitter by the number of expected transmissions from the V13 during a one-hour period; this ratio was then converted to a percentage. For the wind plot along the top x-axis, vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).



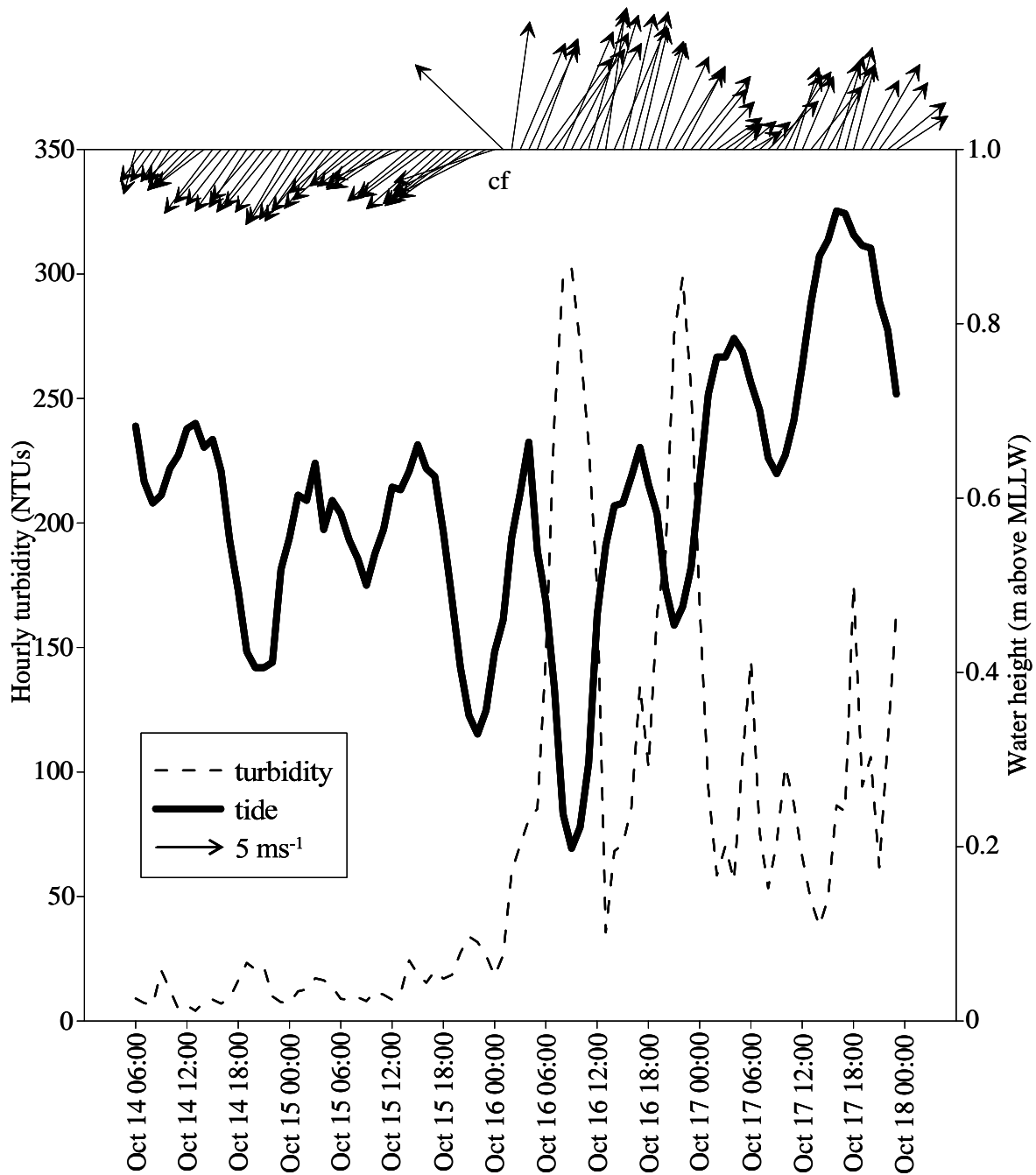


Figure 2.23. Turbidity and water level changes during the passage of a cold front. Ninety consecutive hours of data are shown (October 14-17, 2009) and “cf” indicates when the leading edge of the cold front crossed the study area. For the wind plot along the top x-axis, vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7); tidal data were gleaned from the USGS station at Cameron (Figure 2.12, station 8). “MLLW” = mean lower low water, a USGS tidal level benchmark.

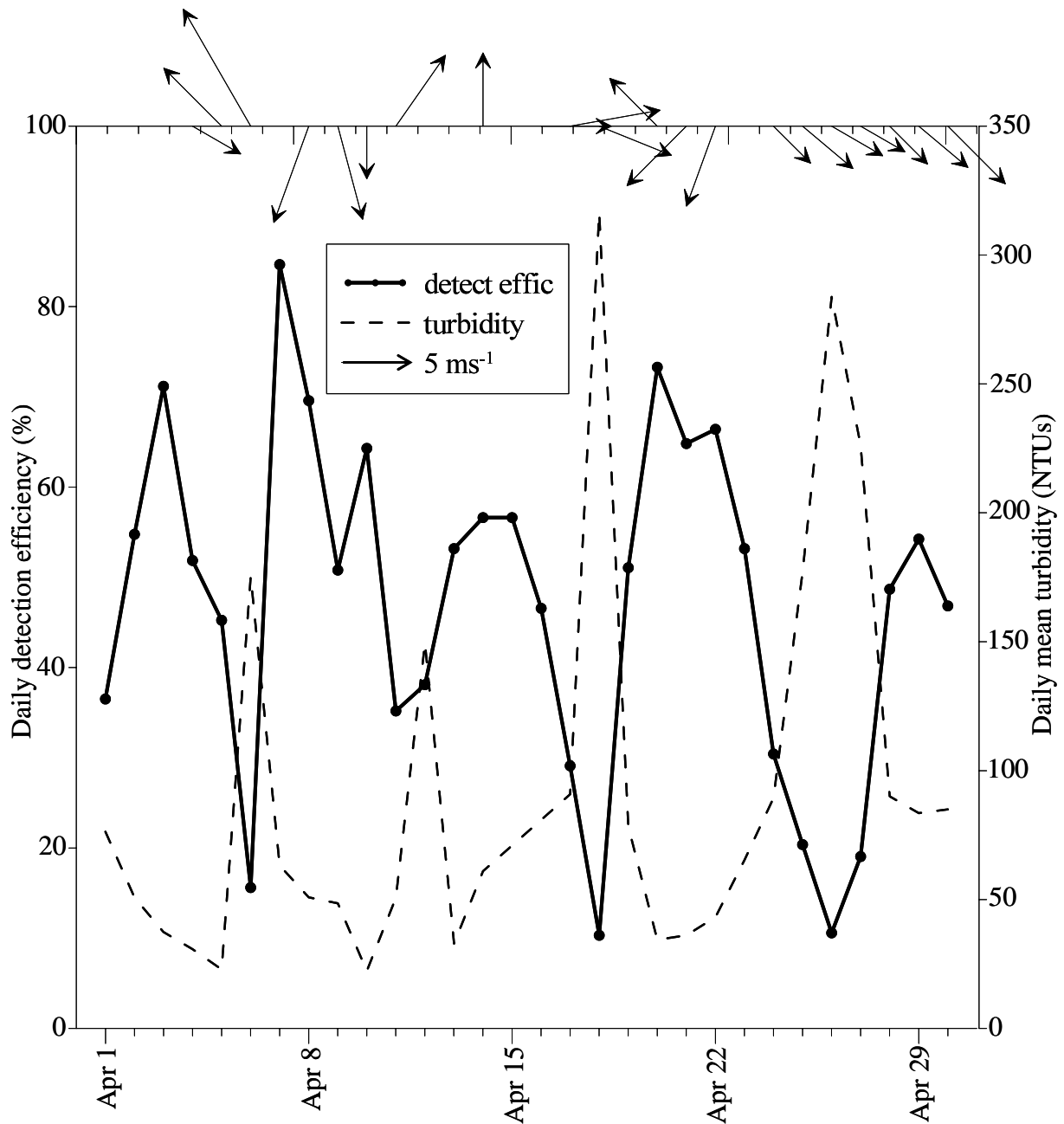


Figure 2.24. Relationship between daily detection efficiencies and turbidity/wind velocity during April 2009 for the 100 m receiver and V9-2H random delay transmitter. Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V9 transmitter by the number of expected transmissions from the V9 during a 24-hour period; this ratio was then converted to a percentage. For the wind plot along the top x-axis, vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).

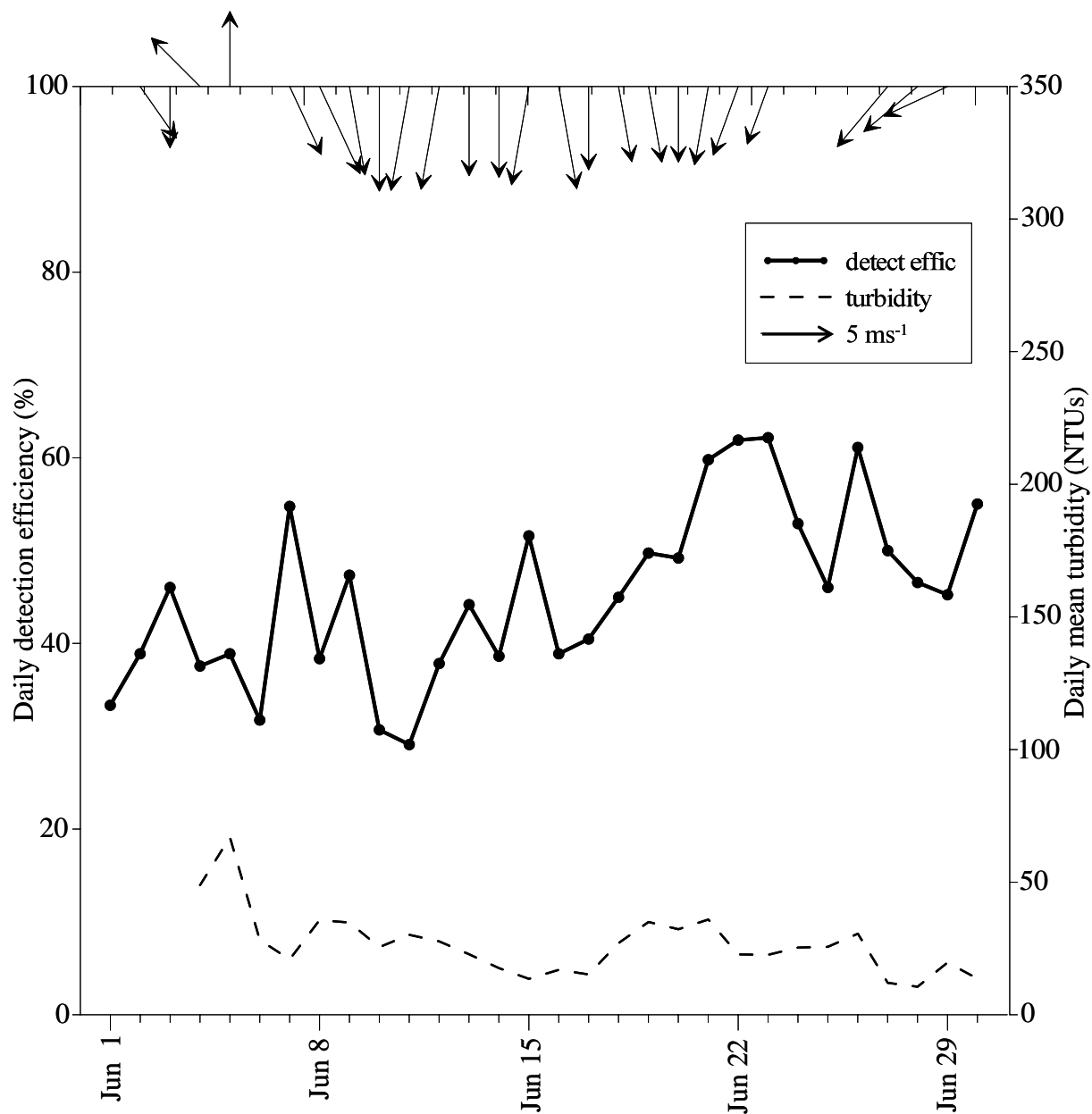


Figure 2.25. Relationship between daily detection efficiencies and turbidity/wind velocity during June 2009 for the 100 m receiver and V9-2H random delay transmitter. Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V9 transmitter by the number of expected transmissions from the V9 during a 24-hour period; this ratio was then converted to a percentage. For the wind plot along the top x-axis, vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).

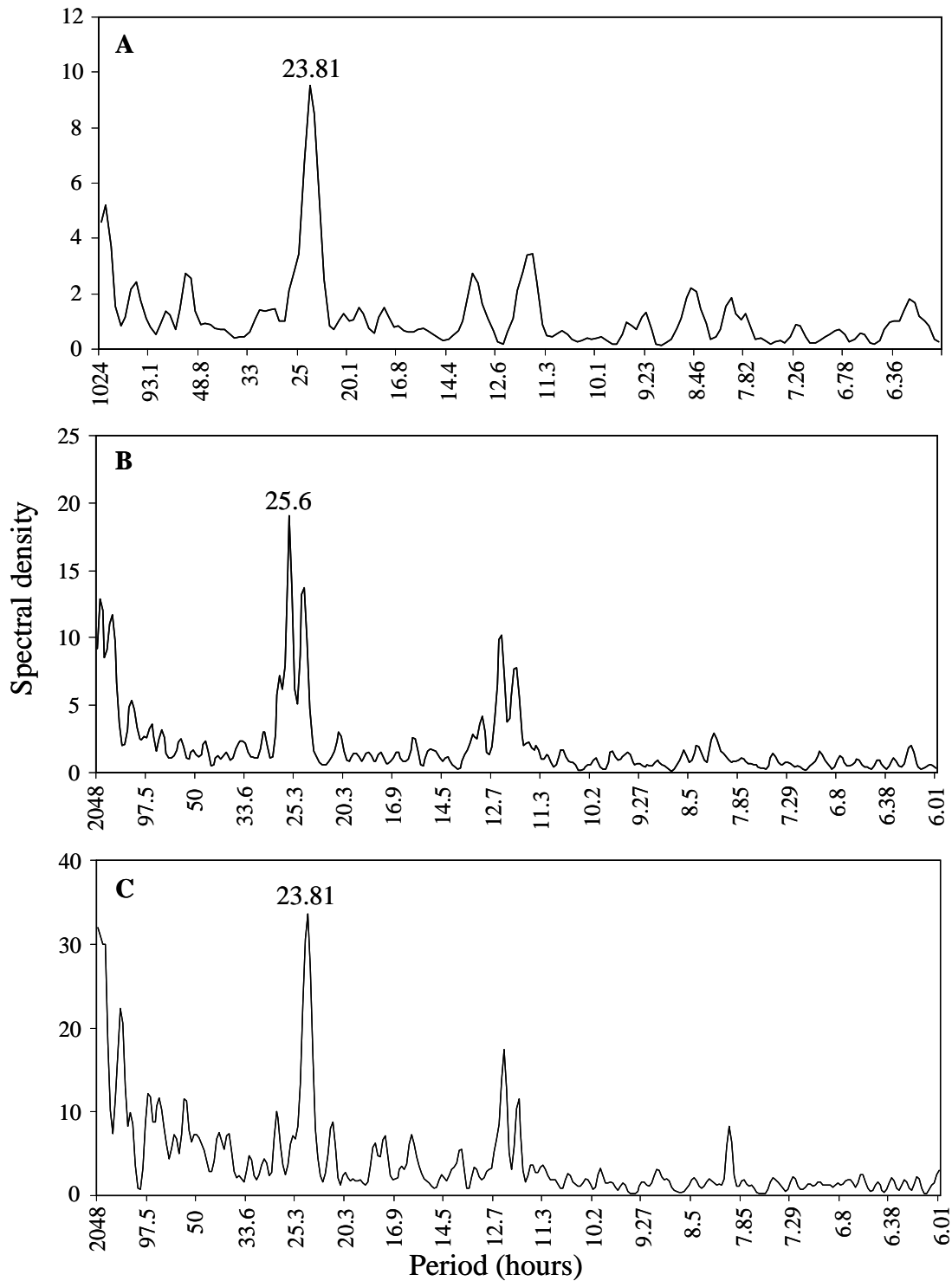


Figure 2.26. Spectral density plots from Fast Fourier Transform analyses of hourly detection efficiencies of the V9-2H fixed delay transmitter for receivers deployed at (A) 500 m, (B) 250 m, and (C) 100 m. The period of peak spectral density is reported in each plot. Analyses were performed for 2,048 continuous hours of data for the 100 and 250 m receivers (July 23 to October 16, 2009) and 1,024 continuous hours of data for the 500 m receiver (July 23 to September 3, 2009).



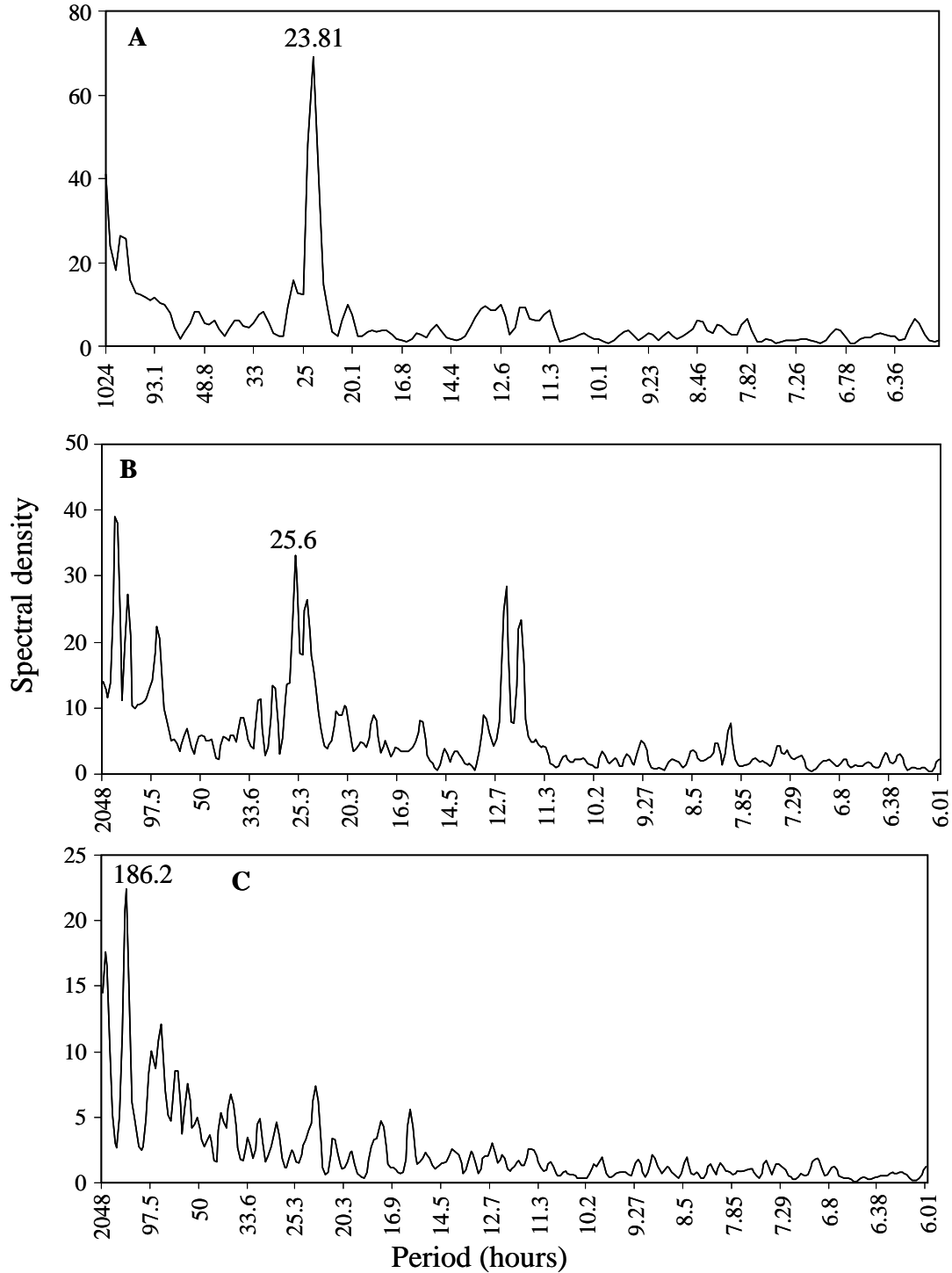


Figure 2.27. Spectral density plots from Fast Fourier Transform analyses of hourly detection efficiencies of the V13T-1H fixed delay transmitter for receivers deployed at (A) 500 m, (B) 250 m, and (C) 100 m. The period of peak spectral density is reported in each plot. Analyses were performed for 2,048 continuous hours of data for the 100 and 250 m receivers (July 23 to October 16, 2009) and 1024 continuous hours of data for the 500 m receiver (July 23 to September 3, 2009).

day (Figure 2.28). Chi-square tests indicated that overall detection efficiencies significantly differed among hours for each transmitter x receiver distance combination ( $p < 0.0001$  across tests).

### Short-Term Range Tests

The inlet gate was effective in detecting towed transmitters. Transmitters were detected during the majority of tows (21 of 25, or 85%) performed through either receiver line of the inlet gate (Figures 2.29-2.33). Transmitter-specific detection rates were 85% (11 of 13 tows) for the V9 and 83% (10 of 12 tows) for the V13. Most importantly, detection rates were similarly high for tows performed through the middle of the channel where an acoustic “dead zone” might be expected because of the increased distance from shoreward receivers. Transmitter-specific detection rates for mid-channel tows were 75% (six of eight tows) for the V9 and 83% (five of six tows) for the V13 (Figures 2.29-2.33). It should be noted that ArcPad malfunctioned during one of the range tests (January 14, 2008); therefore, the locations of each transmission (as presented in Figures 2.29-2.33) could not be determined for this test. Interestingly, range tests also revealed that some transmissions were still detected despite the presence of nearby vessels when the transmitters fired (Figures 2.29, 2.30).

At receiver sites other than the inlet gate, detection ranges for each transmitter (V9, V13) were estimated. At stations 67 and 68, detection ranges for the V9 and V13 were 300 and 350 m, respectively (Figure 2.34). At stations 85 and 86, detection range for the V13 was at least 200 m, and most (80%) transmissions were detected by both stations (Figure 2.35). At the receiver stations tested in West Cove (7, 7A, 10, 10A), detection ranges were approximately 100 m for the V9 and 250 m for the V13 (Figures 2.36, 2.37). At station 36, detection ranges for the V9 and V13 were 250 and 300 m, respectively (Figure 2.38). At station 14, detection ranges for

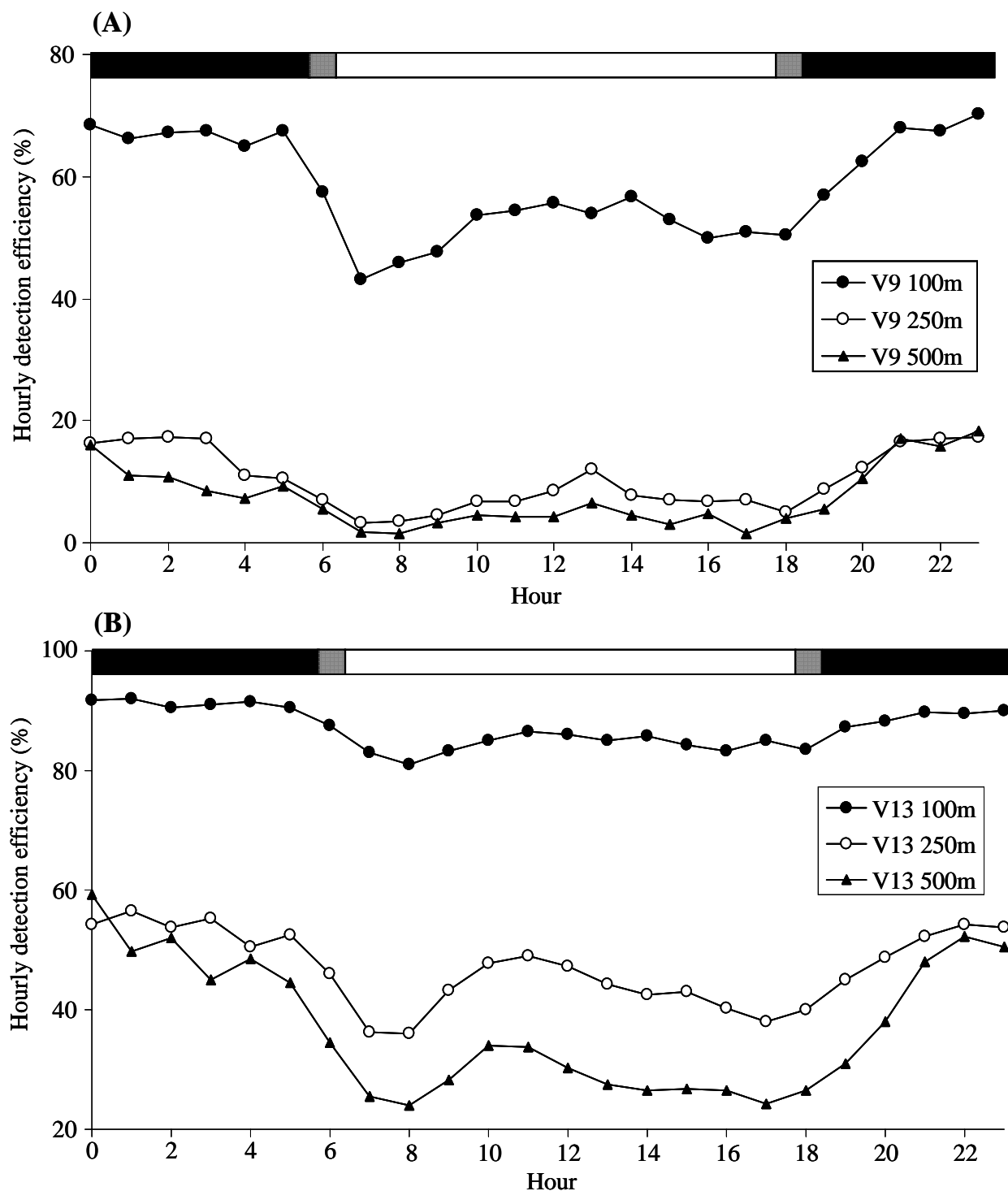


Figure 2.28. Overall hourly detection efficiencies at each receiver distance for (A) V9-2H and (B) V13T-1H fixed delay transmitters. Hour bin “0” represents midnight to 12:59 local time, “1” = 01:00 to 01:59, etc. Black bars along the top of the plot illustrate dark hours, gray bars crepuscular periods, and white bars daylight hours.

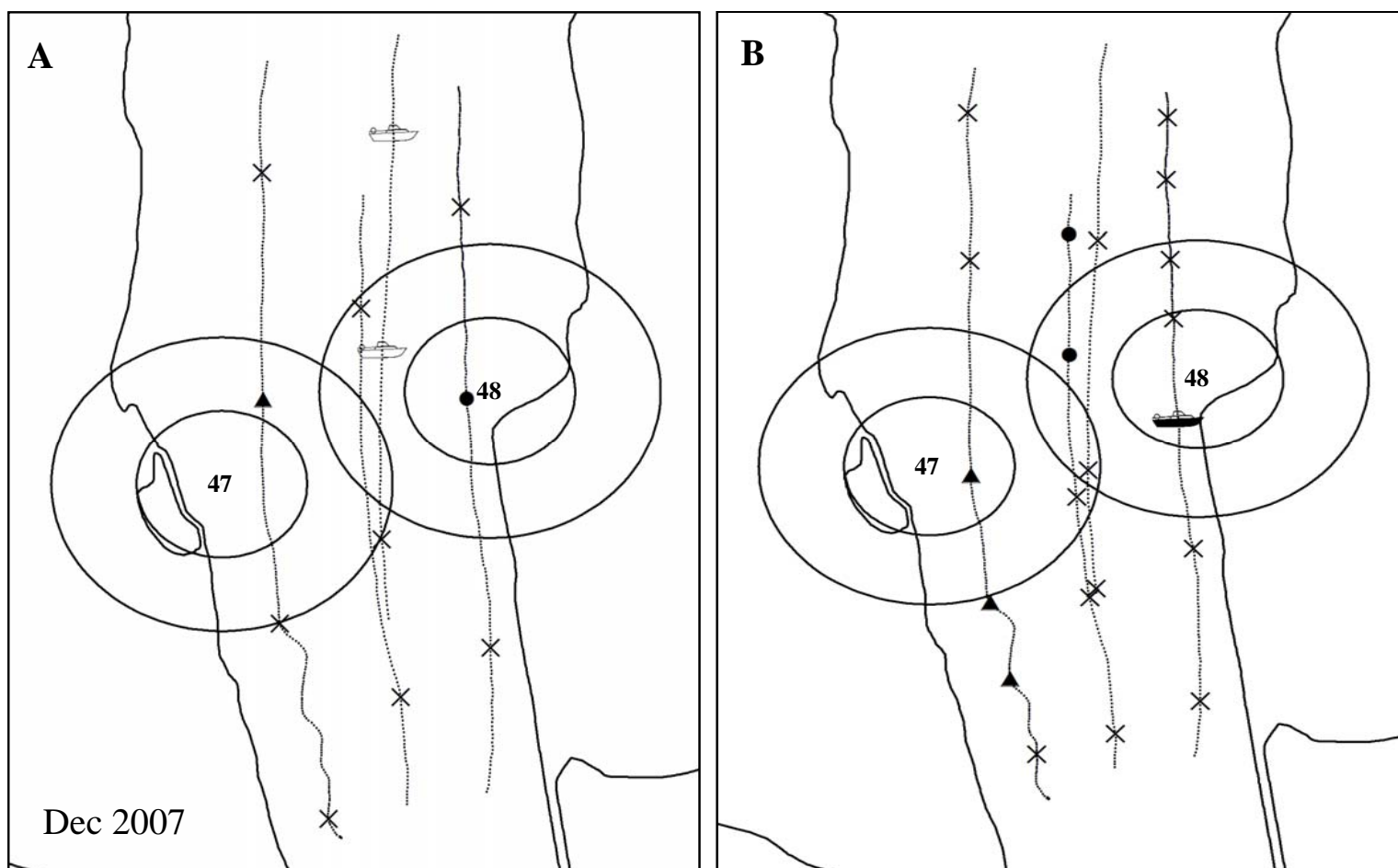


Figure 2.29. Results from the short-term range test at the inlet gate (stations 47 and 48) on December 5, 2007. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13TP-1H random delay transmitters. Tow direction was north for all tows. Triangles designate the location of transmissions that were detected only by station 47, and black dots the locations of transmissions detected only by station 48. "Xs" indicate the locations of transmissions that were not detected by either receiver. Boat symbols depict transmissions during which other vessels were in the vicinity when tags fired; filled boat symbols depict positive detections by station 48 and hollow boat symbols transmissions that were not detected by either receiver station. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

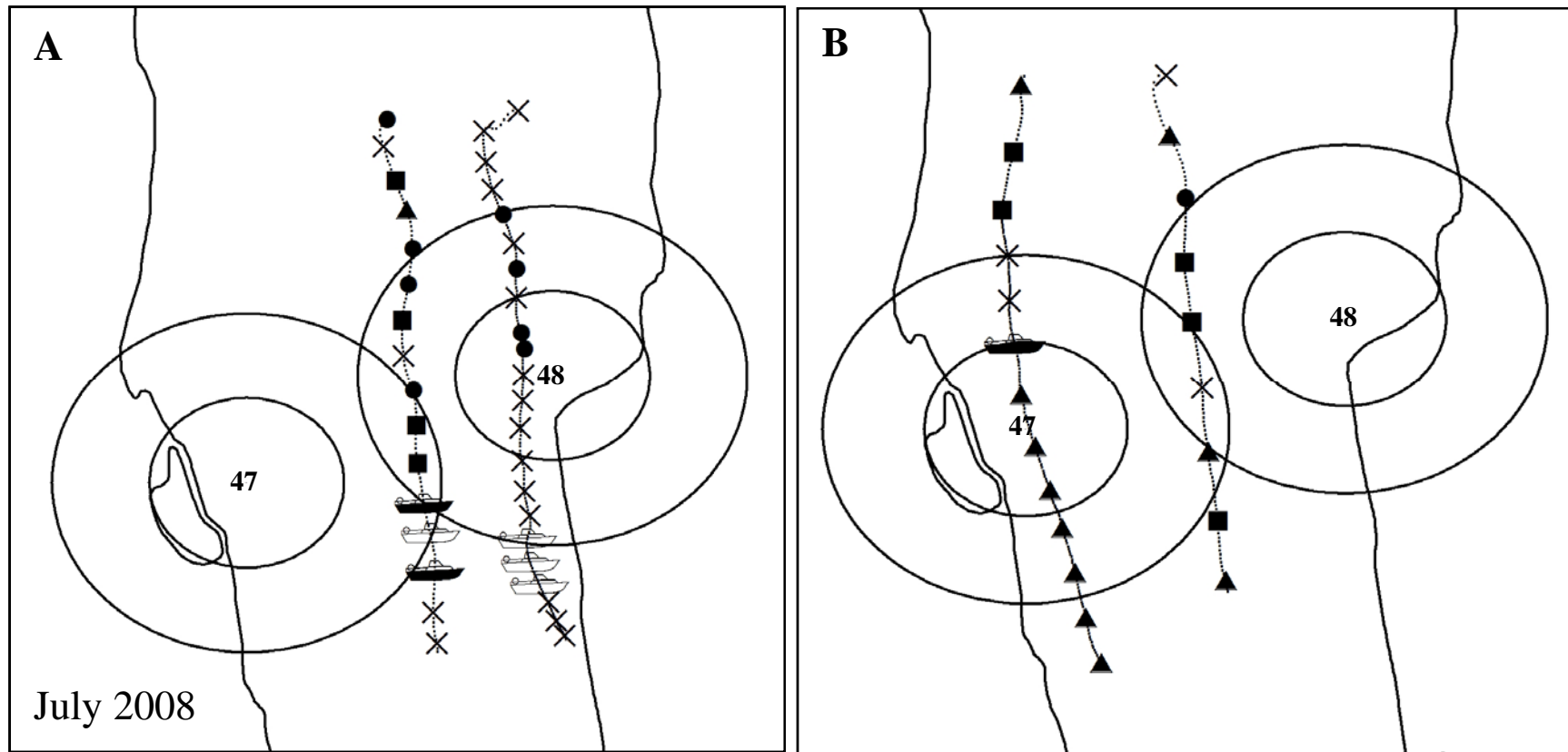


Figure 2.30. Results from the short-term range test at the inlet gate (stations 47 and 48) on July 14, 2008. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13T-1H fixed delay transmitters. Tow direction was south for all tows. Squares designate the location of transmissions that were detected by both stations, triangles locations of transmissions detected only by station 47, and black dots locations of transmissions detected only by station 48. “Xs” indicate the location of transmissions that were not detected by either receiver. Boat symbols depict transmissions during which other vessels were in the vicinity when tags fired; filled boat symbols indicate positive detections by station 47 and hollow boat symbols transmissions that were not detected by either receiver station. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

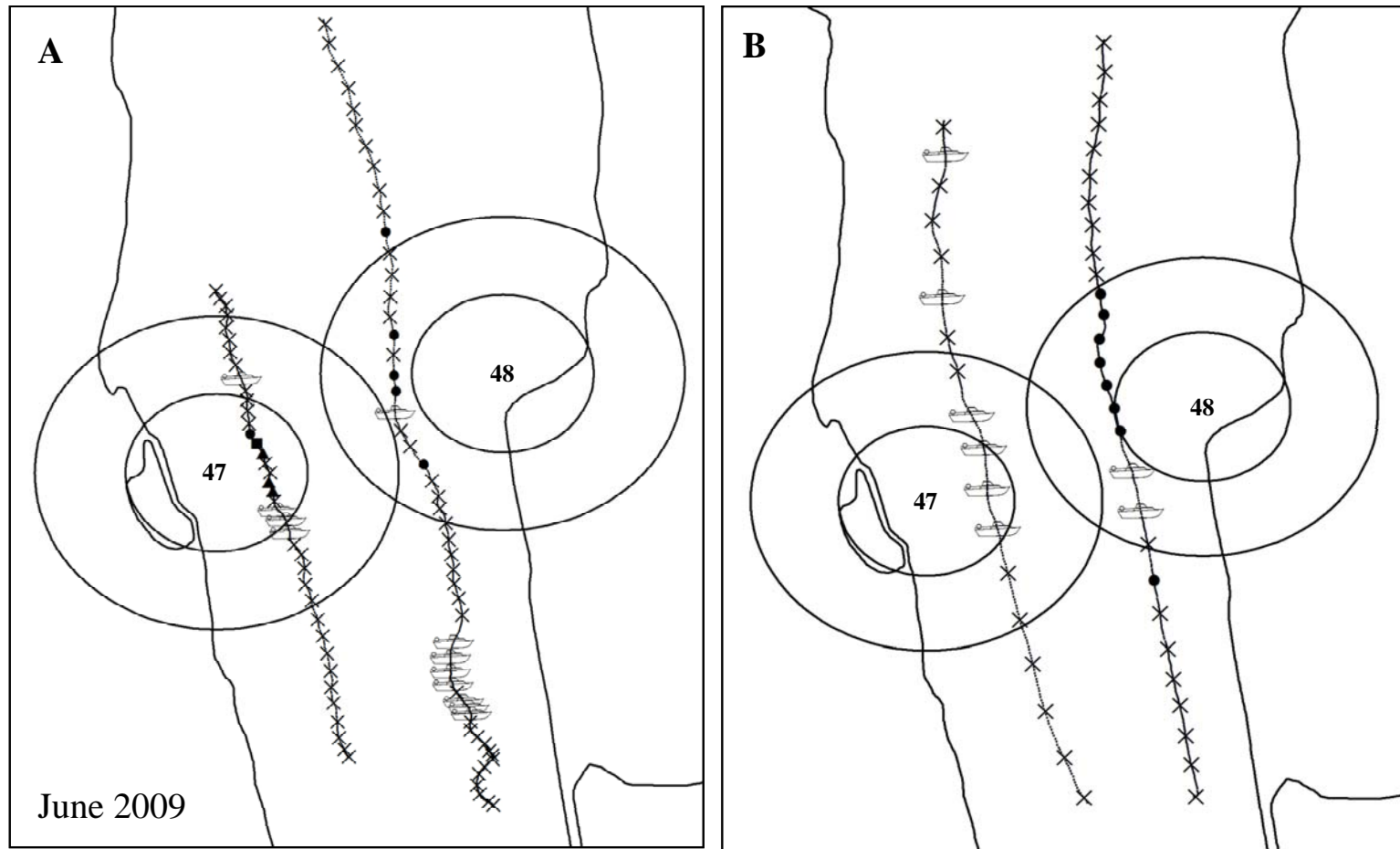


Figure 2.31. Results from the short-term range test at the inlet gate (stations 47 and 48) on June 1, 2009. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13T-1H fixed delay transmitters. Tow direction was south for all tows. Squares designate the location of transmissions that were detected by both stations, triangles the locations of transmissions detected only by station 47, and black dots the locations of transmissions detected only by station 48. “Xs” indicate the location of transmissions that were not detected by either receiver. Boat symbols depict transmissions during which other vessels were in the vicinity when tags fired; hollow boat symbols indicate transmissions that were not detected by either receiver. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

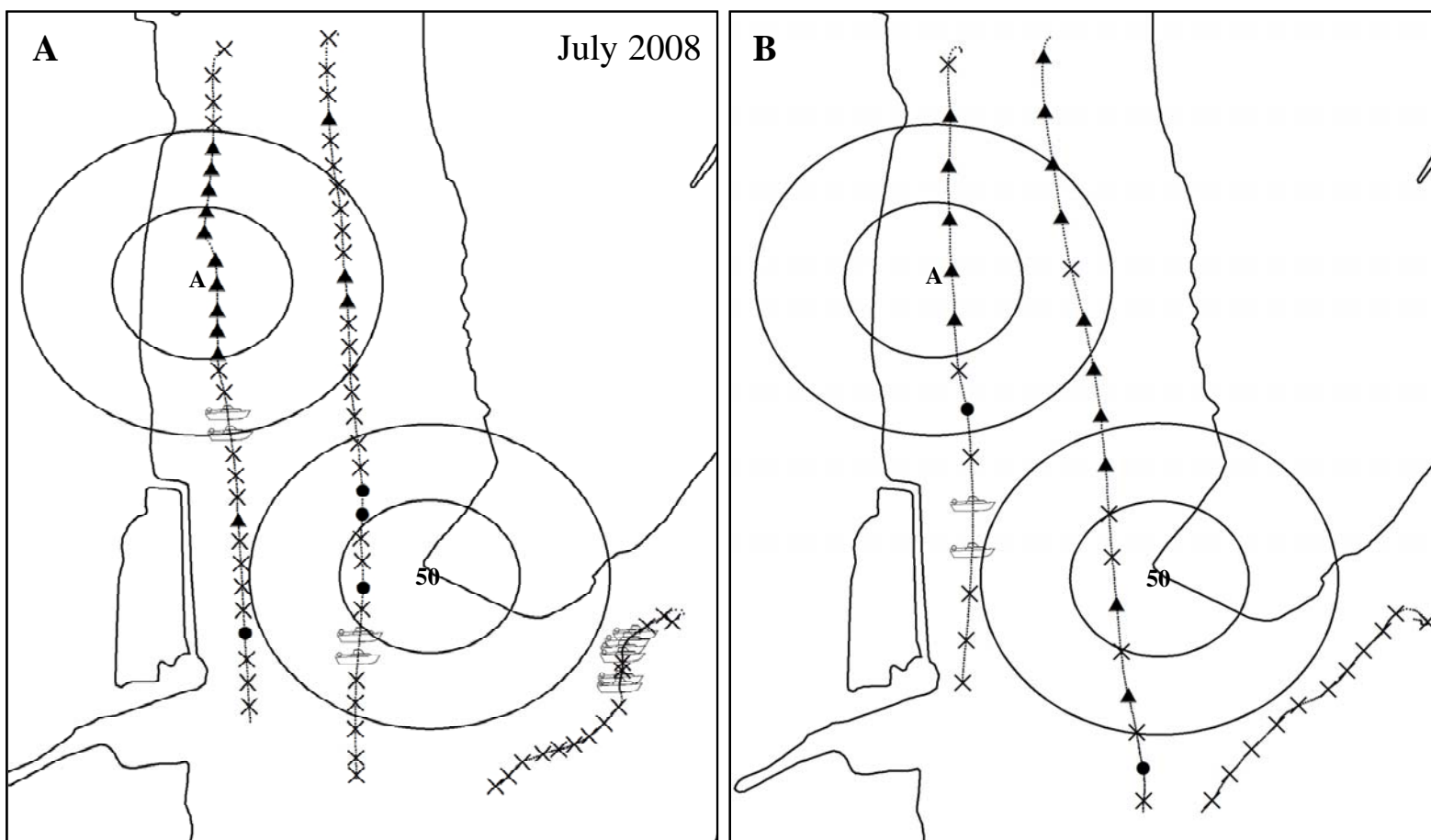


Figure 2.32. Results from the short-term range test at the inlet gate (stations Alpha (A) and 50) on July 14, 2008. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13T-1H fixed delay transmitters. Tow direction was south for all tows. Triangles designate the locations of transmissions that were detected only by station Alpha, and black dots the locations of transmissions detected only by station 50. “Xs” indicate the locations of transmissions that were not detected by either receiver. Boat symbols depict transmissions during which other vessels were in the vicinity when tags fired; hollow boat symbols indicate transmissions that were not detected by either receiver. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

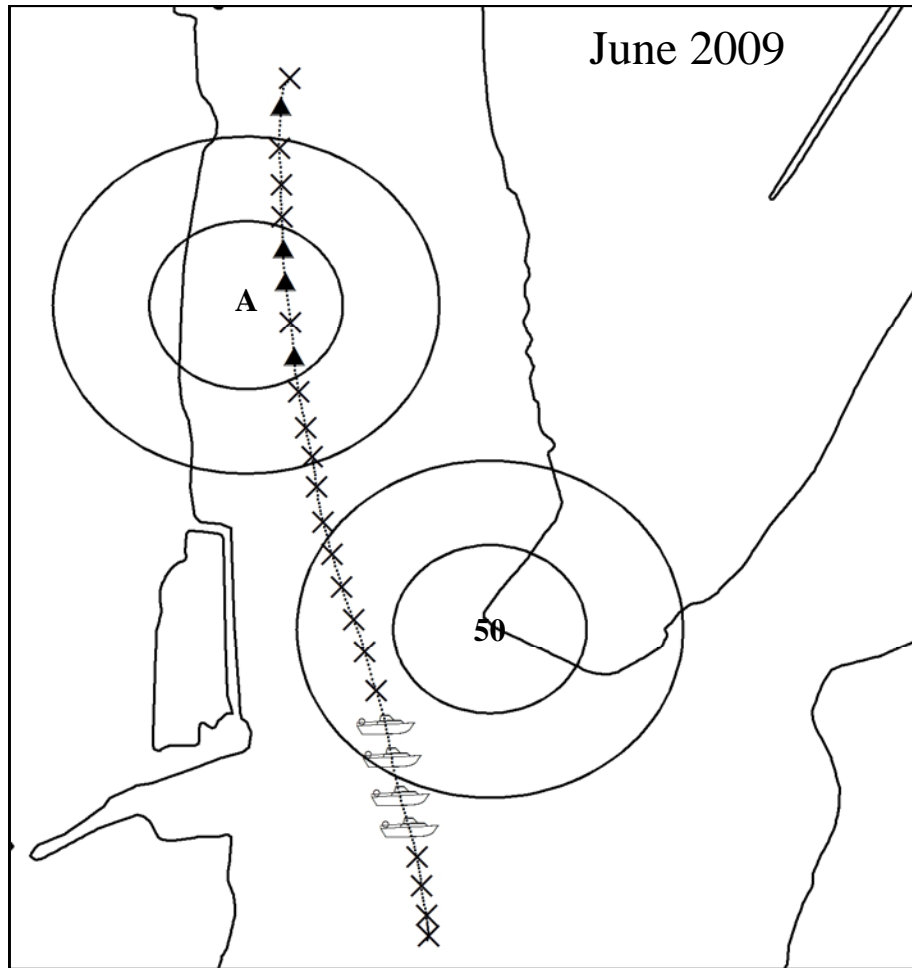


Figure 2.33. Results from the short-term range test at the inlet gate (stations Alpha (A) and 50) on June 1, 2009. The thin dashed line represents vessel positions throughout a single tow of a V9-2H fixed delay transmitter. Tow direction was south for all tows. Triangles designate the locations of transmissions that were detected by station Alpha. “Xs” indicate the locations of transmissions that were not detected by either receiver. Boat symbols depict transmissions during which other vessels were in the vicinity when tags fired; hollow boat symbols indicate transmissions that were not detected by either receiver. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.



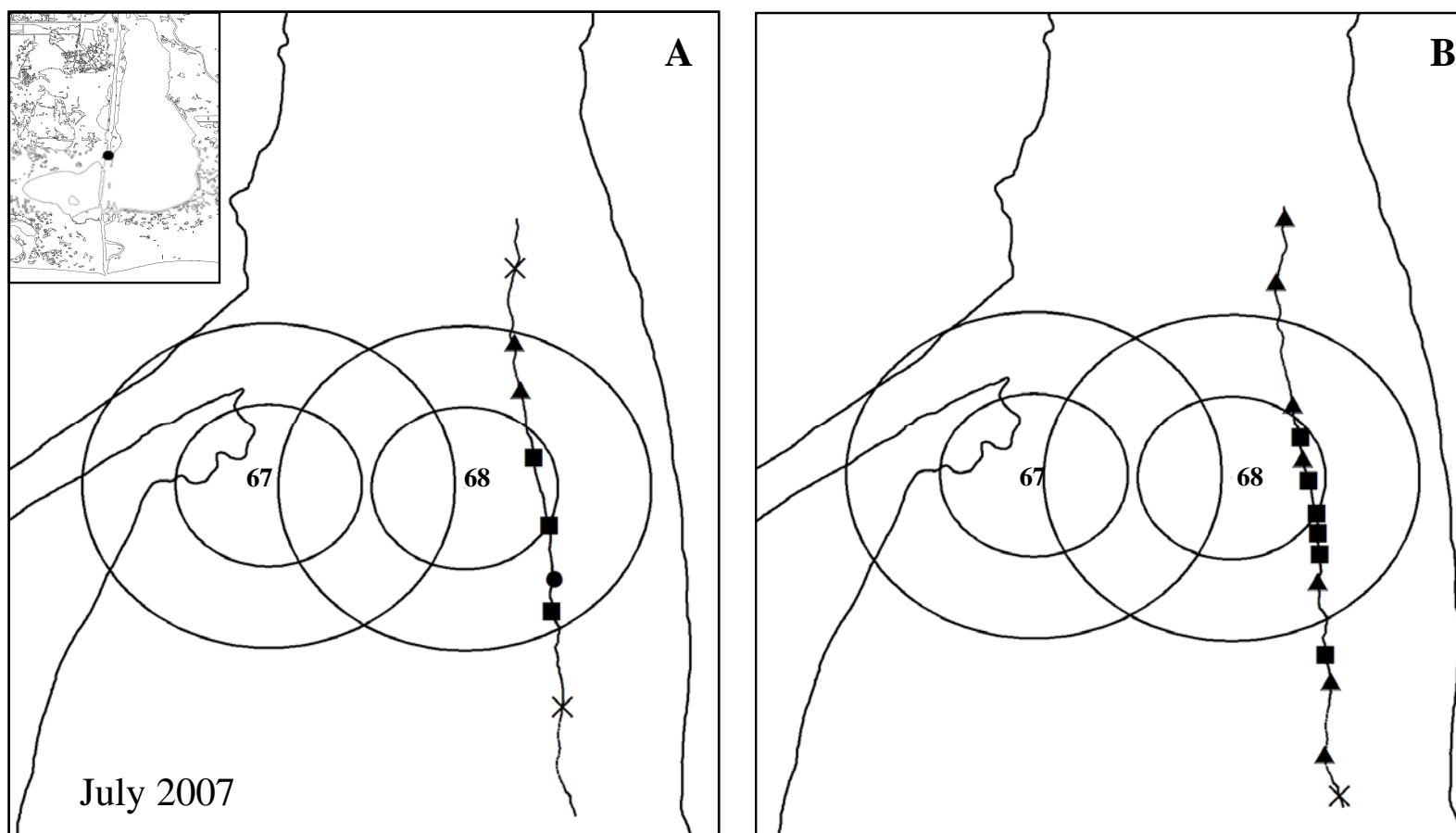


Figure 2.34. Results from the short-term range test at stations 67 and 68 on July 23, 2007. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13TP-1H random delay transmitters. Tow direction was north for all tows. Squares designate locations of transmissions that were detected by both receivers, triangles designate the locations of transmissions detected only by station 67, and black dots the locations of transmissions detected only by station 68. “Xs” indicate the locations of transmissions not detected by either receiver. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

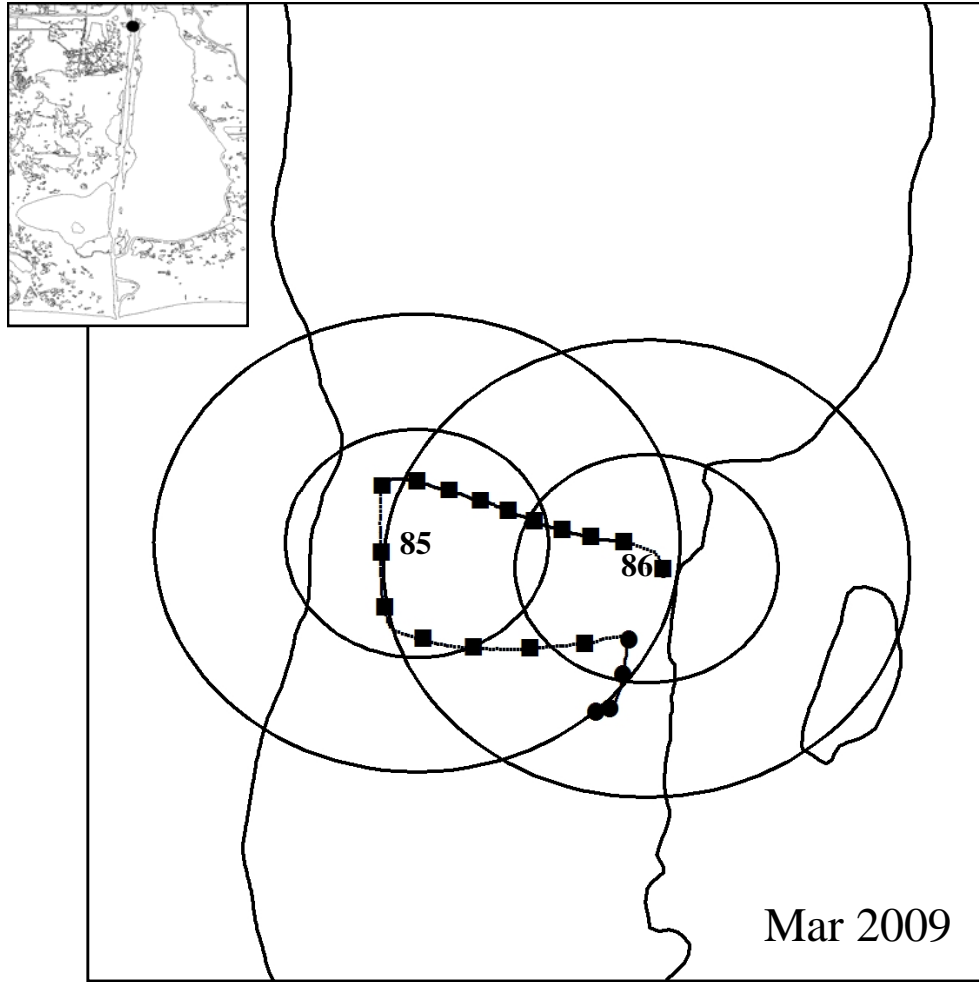


Figure 2.35. Results from the short-term range test at stations 85 and 86 on March 11, 2009. The thin dashed line represents vessel positions throughout a single tow of a V13T-1H fixed delay transmitter. The tow started just east of station 86. Squares designate the locations of transmissions that were detected by both receivers, and black dots the locations of transmissions detected only by station 86. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

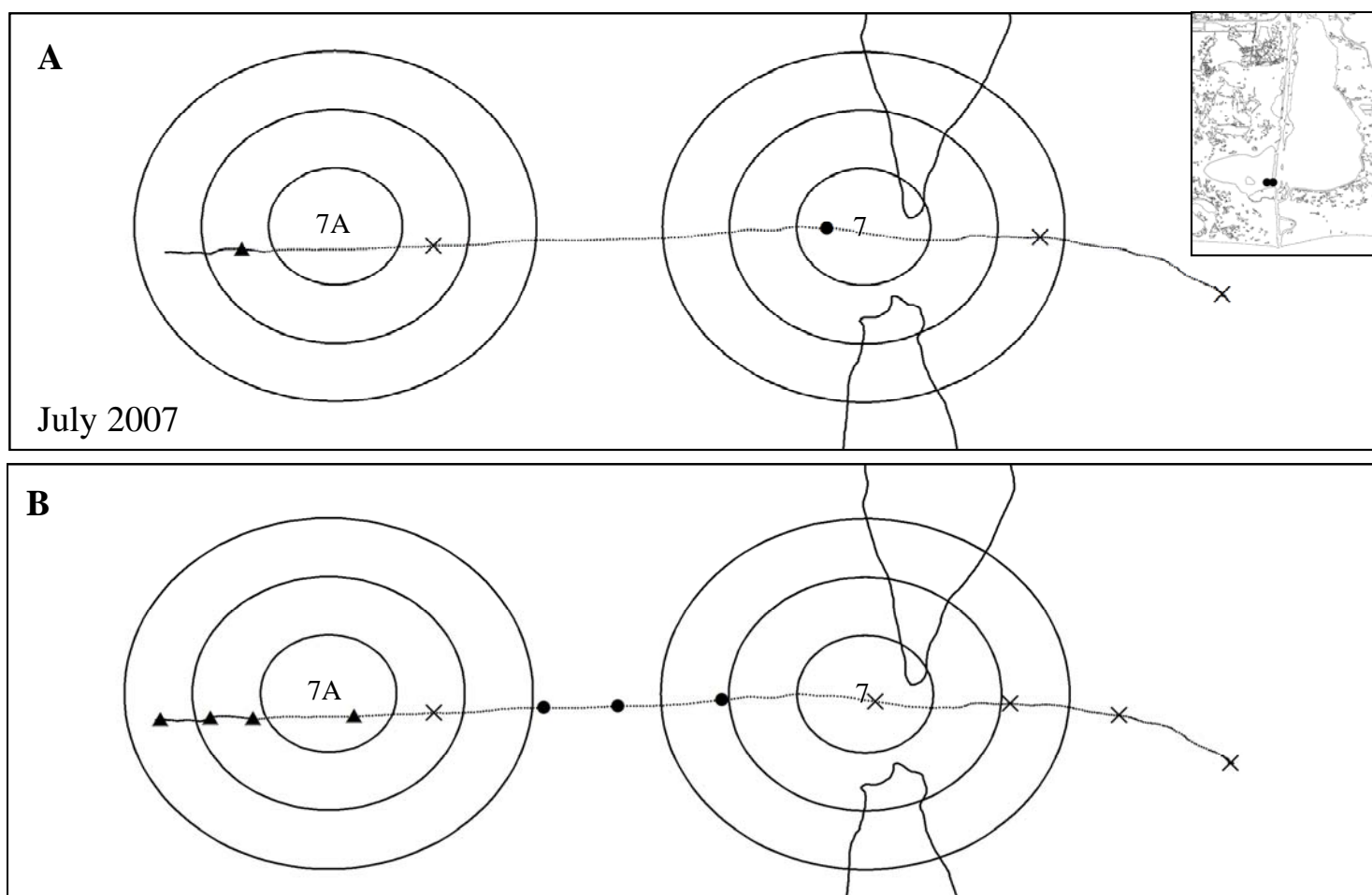


Figure 2.36. Results from the short-term range test at stations 7 and 7A on July 23, 2007. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13TP-1H random delay transmitters. Tow direction was east for all tows. Triangles designate the locations of transmissions that were detected only by station 7A, and black dots the locations of transmissions detected only by station 7. “Xs” indicate the locations of transmissions not detected by either receiver. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

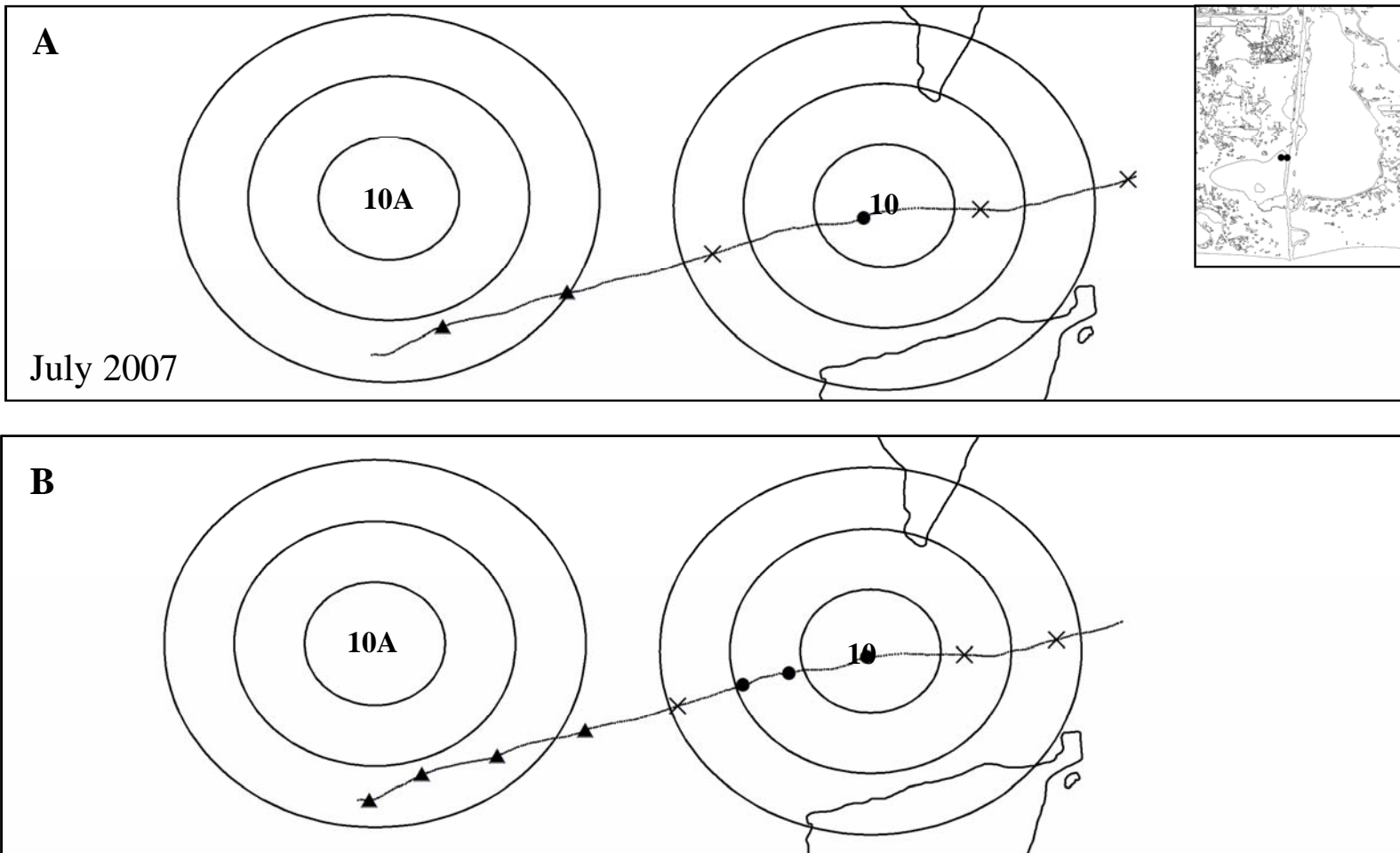


Figure 2.37. Results from the short-term range test at stations 10 and 10A on July 23, 2007. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13TP-1H random delay transmitters. Tow direction was east for all tows. Triangles designate the locations of transmissions detected only by station 10A, and black dots the locations of transmissions detected only by station 10. "Xs" indicate the locations of transmissions not detected by either receiver. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

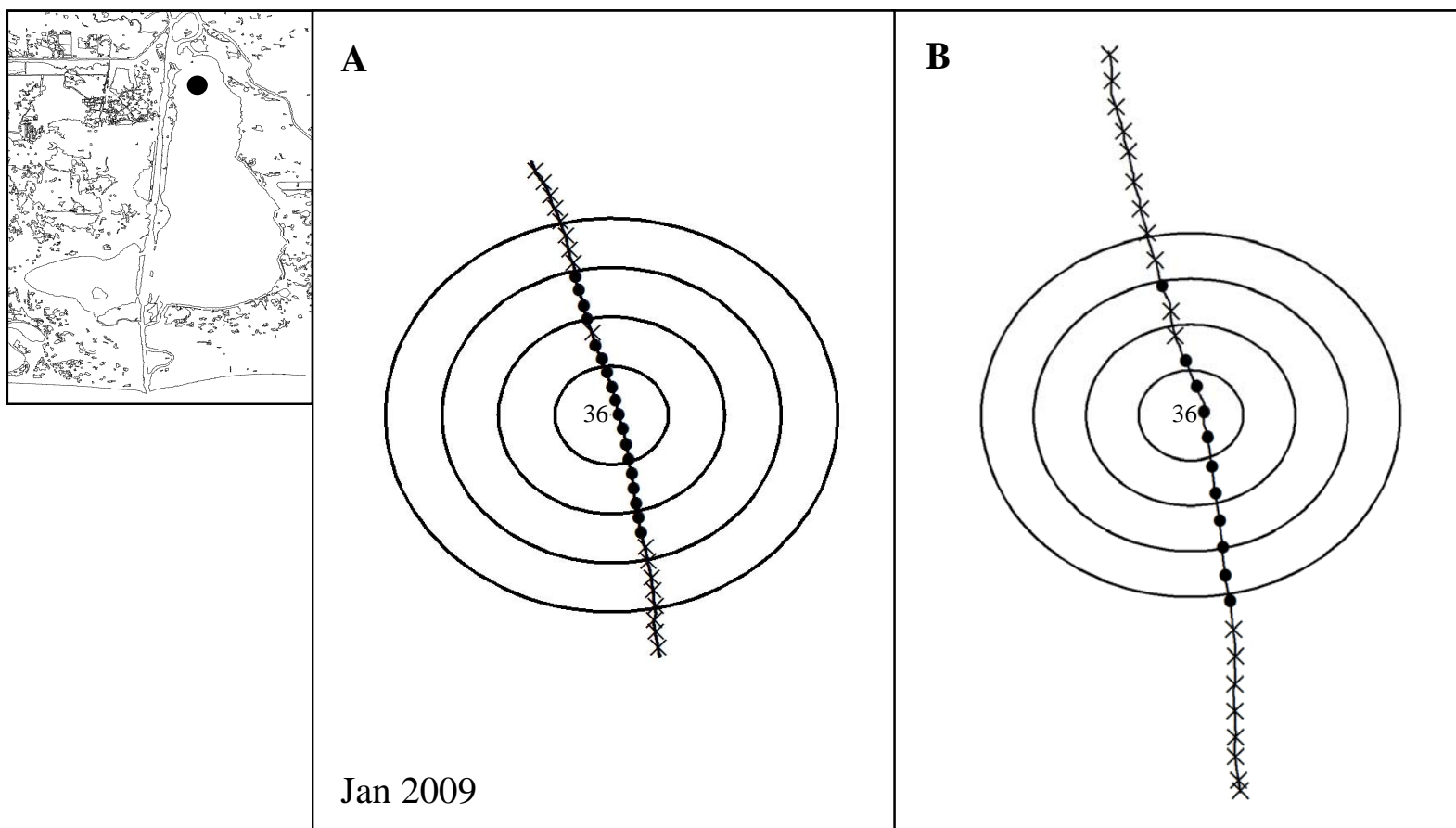


Figure 2.38. Results from the short-term range test at station 36 on January 21, 2009. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13T-1H fixed delay transmitters. Tow direction was north for all tows. Black dots designate the locations of transmissions that were detected, and “Xs” indicate the locations of transmissions not detected by the receiver at station 36. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

V9 and V13 were 300 and 330 m, respectively (Figure 2.39). In marsh habitats along the eastern shoreline of the estuary (stations 30, 31), detection ranges were 100 m for both the V9 and V13 (Figure 2.40).

For short-term range tests in the upper bay (stations 20, 21, 22, and 27) during March 2008, detection ranges for the V9 were 200 m for stations 20 and 27, and 300 m for stations 21 and 22; maximum detection range was 570 m (Figure 2.41). Detection range for the V13 was 350 m across stations, and its maximum range was 760 m (Figure 2.42). Few transmissions along the eastern side of Turners Bay island were detected, as this location may be an acoustic “dead zone” (Figures 2.41, 2.42).

#### Effects of Biofouling on Receiver Performance

A significant decline in DEs over the entire deployment period was only observed for the V13 transmitter at the 500 m receiver ( $p < 0.0001$ , Figure 2.43). No significant decline occurred for the V9 transmitter at this (500 m) receiver. Therefore, the reduction in detection efficiencies was probably related to transmitter performance rather than fouling of receiver mooring gear. The reduction in transmitter performance was probably due to a gradual decline in transmitter power output over time, rather than transmitter fouling, because reference transmitters only exhibited minor fouling at the end of the study; further there was no reduction in DEs for the V13 at the other (100 and 250 m) receivers.

Significant declines in DEs were only present for three inter-downloading periods, and at only one receiver for each period: January 22 to March 8, 2009 (500 m receiver,  $p < 0.02$ ), March 12 to June 1, 2009 (100 m receiver,  $p < 0.04$ ), and July 23 to September 23, 2009 (100 m receiver,  $p < 0.03$ ). Although these relationships were significant, they explained little variation in detection efficiencies ( $< 19\%$ ) and slope magnitudes were very small ( $< 0.37$ ) (Figure 2.44).

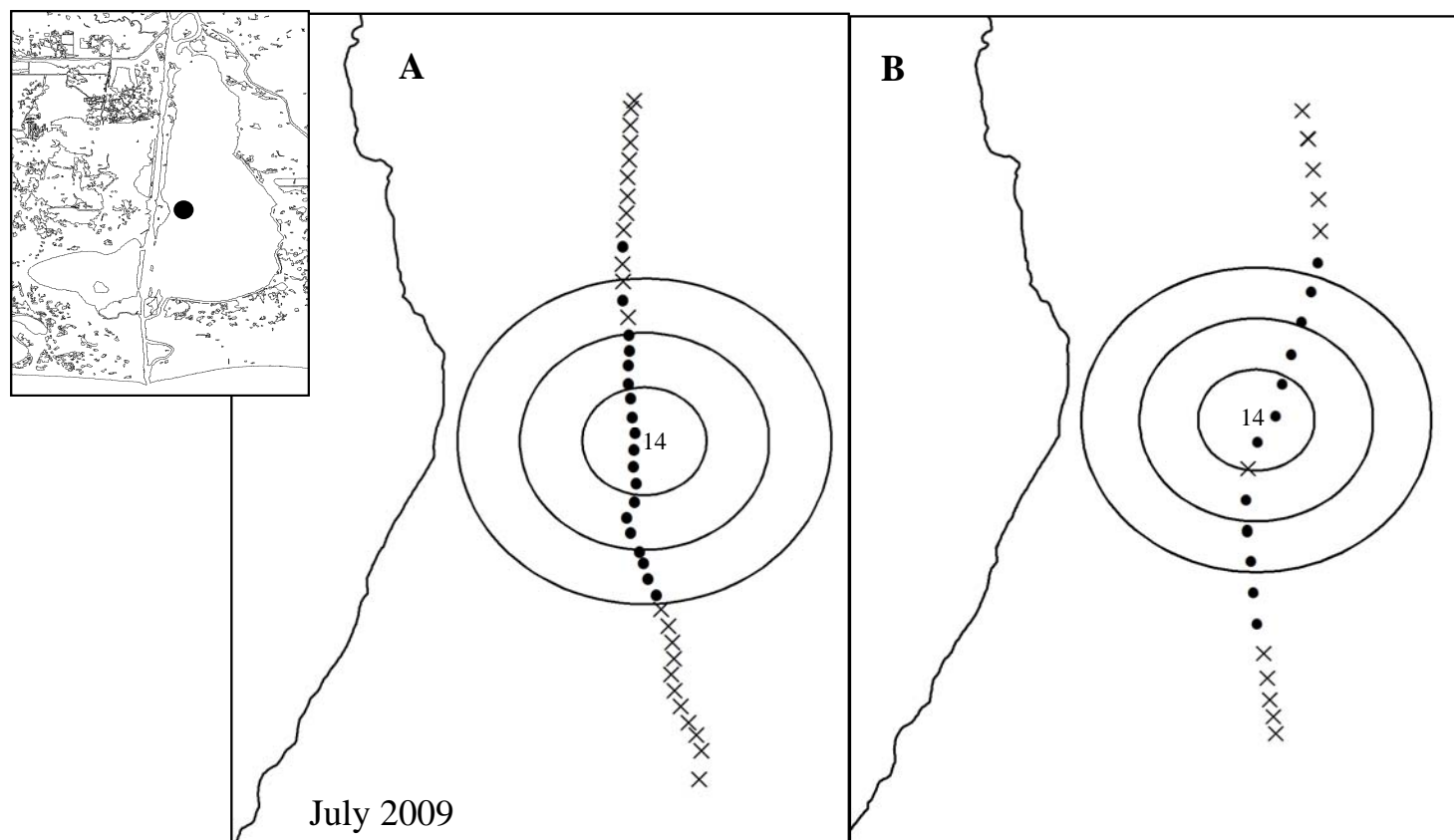


Figure 2.39. Results from the short-term range test at station 14 on July 27, 2009. The thin dashed line represents vessel positions throughout each tow of the **(A)** V9-2H and **(B)** V13T-1H fixed delay transmitters. Tow direction was north for all tows. Black dots designate the locations of transmissions that were detected, and “Xs” indicate the locations of transmissions not detected by the receiver at station 14. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

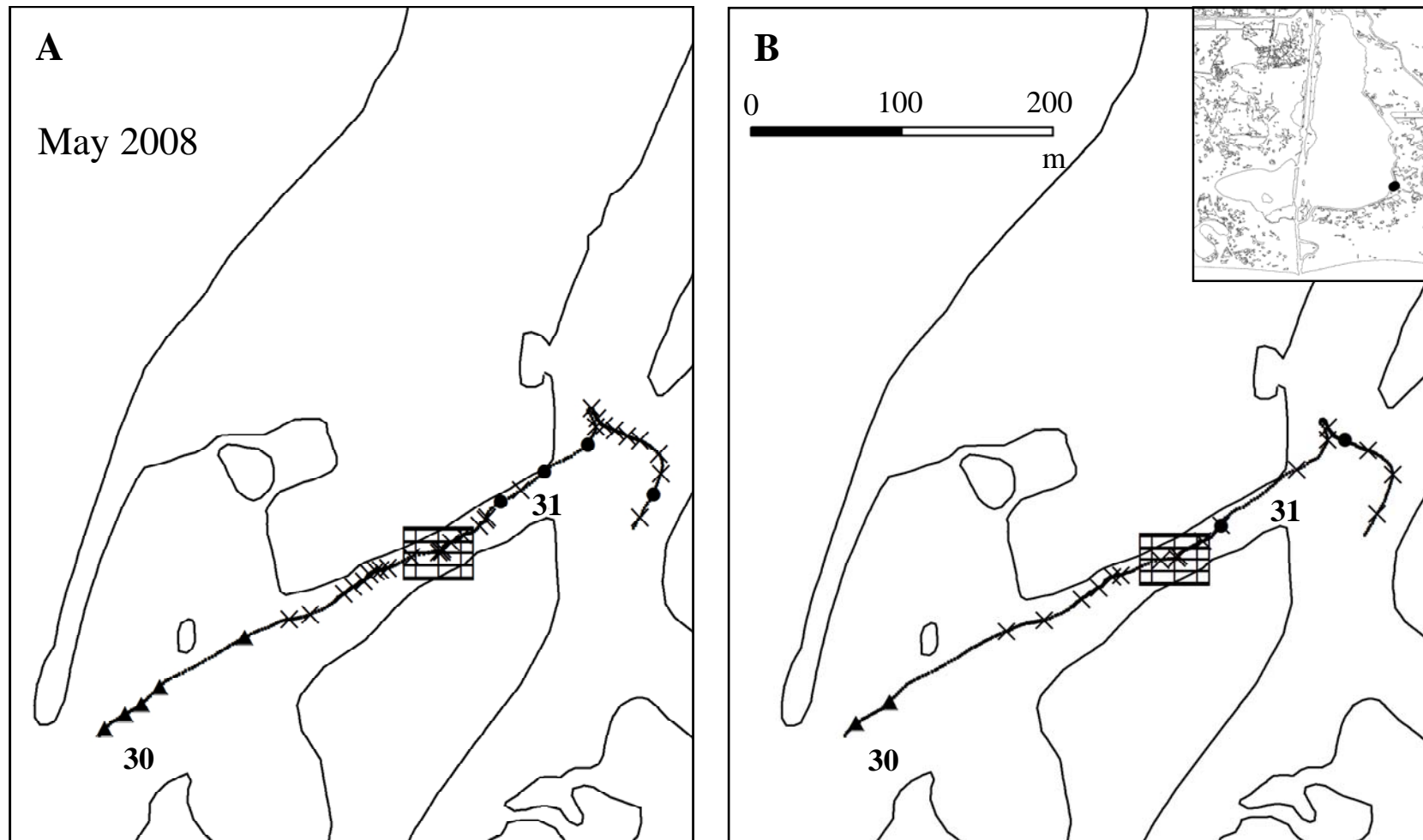


Figure 2.40. Results from the short-term range test at stations 30 and 31 on May 28, 2008. The thin dashed line represents vessel positions throughout each tow of the (A) V9-2H and (B) V13T-1H fixed delay transmitters. Tow direction was west for all tows. Triangles designate the locations of transmissions that were detected only by station 30, and black dots the locations of transmissions detected only by station 31. “Xs” indicate the locations of transmissions that were not detected by either receiver. The fence-like structure depicts the location of the weir that provided access to interior marsh habitats.



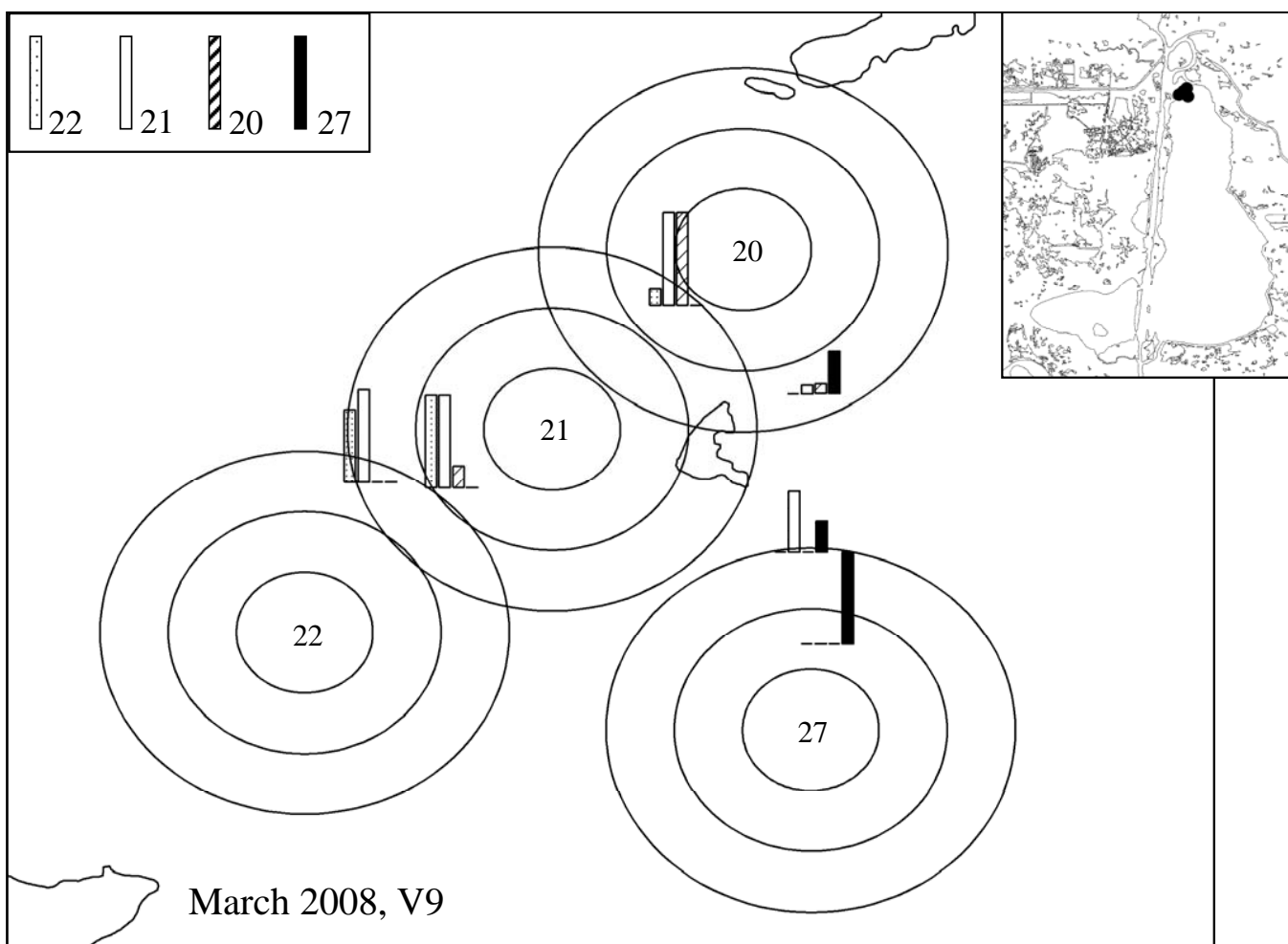


Figure 2.41. Results from the short-term range test conducted in Turners Bay (stations 20, 21, 22, 27) on March 27, 2008 with a V9 fixed delay transmitter. Test methods differed from other short-term range tests in that the vessel (transmitter) was stationary at discrete positions for at least five transmissions. Bars represent detection efficiencies for each receiver station (or the % of stationary transmissions that were detected by a given receiver station). Different bar fills correspond to receiver stations as indicated in the legend; bar heights in the legend represent 100% detection efficiency. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

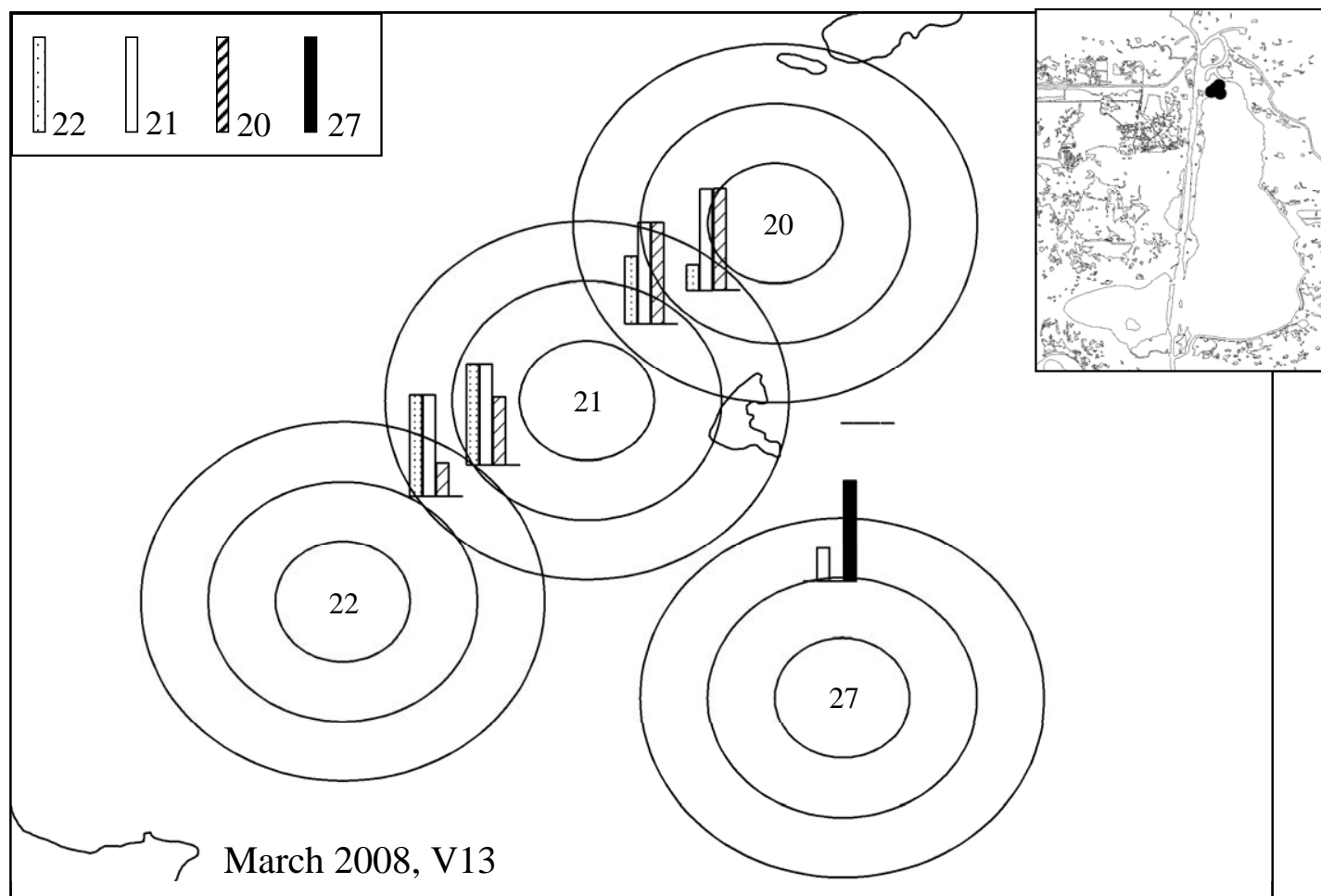


Figure 2.42. Results from the short-term range test conducted in Turners Bay (stations 20, 21, 22, 27) on March 27, 2008 with a V13 fixed delay transmitter. Test methods differed from other short-term range tests in that the vessel (transmitter) was stationary at discrete positions for at least five transmissions. Bars represent detection efficiencies for each receiver station (or the % of stationary transmissions that were detected by a given receiver station). Different bar fills correspond to receiver stations as indicated in the legend; bar heights in the legend represent 100% detection efficiency. Concentric circles around each station are used for scale; the distance from the station to the inner circle and between adjacent circles is 100 m.

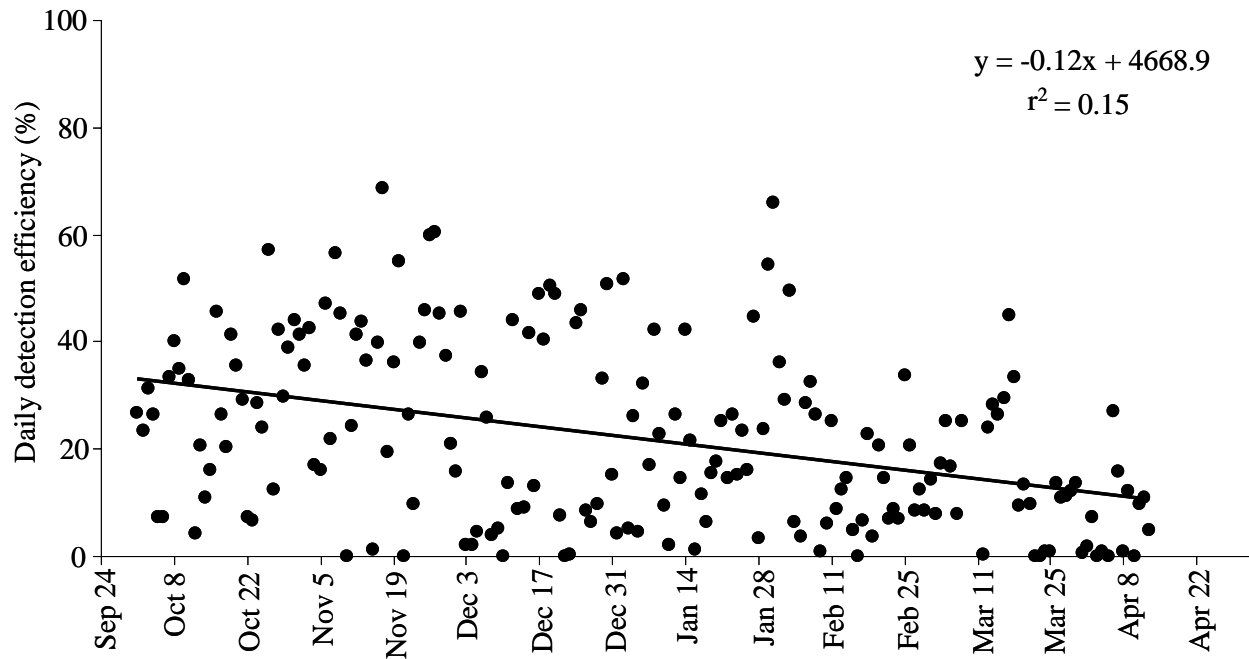


Figure 2.43. Decline in daily detection efficiencies of the V13TP-1H random delay transmitter over the period October 1, 2008 to April 13, 2009. Data is from the 500 m receiver deployed at the long-term range test site. Daily detection efficiencies were calculated by dividing the daily number of recorded detections of the V13 transmitter by the number of expected transmissions from the V13 during a 24-hour period; this ratio was then converted to a percentage.

#### Inter-Receiver Performance

There appeared to be little individual variation in receiver performance. Differences in the total number of detections among individual receivers (deployed equidistant from reference transmitters) were small, and ranged from 0.9 to 3.5% across both inter-receiver performance tests. For the three receivers used in the long-term range test, both VR2Ws recorded the same number of detections (1011), only 1.7% lower than the number of detections (1028) recorded by the VR2 over the 22 hour test period.

#### Transmitter Operation

Four of five reference transmitters operated at least as long as their rated battery lifespan (Table 2.4). Surprisingly, both V9 transmitters continued to operate four to five months beyond their rated lifespan. The long-delay V13 transmitter deployed in spring 2008 operated for 334

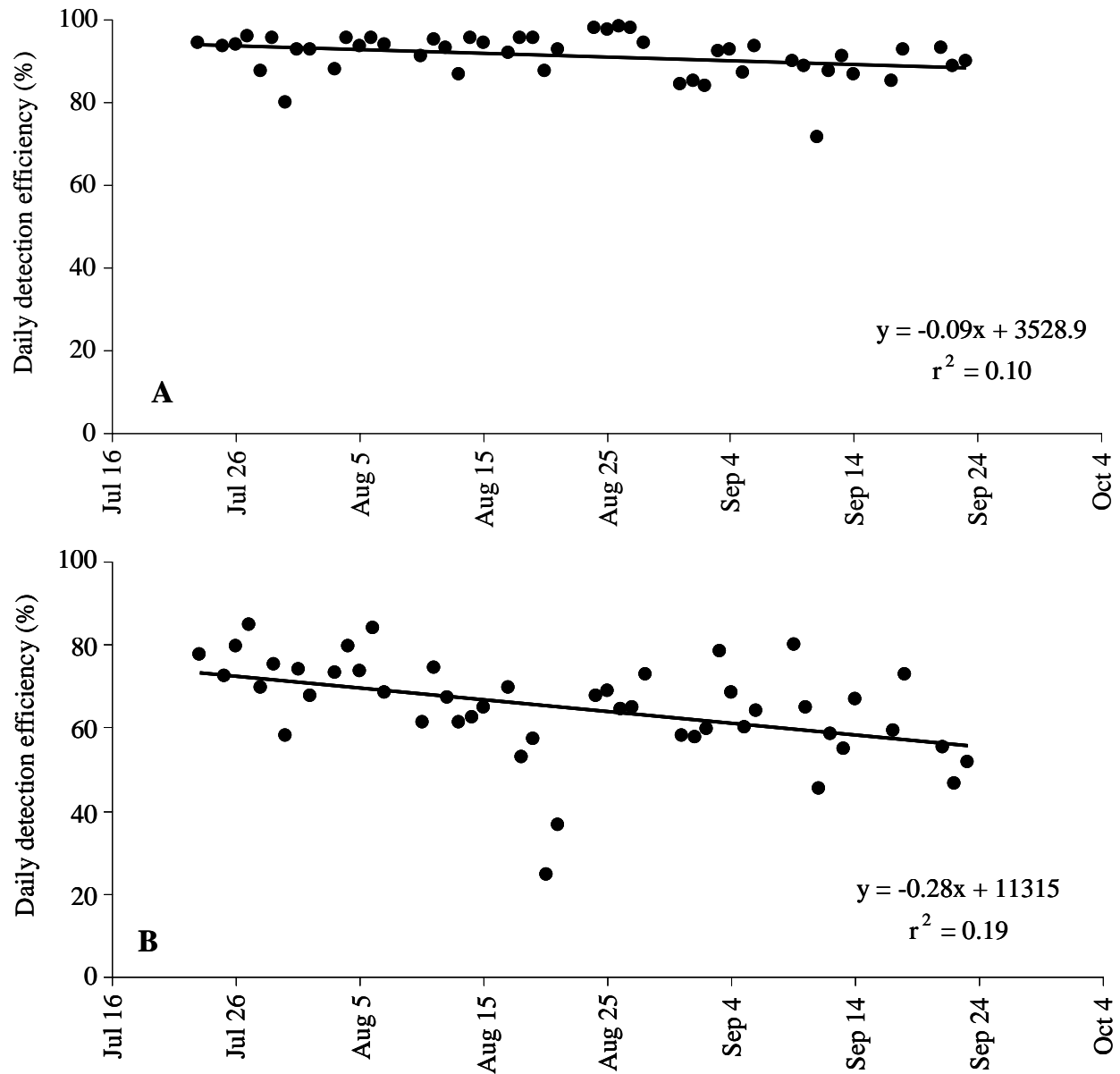


Figure 2.44. Example of a decline in detection efficiencies over an inter-downloading period (July 23 to September 23, 2009) for the 100 m receiver and the (A) V13TP-1H and (B) V9-2H random delay transmitters. Daily detection efficiencies were calculated by dividing the daily number of recorded detections of a particular transmitter by the number of expected transmissions from respective transmitters during a 24-hour period; this ratio was then converted to a percentage.

Table 2.4. *In-situ* battery lives for two sets of random delay reference transmitters deployed at the long-term range test site. The average delay (seconds) for each transmitter is given parenthetically. Estimates of expected battery lives were provided by the manufacturer (VEMCO).

Transmitter	Expected batt. life (days)	Observed batt. life (days)	Difference b/w actual and estimated
Spring 2007			
V9-2H (225 sec)	230	357	+127
V13TP-1H (120 sec)	340	389	+49
Spring 2008			
V9-2H (225 sec)	310	447	+137
V13TP-1H (120 sec)	370	369	-1
V13TP-1H (150 sec)	460	334	-126

days and expired four months prematurely (Table 2.4). Still, numerous fish implanted with V13 long-delay transmitters from the same production batch were detected 440 to 460 days post-release (see chapter 3). Thus, the early failure of the reference V13 transmitter appeared to be an isolated event rather than a widespread problem across all transmitters from that batch.

For the sensor accuracy tests, temperature values were significantly different between measurement devices (sensor transmitter vs. YSI sonde) for all days examined ( $p < 0.05$  across all four paired t-tests). Temperatures from the 2008 sensor transmitter were consistently higher than sonde temperatures, but no such trends were evident for the 2007 transmitter. Although temperature measurements differed significantly between devices, differences were small, typically less than  $0.3^{\circ}\text{C}$ . Moreover, only three of 95 (~3%) matched observations differed by more than  $0.5^{\circ}\text{C}$ , the reported accuracy of sensor transmitters. Depth transmitters performed as expected, given their coarse measurement resolution (0.22 m); they were able to document the difference between high and low water (0.6 m difference) during a complete tidal cycle (Figure 2.45).

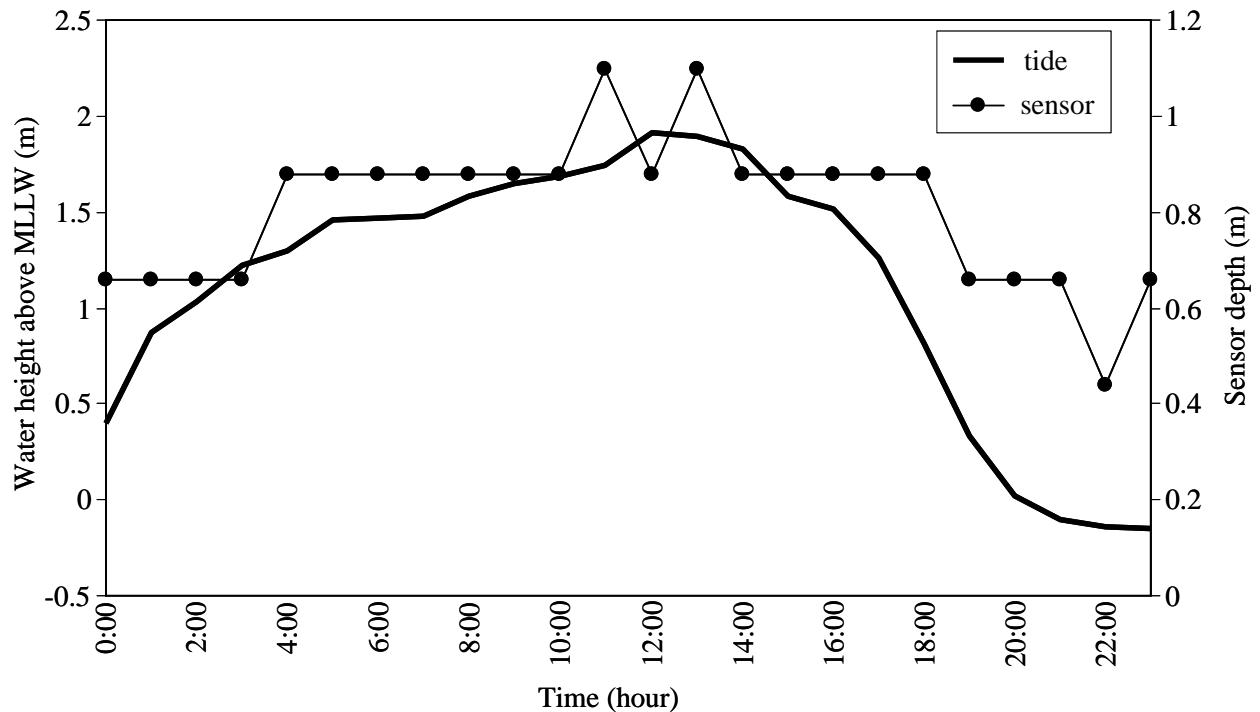


Figure 2.45. Depth sensor performance. Sensor values are for a stationary V13TP-1H transmitter permanently mounted to a piling at the long-term range test site during a complete tidal cycle on July 30, 2008. Tidal data were obtained from the USGS station at Cameron (Fig. 2.12, station 8).

For the transmitter power test, detection efficiencies were 25 and 49% higher for the newer V9 transmitter at the 100 m and 250 m receivers, respectively. The older V9 used in the power test was near the end of its lifespan, as it expired two weeks later in the laboratory. This older transmitter operated 40 days beyond its rated battery life of 426 days.

## Discussion

The long-term range test revealed that receiver performance was primarily controlled by turbidity and wind velocity. Surprisingly, receiver performance was unrelated to salinity, temperature, and dissolved oxygen. Although detection ranges appeared to be dynamic, both short- and long-term range tests indicated that detection ranges for V9 transmitters were typically 100 to 200 m, and for the more powerful V13s generally 200 to 300 m. Short-term range tests

verified that the inlet gate was effective at detecting towed transmitters (which simulated fish passage) as detection rates were high (~85%) for both V9 and V13 transmitters. I also evaluated several other aspects of receiver and transmitter performance, namely verifying transmitter battery lives and sensor operation and evaluating the potential effects of biofouling in long-term deployments of telemetry equipment. Results from this study will be used to aid interpretations of telemetry results presented in later chapters (3-5) of this dissertation; additionally should prove useful to other telemetry researchers, particularly in regards to determining the questions that can be adequately addressed with remote telemetry and also designing receiver arrays.

#### Effects of Environmental Conditions on Receiver Performance

Receiver performance deteriorated most rapidly under a northerly wind field. The long-term range test site was located near the southern end of the estuary proper. Therefore, fetch length and associated sea state (wave height) are greater at this site during northerly than southerly winds of similar duration. Wind-generated waves can easily resuspend bottom sediments due to the shallow depth of the estuary; as expected, turbidity at the test site displayed a much stronger (positive) relationship with wind speed on days when winds were northerly (Figure 2.46). Accordingly, poor receiver performance during periods of strong northern winds (> 10 knots) was likely due to significant absorption of transmitter signals by suspended particles and air bubbles generated by increased wave action. In addition, interference noise from breaking waves probably contributed to poor performance and reduced detection ranges. This mechanism also explains why receiver performance was extremely poor during cold fronts, as strong northerly winds often persist for 18 to 24 hours after frontal passages.

An underlying diel trend in receiver performance was observed, whereby performance was higher at night than during the day. A day-night cycle suggests a circadian biological

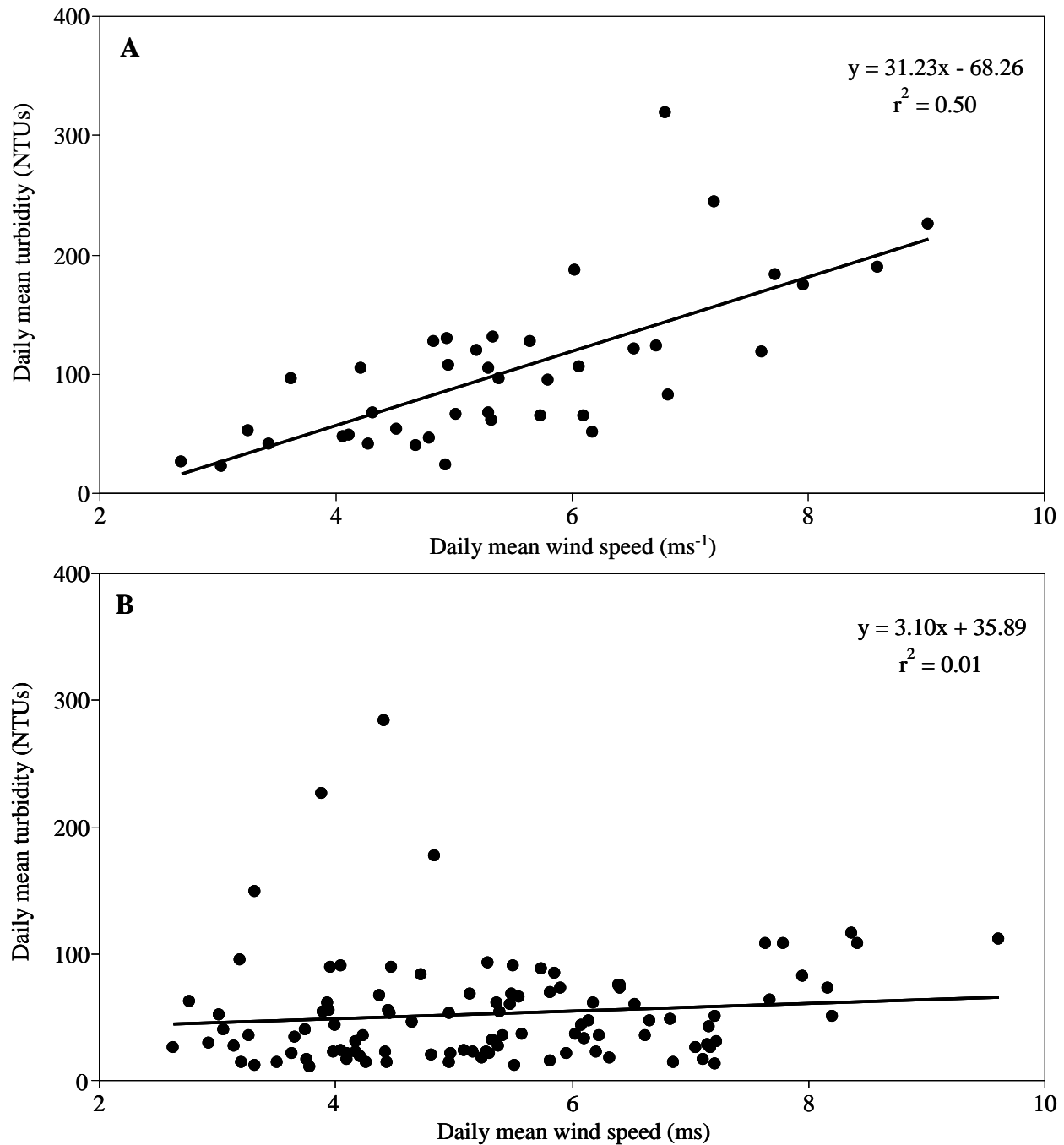


Figure 2.46. Relationship between daily mean wind speed and turbidity for days during the long-term range test that winds were predominantly (A) north (345-45°),  $n = 41$  days and (B) south (120-225°),  $n = 105$  days. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9); turbidity was measured by a YSI 6600 V2 sonde deployed at the long-term range test site (Figure 2.12, station 7).



rhythm may be involved in modulating receiver performance. For instance, higher diurnal noise production by snapping shrimp, bottlenose dolphins, or filter feeders (barnacles, oysters) may reduce receiver performance during the day. Nevertheless, studies on noise production in these soniferous organisms do not support this notion. Snapping shrimp noise may actually be higher during nocturnal and crepuscular periods, when shrimp are more active and leave their burrows (Nolan and Salmon 1970; Au and Banks 1998). Also, dolphin noise persists at night because echolocation (sound production) is used for hunting prey during nocturnal periods (Goold 2000). Additionally, feeding activity and associated sound production of filter feeders is probably more related to tidal dynamics than light levels. Lower receiver performance during the day could be due to increased vessel noise, particularly from recreational boats. During servicing trips, we often observed recreational vessels fishing in close proximity to buoyed receivers, including the long-term test site. Furthermore, recreational boat traffic is heavy through the West Cove inlet immediately north of the test site (Figure 2.7). Based on manual tracking surveys with the VR28 system, which contains a stereo output of sounds detected by the hydrophone (see chapter 3), engine noise from passing vessels and echosounder pings from stationary vessels were evident in the listening frequency of the system. Moreover, fishing activity is high during the period (July to October) over which hourly DEs were examined. Still, without continuous sound-recordings from the test site, this mechanism of increased vessel noise during the day could not be confirmed as the primary cause of diel variation in receiver performance.

A myriad of environmental variables can affect receiver performance. Although wind-induced turbidity and wave noise appeared to be the dominant factors in controlling receiver performance in this study, no single variable was able to explain more than 50% of the total variation in receiver performance. Thus, unmeasured variables additionally affected

performance. In particular, current velocities can impact receiver performance, but were not measured in this study. High current velocities and turbulent flow may reduce performance by increasing the absorption and scattering of acoustic signals (Thorstad et al. 2000).

Few studies have quantitatively assessed the effects of environmental conditions on receiver performance. Simpfendorfer et al. (2008) reported that code detection efficiencies were not significantly related to temperature, salinity, and river flow in the Caloosahatchee Estuary in southwestern Florida. However, this study had poor resolution as their performance metrics were calculated for the entire period between successive downloads (7 to 42 days) instead of at hourly and daily scales. For example, code detection efficiencies for one month periods between downloading events were related to average monthly, not daily, river flow. The resolution of their study was constrained because the authors relied on diagnostic data from VR2 receivers to calculate performance metrics. The VR2 receiver only provides the cumulative number of syncs, pings, and rejections since the receiver was last downloaded, whereas the newer VR2Ws afford the user daily summaries of diagnostic data. Another major limitation in the Simpfendorfer et al. (2008) study was that performance metrics were based upon opportunistic detections from free-ranging, telemetered sharks and rays instead of stationary reference transmitters; hence, detection ranges and true detection efficiencies could not be evaluated. Code detection efficiencies were calculated as the ratio of the total number of detections relative to the total number of syncs for each download period. Nevertheless, my data indicate the number of syncs heard by receivers is sensitive to environmental conditions (Figures 2.10, 2.47) and thus cannot be assumed as representative of the total number of transmissions that occurred within a given time period, information that is necessary to calculate 'true' detection efficiencies.

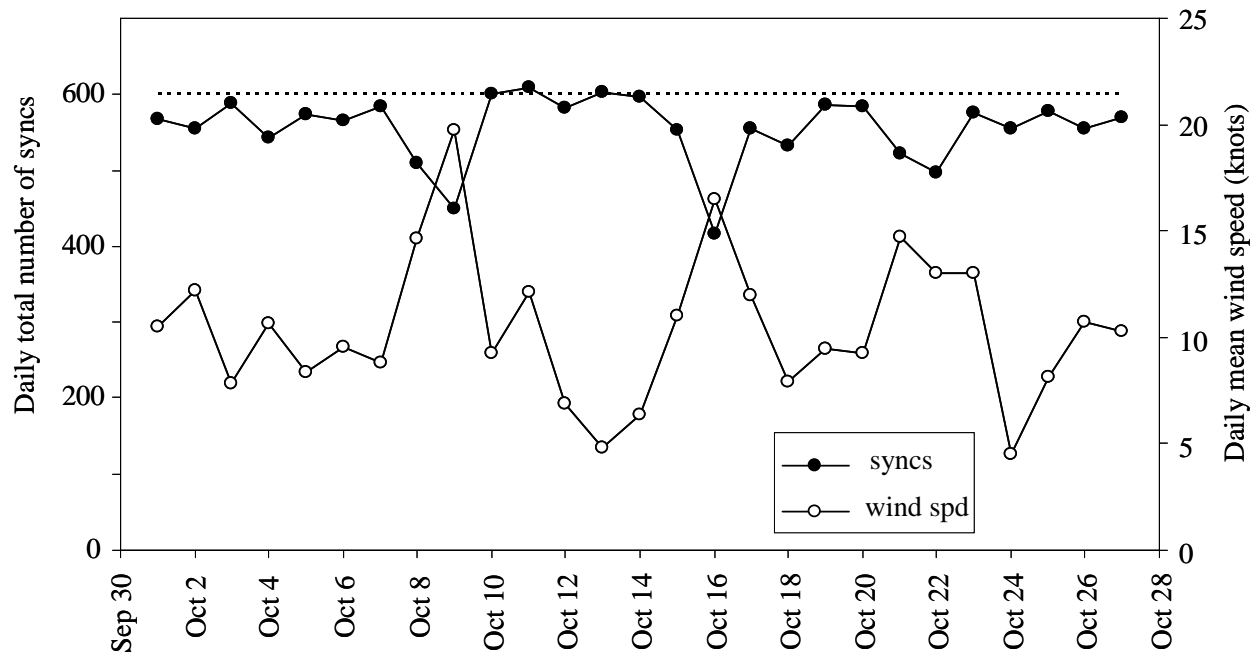


Figure 2.47. Daily total number of syncs (black dots) recorded by the 100 m receiver during October 2009. Only the two fixed delay transmitters were active during this period; hence, the expected daily total number of transmissions (syncs) was constant at 600, as shown by the dotted line. Daily mean wind speeds are depicted by the open dots. Wind data were obtained from the NOAA station at Cameron (Figure 2.12, station 9).

In another study, Lembo et al. (2002) noted that the total number of detections from telemetered grouper were lower on days with strong winds. Still, performance was not quantitatively related to environmental variables, and similar to Simpfendorfer et al. (2008), the study was not systematically designed to investigate receiver performance because detection data were based on telemetered fish instead of reference transmitters.

#### Implications of Receiver Performance Dynamics for the Interpretation of Telemetry Data

In this study, I showed that receiver performance was largely unrelated to water temperature, salinity, and dissolved oxygen. Accordingly, remote telemetry should be a reliable tool to investigate the effects of these environmental variables on fish movement and distribution (at least for the ranges of these variables I examined herein). For example, in chapter 4, I relate fish use of the upper bay to salinity. Given that receiver performance was unrelated to salinity,

detection metrics (e.g., the number of daily detections) could be validly compared among salinity values of interest. This study did show that receiver performance was strongly affected (negatively) by wind velocity and turbidity. Consequently, acoustic telemetry users should not expect high data acquisition rates when wind speeds and turbidity are high; for example, during severe weather events such as hurricanes, tropical storms, floods, and cold fronts. Moreover, a lack of detections during severe weather events should not be assumed to represent emigration from a study area because receivers may not be capable of detecting fish due to poor acoustic conditions.

In chapter 3, I calculate emigration rates of spotted seatrout from Calcasieu Lake based on the number of telemetered fish that passed through the inlet gate. Obviously, the accuracy of emigration rates depends on the ability of this acoustic gate to detect migrating fish. In this study, I towed transmitters through the inlet gate to simulate fish passage. Results from these short-term range tests demonstrated the gate was highly efficient (85% detection rate) in documenting simulated fish migration. Still, it is possible that fish behavior could cause my detection rates to be overestimated. During tow simulations, the test transmitters fired numerous times while within the presumed detection range ( $< 200$  m) of the receivers comprising the inlet gate. Yet, it is possible that fish implanted with transmitters could move through the gate rapidly enough such that their transmitters do not fire while within the detection range of receivers, in which case fish would pass through the gate undetected.

To explore the effects of swimming speed on the detection efficiency of the inlet gate, I calculated the minimum swimming speeds necessary for a fish to pass through an acoustic gate undetected (i.e., without emitting a single transmission), for different scenarios of detection ranges (100 m, 200 m) and transmitter delays (Table 2.5). Spotted seatrout typically employ a

Table 2.5. Minimum swimming speeds ( $\text{ms}^{-1}$ ) necessary for a single telemetered fish to pass through an acoustic gate (two receivers) without emitting a transmission. Calculations are presented for the minimum, average, and maximum delays of each random delay transmitter type used in the study and for detection ranges of 100 m and 200 m, the latter which provided complete cross-channel coverage at the main tidal inlet.

Transmitter:	<u>V9-2H</u>			<u>V13TP-1H</u>			<u>V13TP-1H</u>		
Delay (sec):	150	225	300	60	120	180	75	150	225
Min swim speed range = 100m	1.3	0.9	0.7	3.3	1.7	1.1	2.7	1.3	0.9
Min swim speed range = 200m	2.7	1.8	1.3	6.7	3.3	2.2	5.3	2.7	1.8

subcarangiform swimming mode (based on tank observations, chapter 1), for which maximum sustained swimming speeds are one to two body lengths per second (Helfman et al. 2000). Fish implanted with V9s ranged in length from 300 to 450 mm, and those implanted with V13s were mostly 450 to 600 mm. Accordingly, theoretical maximum sustained swimming speeds were 0.6 to  $0.9 \text{ ms}^{-1}$  and 0.9 to  $1.2 \text{ ms}^{-1}$  for spotted seatrout implanted with V9s and V13s, respectively. These maximum attainable swimming speeds were typically less than those required to pass through the gate undetected (i.e., fish were not theoretically able to swim fast enough to pass through the gate without emitting at least one transmission) (Table 2.5). Only when detection range was 100 m and the transmitter selected the longest possible delay were hypothetical maximum speeds fast enough to allow fish to pass through the gate undetected. These simulations assumed fish swam singly through the gate. If multiple fish simultaneously pass through the gate, collisions may reduce detection probabilities. However, this situation was highly unlikely because there were never more than two fish present (detected) at the inlet gate on the same day. Hence, it appears the ability of the inlet gate to detect migrants was not limited by swimming speeds of spotted seatrout. It is possible that tidal currents could assist migration

by increasing net velocities (*sensu* Melnychuk and Walters 2010). Maximum tidal currents in the ship channel are approximately  $0.5 \text{ ms}^{-1}$  (Lee et al. 1990). Accordingly, maximum net fish speeds (current + swimming speeds) would be  $1.1$  to  $1.4 \text{ ms}^{-1}$  for smaller (V9-implanted) fish and  $1.4$  to  $1.7 \text{ ms}^{-1}$  for larger (V13-implanted) fish. These attainable net speeds are still generally less than those required to pass through the inlet gate undetected. Thus, the inlet gate appears capable of detecting the majority of migrants; I provide further support for this conclusion based on data from telemetered fish that were known to have passed through the gate (see chapter 3).

Biofouling can significantly reduce the performance of receivers deployed for extended periods (months), especially if telemetry equipment is not coated with anti-fouling paint (Heupel et al. 2008). I used anti-fouling paint on all receivers and mooring gear, and re-applied paint on receiver hydrophones during servicing trips. These practices appeared to mitigate biofouling impacts. At most, biofouling of receiver hydrophones caused a gradual 10% decline in DEs over a one to two month period between downloads. Thus, telemetry data were not compromised or significantly affected by biofouling.

I also investigated several aspects of transmitter performance in this study. First, I showed that the majority of transmitters (four of five) operated at least as long as their rated battery lives. This was an important finding because pervasive transmitter failure can result in spurious estimates of migration and mortality rates. Secondly, I verified the accuracy of temperature and depth sensors of V13 transmitters. Because sensors performed as expected, data from V13 transmitters can be reliably used to investigate temperature and depth preferences of implanted fish (see chapter 4).

The main limitation in this study was that spatial variation in receiver performance was not quantitatively examined, as most data analyses were based on detection data from a single site. Some areas or habitats may be more favorable for acoustic propagation than others due to substrate type/topography, the presence or absence of structure, or water depth. For example, at sites with a hard substrate (e.g., oyster reefs) and more structure (e.g., wellheads, pilings), acoustic signals may frequently be deflected by obstructions and prone to multipath propagation (Starr et al. 2000; Giacalone et al. 2005). Both of these mechanisms would decrease receiver performance. If spatial (site or habitat) variation in receiver performance is substantial and not accounted for in habitat use analyses, sites or habitats with inherently superior acoustic properties would be erroneously assumed to be utilized to a greater extent by study species (Simpfendorfer et al. 2008). Because I did not examine habitat-specific receiver performance, it was not possible to adjust my habitat use data (see chapter 5) for possible performance differences among habitat types. To investigate spatial variation in receiver performance, it is necessary to control for temporal variation. For instance, if short-term range tests are conducted at two sites, with a few hours between tests, differences in performance could be due to a temporal change in the wind field instead of a site effect. A more suitable method would be to conduct simultaneous long-term range tests at the sites or habitats of interest over the course of a few weeks or months.

Telemetry studies can provide unprecedented information on the behavior and movement of aquatic organisms. Still, researchers employing telemetry techniques must acknowledge the limitations of their data, one of which is equipment performance. Across the literature, there seems to be a commonplace ignorance of how the performance of telemetry equipment affects data interpretations and analyses. Most researchers simply take detection data at face value with

little consideration of performance dynamics. As one of the most thorough studies of the performance of acoustic telemetry systems to date, this study showed that receiver performance was dynamic and generally controlled by meteorological conditions. The dynamic nature of receiver performance has important implications for studies of fish migration, distribution, and habitat use, as discussed above. My results are probably applicable to other telemetry studies using VEMCO equipment in shallow, turbid estuaries. However, system performance undoubtedly varies by receiver type, transmitter sizes, manufacturers, and macrohabitats in which studies are conducted. Therefore, range testing should be conducted on a study-specific basis to facilitate a synoptic understanding of telemetry system performance which can ultimately guide the design and deployment of receiver arrays and interpretations of telemetry data.

## References

- Able, K.W., and T.M. Grothues. 2007. Diversity of estuarine movements of striped bass (*Morone saxatilis*): a synoptic examination of an estuarine system in southern New Jersey. *Fishery Bulletin* 105:426-435.
- Afonso, P., J. Fontes, K.N. Holland, and R.S. Santos. 2008. Social status determines behavior and habitat usage in a temperate parrotfish: implications for marine reserve design. *Marine Ecology Progress Series* 359:215-227.
- Afonso, P., J. Fontes, K.N. Holland, and R.S. Santos. 2009. Multi-scale patterns of habitat use in a highly mobile reef fish, the white trevally *Pseudocaranx dentex*, and their implications for marine reserve design. *Marine Ecology Progress Series* 381:273-286.
- Arendt, M.D., J.A. Lucy, and D.A. Evans. 2001. Diel and seasonal activity patterns of adult tautog, *Tautoga onitis*, in lower Chesapeake Bay, inferred from ultrasonic telemetry. *Environmental Biology of Fishes* 62:379-391.
- Au, W.W.L., and K. Banks. 1998. The acoustics of the snapping shrimp *Synalpheus parneomeris* in Kaneohe Bay. *Journal of the Acoustical Society of America* 103(1):41-47.
- Bradshaw, C.J.A., D.W. Sims, and G.C. Hays. 2007. Measurement error causes scale-dependent threshold erosion of biological signals in animal movement data. *Ecological Applications* 17(2):628-638.



- Clements, S., D. Japsen, M. Karnowski, and C.B. Schreck. 2005. Optimization of an acoustic telemetry array for detecting transmitter-implanted fish. *North American Journal of Fisheries Management* 25:429-436.
- Comeau, L.A., S.E. Campana, and M. Castonguay. 2002. Automated monitoring of a large-scale cod (*gadus morhua*) migration in the open sea. *Canadian Journal of Fisheries and Aquatic Sciences* 59:1845-1850.
- Dresser, B.K., and R.T. Kneib. 2007. Site fidelity and movement patterns of wild subadult red drum, *Sciaenops ocellatus* (Linnaeus), within a salt marsh-dominated estuarine landscape. *Fisheries Management and Ecology* 14:183-190.
- Evans, K., and G. Arnold. 2009. Summary report of a workshop on geolocation methods for marine animals. Pages 343-363 in J.L. Nielsen, H. Arrizabalaga, N. Fragoso, A. Hobday, M. Lutcavage, and J. Sibert, editors. *Tagging and Tracking of Marine Animals with Electronic Devices*, Springer, London.
- Finstad, B., F. Okland, E.B. Thorstad, P.A. Bjorn, and R.S. McKinley. 2005. Migration of hatchery-reared Atlantic salmon and wild anadromous brown trout post-smolts in a Norwegian fjord system. *Journal of Fish Biology* 66:86-96.
- Giocalone, V.M., G.D. Anna, G. Garafalo, K. Collins, and F. Badalamenti. 2005. Estimation of positioning error from an array of automated omni-directional receivers in an artificial reef area. Pages 245-253 in *Aquatic telemetry: advances and applications, proceedings of the fifth conference on fish telemetry held in Europe*, FAO/COISPA, Rome.
- Goold, J.C. 2000. A diel pattern in vocal activity of short-beaked common dolphins *Delphinus delphis*. *Marine Mammal Science* 16(1):240-244.
- Grothues, T.M., K.W. Able, J. McDonnell, and M.M. Sisak. 2005. An estuarine observatory for real-time telemetry of migrant macrofauna: design, performance, and constraints. *Limnology and Oceanography:Methods* 3:275-289.
- Hartill, B.W., M.A. Morrison, M.D. Smith, J. Boubée, and D.M. Parsons. 2003. Diurnal and tidal movements of snapper (*Pagrus auratus*, Sparidae) in an estuarine environment. *Marine and Freshwater Research* 54:931-940.
- Helfman, G.S., B.B. Collette, and D.E. Facey. 2000. *The diversity of fishes*. Blackwell Science, Malden, Massachusetts.
- Heupel, M.R., and R.E. Hueter. 2001. Use of an automated acoustic telemetry system to passively track juvenile blacktip shark movements. Pages 217-236 in J.R. Sibert and J.L. Nielsen, editors. *Electronic Tagging and Tracking in Marine Fisheries*. Kluwer Academic Publishers, Netherlands.

- Heupel, M.R., J.M. Semmens, and A.J. Hobday. 2006. Automated acoustic tracking of aquatic animals: scales, designs, and deployment of listening station arrays. *Marine and Freshwater Research* 57:1-13.
- Heupel, M.R., K.L. Reiss, B.G. Yeiser, and C.A. Simpfendorfer. 2008. Effects of biofouling on performance of moored data logging acoustic receivers. *Limnology and Oceanography: Methods* 6:327-335.
- Hindell, J.S., G.P. Jenkins, and B. Womersley. 2008. Habitat utilization and movement of black bream *Acanthopagrus butcheri* (Sparidae) in an Australian estuary. *Marine Ecology Progress Series* 366:219-229.
- Humston, R., J.S. Ault, M.F. Larkin, and J. Luo. 2005. Movement and site fidelity of the bonefish *Albula vulpes* in the northern Florida Keys determined by acoustic telemetry. *Marine Ecology Progress Series* 291:237-248.
- Klimley, A.P., F. Voegeli, S.C. Beavers, and B.J. Le Boeuf. 1998. Automated listening stations for tagged marine fishes. *Marine Technological Society Journal* 32(1):94-101.
- Lee, J.M., W.J. Wiseman, Jr., and F.J. Kelly. 1990. Barotropic, subtidal exchange between Calcasieu Lake and the Gulf of Mexico. *Estuaries* 13(3):258-264.
- Lembo, G., M.T. Spedicato, F. Okland, P. Carbonara, I.A. Fleming, R.S. McKinley, E.B. Thorstad, M.M. Sisak, and S. Ragonese. 2002. A wireless communication system for determining site fidelity of juvenile dusky groupers *Epinephelus marginatus* (Lowe, 1834) using coded acoustic transmitters. *Hydrobiologia* 483:249-257.
- Lindholm, J., P.J. Auster, and A. Knight. 2007. Site fidelity and movement of adult Atlantic cod *Gadus morhua* at deep boulder reefs in the western Gulf of Maine, USA. *Marine Ecology Progress Series* 342:239-247.
- Lowe, C.G., D.T. Topping, D.P. Cartamil, and Y.P. Papastamatiou. 2003. Movement patterns, home range, and habitat utilization of adult kelp bass *Paralabrax clathrus* in a temperate no-take marine reserve. *Marine Ecology Progress Series* 256:205-216.
- Lurton, X. 2002. An introduction to underwater acoustics principles and applications. Springer Praxis, London.
- McBride, R.A., M.J. Taylor, and M.R. Byrnes. 2006. Coastal morphodynamics and Chenier-Plain evolution in southwestern Louisiana, USA: a geomorphic model. *Geomorphology* 88:367-422.
- Melnychuk, M.C., D.W. Welch, C.J. Walters, and V. Christensen. 2007. Riverine and early ocean migration and mortality patterns of juvenile steelhead trout (*Oncorhynchus mykiss*) from the Cheakamus River, British Columbia. *Hydrobiologia* 582:55-65.

- Melnychuk, M.C., and C.J. Walters. 2010. Estimating detection probabilities of tagged fish migrating past fixed receiver stations using only local information. *Canadian Journal of Fisheries and Aquatic Sciences* 67:641-658.
- Meyer, C.G., T.B. Clark, Y.P. Papastamatiou, N.M. Whitney, and K.N. Holland. 2009. Long-term movement patterns of tiger sharks *Galeocerdo cuvier* in Hawaii. *Marine Ecology Progress Series* 381:223-235.
- Mitamura, H., A. Nobuaki, Y. Mitsunaga, T. Yokota, H. Takeuchi, T. Tsuzaki, and M. Itani. 2005. Directed movements and diel burrow fidelity patterns of ref tilefish *Branchiostegus japonicus* determined using ultrasonic telemetry. *Fisheries Science* 71:491-498.
- Moeller, C.C., O.K. Huh, H.H. Roberts, L.E. Gumley, and W.P. Menzel. 1993. Response of Louisiana coastal environments to a cold front passage. *Journal of Coastal Research* 9(2):434-447.
- Nichol, S.L., R. Boyd, and S. Penland. 1992. Hydrology of a wave-dominated estuary: Lake Calcasieu, southwest Louisiana. *Gulf Coast Association of Geological Societies* 42:835 - 844.
- Nichol, S.L., R. Boyd, and S. Penland. 1996. Sequence stratigraphy of a coastal-plain incised valley estuary: Lake Calcasieu, Louisiana. *Journal of Sedimentary Research* 66(4):847-857.
- Nolan, B.A., and M. Salmon. 1970. The behavior and ecology of snapping shrimp (Crustacea: *Alpheus heterochaelis* and *Alpheus noraonni*). *Form and Function* 2:289-335.
- Simpfendorfer, C.A., M.R. Heupel, and A.B. Collins. 2008. Variation in the performance of acoustic receivers and its implication for positioning algorithms in a riverine setting. *Canadian Journal of Fisheries and Aquatic Sciences* 65:482-492.
- Starr, R.M., J.N. Heine, and K.A. Johnson. 2000. Techniques for tagging and tracking deepwater rockfishes. *North American Journal of Fisheries Management* 20:597-609.
- Thorstad, E.B., F. Okland, D. Rowsell, and R.S. McKinley. 2000. A system for automatic recording of fish tagged with coded acoustic transmitters. *Fisheries Management and Ecology* 7:281-294.
- Topping, D.T., C.G. Lowe, and J.E. Caselle. 2006. Site fidelity and seasonal movement patterns of adult California sheephead *Semicossyphus pulcher* (Labridae): an acoustic monitoring study. *Marine Ecology Progress Series* 326:257-267.
- Voegeli, F.A., and D.G. Pincock. 1996. Overview of acoustics as it applies to telemetry. Pages 23-30 in E. Baras, and J.C. Philippart, editors. *Underwater biotelemetry*. University of Liege, Liege, Belgium.

- Voegeli, F.A., M.J. Smale, D.M. Webber, Y. Andrade, and R.K. O'Dor. 2001. Ultrasonic telemetry, tracking and automated monitoring technology for sharks. *Environmental Biology of Fishes* 60:267-281.
- Westmeyer, M.P., C.A. Wilson, and D.L. Nieland. 2007. Fidelity of red snapper to petroleum platforms in the Northern Gulf of Mexico. Pages 105-121 *in* W.F. Patterson, J.H. Cowan, Jr., G.R. Fitzhugh, and D.L. Nieland, editors. Red snapper ecology and fisheries in the U.S. Gulf of Mexico. American Fisheries Society Symposium 60, Bethesda, Maryland.

# **CHAPTER 3: STOCK STRUCTURE OF SPOTTED SEATROUT IN LOUISIANA INFERRED FROM CONVENTIONAL TAGGING AND ACOUSTIC TELEMETRY DATA**

## **Introduction**

Due to their mobility, adult fishes have a high capacity for dispersal, especially in open systems such as marine and coastal environments. Still, few marine fishes are panmictic and move throughout their entire geographic ranges, which can be thousands of kilometers (Pawson and Jennings 1996; Metcalfe 2006). Instead, movement scales of adults are typically much smaller than their respective geographic ranges, resulting in groups of fish (stocks) that do not extensively mix and interact with each other throughout their lifetime. Thus, knowledge of adult movements is an essential component in delineating stock structure, which in turn facilitates decisions regarding the appropriate management scale for important fishery resources.

For some fishery species, movement information is insufficient to determine stock structure or political boundaries are used to designate management units simply out of convenience (e.g., the same regulations may apply state-wide). In these situations, management units may correspond poorly with the movements and associated stock structure of a species. For instance, multiple stocks may be present within the same management unit or the spatial extent of a given stock may span numerous management units. Consequently, regulations may be ineffective or negatively impact stock abundance (Dunn and Pawson 2002). A classic example is the highly contentious bluefin tuna fishery in the Atlantic Ocean, where two management zones exist east and west of the 45° W meridian (Fromentin and Powers 2005). Some bluefin tuna (~20-30%) undergo extensive trans-Atlantic migrations from their respective spawning grounds in the Gulf of Mexico (GOM) or Mediterranean Sea and cross this boundary. Catch quotas are much higher for the eastern zone; hence, the more stringent regulations in the

western zone are partly nullified by movement to and harvest of individuals in the eastern zone (Fromentin and Powers 2005; Rooker et al. 2007). For coastal species with smaller movement scales, the opposite scenario may be more common whereby multiple stocks, with largely independent dynamics, are present within the same prescribed management unit (Stephenson 1999; Jones 2006). In this case, important differences in stock status arising from localized anthropogenic and/or environmental effects may be masked if assessment metrics are based upon data pooled across an entire management unit (i.e., multiple stocks). For example, a declining recruitment index for one stock can be offset by an increasing recruitment index for another stock if data are aggregated. Thus, management could prove more effective in this situation under a spatially explicit, finer-scale approach that considers the underlying stock structure of a species.

One species that may exhibit stock structure at relatively small spatial scales (hundreds of kilometers) is spotted seatrout, *Cynoscion nebulosus*. Adults of this species purportedly remain near their natal areas and have limited movement ranges of less than 50 km (Iversen and Tabb 1962; Baker et al. 1986; Hendon 2002; Bortone 2003). Spotted seatrout occur in estuaries and nearshore coastal waters from Cape Cod, Massachusetts to the Bay of Campeche, Mexico and are an extremely important recreational species (Tabb 1966). This popular sportfish had the highest recreational catch in US waters (in terms of numbers caught) in eight of the past ten years (2000-2009) (personal communication from the National Marine Fisheries Service, Fisheries Statistics Division, May 2010). Most of the recreational catch (~85%) is taken in the northern GOM (Florida to Texas) where spotted seatrout are abundant (personal communication from the National Marine Fisheries Service, Fisheries Statistics Division, May 2010).

Despite the considerable recreational and economic importance of spotted seatrout, the stock structure of this species remains poorly resolved in the northern GOM, particularly in Louisiana where there is a paucity of movement data. Information on adult movements in Louisiana is restricted to a few historical tagging studies conducted by the Louisiana Department of Wildlife and Fisheries (LDWF) that were either limited in their spatial scope (i.e., fish were only tagged in one estuary: Rogillio 1980; Rogillio 1982; Arnoldi 1985) or had a low number of tag returns (n=30, Adkins et al. 1979). Additional movement data are therefore necessary to delineate the stock structure of spotted seatrout in Louisiana in support of fisheries management. In Louisiana, spotted seatrout are currently managed and assessed as a single, state-wide stock, with the exception of Calcasieu Lake. Yet, it is possible that numerous ‘ecological’ stocks exist along the vast 600 km Louisiana coastline, in which case assessment and management could be enhanced by accounting for spatial (stock) structure.

To aid stock identification of spotted seatrout in Louisiana, I investigated adult movements using two approaches, conventional tagging and acoustic telemetry. In the 2.5 year telemetry study (May 2007 to October 2009), I used acoustic receivers to continuously monitor the exit routes from an estuary (Calcasieu Lake) to quantify emigration of telemetered fish. The conventional tagging data were obtained from a large-scale (state-wide) and long-term (20-year) tagging program; thus, provided important information on adult mixing rates along the Louisiana coast and also maximum movement ranges. I hypothesize that adult spotted seatrout in Louisiana have restricted ranges and rarely move more than 50 km; as a corollary, they form a number of semi-discrete stocks, each of which are possibly centered around a major estuary (nursery) (*sensu* Iversen and Tabb 1962; Gold et al. 2003).

## Methods

### Telemetry Study Area

Calcasieu Lake is an optimal system for telemetry because there are only two exit points from the estuary: 1) the main tidal inlet connecting the estuary proper to the nearshore GOM and 2) the Gulf Intracoastal Waterway (GIWW) which provides inshore access to adjacent estuarine basins (Sabine Lake to the west and Vermilion Bay to the east). Both of these exit points are narrow waterways (inlet ~400 m, GIWW ~100 m) that can be effectively monitored with a few acoustic receivers. Accordingly, I deployed receivers in an “acoustic gate” configuration at these exit points to detect emigrating fish (see chapter 2 for details on receiver deployment and operation). The inlet gate consisted of two lines of receivers, with two receivers in each line (stations Alpha/50 and 47/48) (Figure 3.1). The gate in the western portion of the GIWW included two individual receivers separated by 3.4 km (stations 26A, 28) (Figure 3.1).

The eastern access point to the GIWW contained a navigation lock, the Calcasieu Lock (Figure 3.1). I did not deploy a receiver at this location because I assumed it was highly unlikely fish would pass through this narrow lock (~25 m) when it was opened to allow vessel passage or occasionally for flood control. Even if fish were able to pass through the lock into the eastern GIWW, it is improbable the 120 km section of the GIWW between the Calcasieu Lock and Vermilion Bay is used as a migration corridor due to its extremely low salinity. For instance, where the GIWW intersects the Mermentau River, 50 km east of the Calcasieu Lock, the average salinity from 1998 through 2009 was 0.3, 90% of all salinities were less than 1, and the maximum was 1.5 (<http://www.mvn.usace.army.mil/ops/sms/grand.asp>). Hence, to migrate eastward via the GIWW from the Calcasieu Lock to the nearest water body of appreciable salinity (Vermilion Bay), a spotted seatrout would have to traverse 120 km of essentially



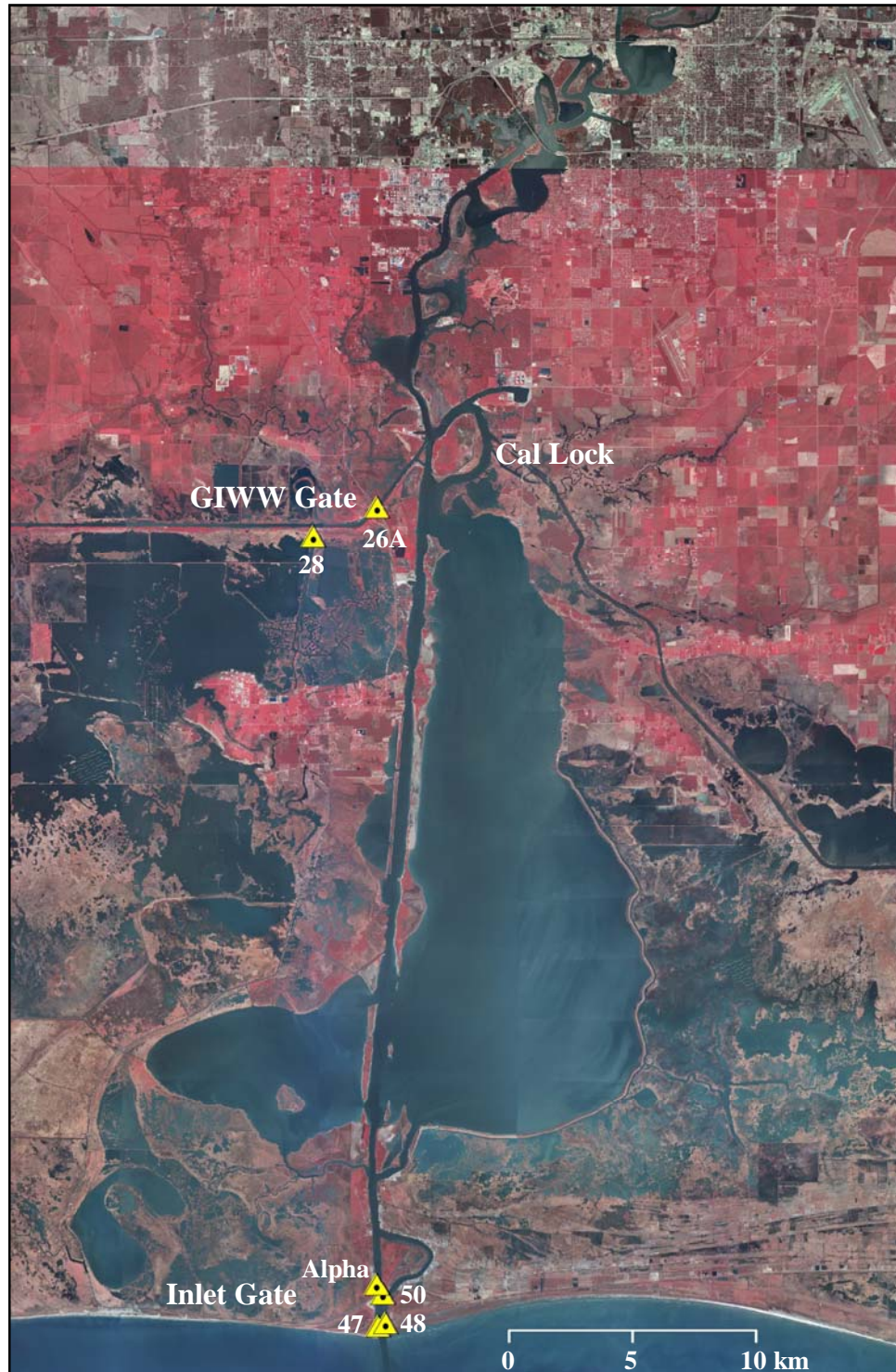


Figure 3.1. Location of the two terminal acoustic gates (inlet and Gulf Intracoastal Waterway, GIWW) used to continuously monitor the emigration of telemetered spotted seatrout from the Calcasieu Lake estuary. Four acoustic receivers (stations Alpha, 50, 47, 48) were deployed at the inlet gate and two receivers (26A, 28) at the GIWW gate. The location of the Calcasieu navigation Lock (“Cal Lock”) is also shown on the map.

freshwater. Although spotted seatrout are a euryhaline species, they probably do not exhibit such behavior which would involve an abrupt shift from salt- to freshwater. A rapid transition to freshwater could be lethal due to increased osmoregulatory costs (Lee et al. 2005; Hyndman and Evans 2009). For example, Serafy et al. (1997) reported 100% mortality of juvenile spotted seatrout exposed to a freshwater pulse in the laboratory.

### Fish Tagging – Telemetry Study

All tagging operations for the Calcasieu Lake telemetry study were conducted in the field. Volunteer anglers from the Coastal Conservation Association (CCA) caught spotted seatrout and transported them to the tagging vessel where fish were held in a flow-through system (~600 L capacity) until processed. Fish in good condition (see chapter 1) were removed from the flow-through system with a rubber-coated net, anesthetized, then measured to the nearest millimeter (standard and total length, TL), and weighed with a motion-corrected electronic scale. Subsequently, I externally tagged, sexed, and surgically implanted acoustic transmitters into fish using methods described in chapter 1. Fish were then placed in the flow-through system to recover from surgery, and if in good condition after 10 minutes, released into the estuary.

Depending on their size, spotted seatrout were implanted with one of two transmitters. Fish larger than 430 mm TL and 700 g were implanted with V13TP-1H transmitters, whereas smaller fish (> 300 mm TL and at least 250 g) were equipped with the smaller V9-2H transmitters. All V9-2H transmitters had a random delay of 150 to 300 seconds and a battery life of approximately 11 months. Most V13TP-1H transmitters had a random delay of 60 to 180 seconds and an approximate battery life of one year. A subset of fish from the spring 2008 release group (see below) were implanted with V13s that had a longer random delay (75 to 225

seconds) and consequently, an extended battery life (~15 months). Only the V13TP-1H transmitters contained sensors (temperature and depth). I assumed telemetered fish were sexually mature because all individuals were larger than reported sizes at sexual maturity (~250 mm TL) (Nieland et al. 2002; Brown-Peterson 2003).

A total of 172 spotted seatrout (300-725 mm TL, 262-3826 g) (Figure 3.2) were equipped with transmitters and released across four tagging events (Table 3.1). Tagging occurred during the spring (April-May) and fall (October) in each of two years, 2007 and 2008 (Table 3.1). Hereafter, the term ‘release group’ refers to all fish released during the same season x year combination (e.g., the spring 2007 release group) (Table 3.1). Most fish were released in the southern portion of the estuary, except during fall 2008, when the majority of fish were released at Commissary Point, which lies along the eastern shoreline in the central portion of the estuary (Figure 3.3).

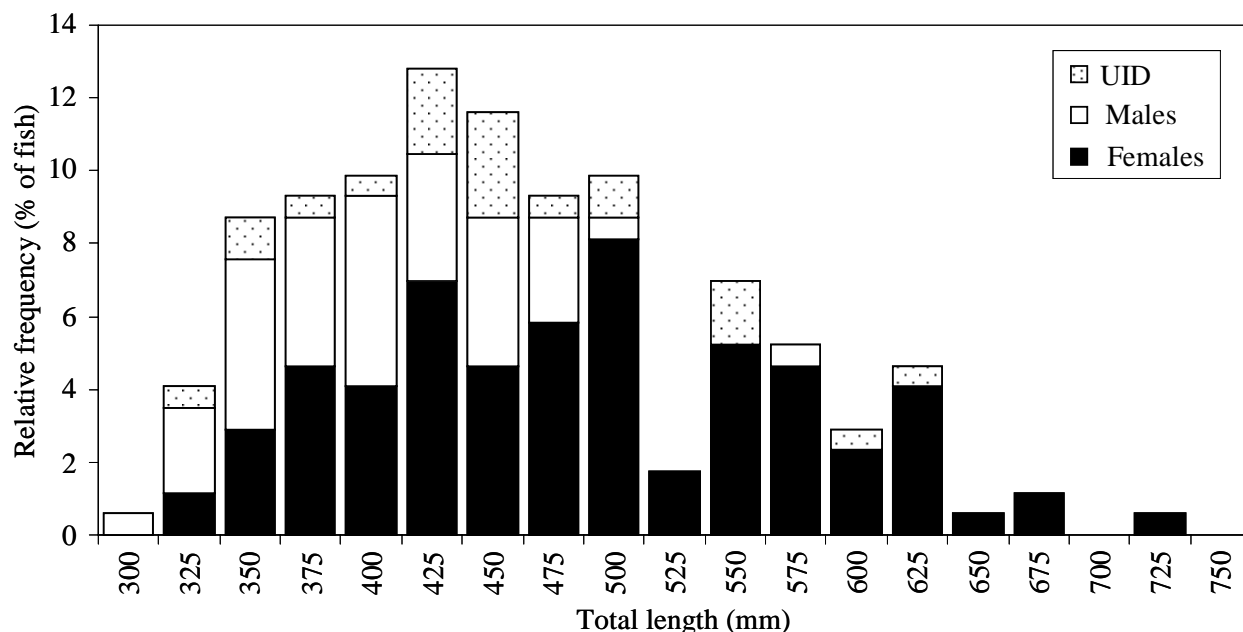


Figure 3.2. Length frequency distribution of telemetered spotted seatrout ( $n = 172$ ). Black bars represent females ( $n = 101$ ), white bars males ( $n = 49$ ), and stippled bars individuals whose sex was undetermined (UID,  $n = 22$ ). Total length values along the x-axis correspond to the upper size limits for each 25 mm size bin (e.g., fish between 476 and 500 mm in length are included in the 500 mm bin).

Table 3.1. Characteristics of telemetered spotted seatrout by release group. Sex-specific values are reported for the number of fish released and their corresponding size range; “UID” refers to fish whose sex was unable to be determined. The number of fish implanted with each transmitter type (within each release group) is also reported. V9=V9-2H transmitters (average random delay of 225 sec, battery life ~11 months), V13 short=V13TP-1H transmitters (average random delay of 120 seconds, battery life ~1 year), and V13 long=V13TP-1H transmitters (average delay of 150 seconds, battery life ~15 months).

Release Group	Release Dates	Females	Males	UID	V9	V13 short	V13 long
Spring 2007	May 9-12, 2007 (n = 51)	33 (358-725 mm)	11 (302-470 mm)	7 (327-609 mm)	25	26	0
Fall 2007	Oct 9-11, 2007 (n = 24)	12 (317-604 mm)	8 (328-452 mm)	4 (420-496 mm)	12	12	0
Spring 2008	Apr 14-20, 2008 (n = 55)	26 (375-658 mm)	23 (300-559 mm)	6 (325-448 mm)	24	14	17
	May 31, 2008 (n = 5)	5 (450-640 mm)	0	0	0	4	1
Fall 2008	Oct 13-15, 2008 (n = 34)	25 (317-545 mm)	6 (303-451 mm)	3 (333-466 mm)	20	14	0
	Dec 12, 2008 (n = 3)	0	1 433 mm	2 (429,591 mm)	0	3	0





Figure 3.3. Release locations for telemetered spotted seatrout. Release groups are color-coded: blue=spring 2007, green=fall 2007, yellow=spring 2008, white=fall 2008. The sizes of circles are a proxy for the number of fish released at each site as indicated in the legend.

## Data Analyses – Telemetry Study

For the purposes of this study, I assumed telemetered fish last detected at either of the terminal acoustic gates (inlet or western GIWW) emigrated from the estuary. I calculated emigration rates by dividing the number of fish that emigrated by the total number ‘available’ to emigrate; converted this ratio to a percentage through multiplication by 100. Based on my holding experiment (chapter 1), mortality associated with the tagging process (fish capture, transport, and surgical implantation of transmitters) was acute and occurred almost exclusively within one week post-capture. Accordingly, only fish detected more than a week after being released and at multiple stations were considered as potential emigrants because these individuals appeared to survive the tagging process and were moving throughout the estuary. As an example of how emigration rates were calculated: if 50 fish from a given release group were detected at least one week post-release and five of those fish subsequently emigrated from the estuary, the emigration rate for that release group would be 10%.

I used multiple logistic regression to evaluate size and sex differences in emigration rates. I only included in this analysis individuals that survived the tagging process and were able to be sexed (n=125). I defined three size (length) classes as follows: small (< 400 mm TL), medium (400-499 mm TL), and large (> 500 mm TL). Sample sizes for certain size x sex combinations were low for some release groups. For example, only four large females were released across both fall tagging events. Therefore, I pooled data across all release groups to generate a contingency table of the number of emigrants and non-emigrants for each of six combinations of size x sex (e.g., large females). Although pooling ensured an adequate sample size for each class combination, overall emigration incidence was low, resulting in small cell counts (often < 5) for the number of emigrants. Thus, it was not appropriate to use large-sample approximations of test

statistics to evaluate hypotheses for model parameters obtained via ordinary maximum likelihood estimation (Agresti 1996). Instead, I used exact logistic regression, a more prudent method for small counts, to test for size and sex differences in emigration rates (Derr 2000; Stokes et al. 2000).

### VR28 Surveys

To explore the possibility that emigrants remained in the immediate vicinity of the inlet, I also conducted manual telemetry surveys with a VR28 system manufactured by VEMCO. The VR28 consisted of a four element directional hydrophone and computer-controlled receiver. The hydrophone was mounted to the starboard corner (stern) of a 9 m vessel. Specifically, a bracket containing a collar was bolted to a metal swimming platform on the transom, and a 2 m aluminum pole bearing the hydrophone was inserted into the collar of the bracket (Figure 3.4). The hydrophone was attached to a plate on the bottom of the aluminum pole. The depth of the hydrophone could be adjusted by raising and lowering the pole via two bolts on the collar (Figure 3.4C). The receiver and computer were housed in the cabin of the vessel (Figure 3.4D). I powered the receiver with an independent 12 VDC marine battery to reduce electromagnetic noise within the system. I also grounded the system by attaching a copper wire to the metal chassis of the receiver and trailing the other end of the wire in the water during transit, as this significantly reduced interference noise (D.M. Webber, VEMCO, personal communication).

Seven VR28 surveys were conducted from July 2008 through July 2009. Survey dates were: July 18, 2008; August 27, 2008; January 26, 2009; March 5, 2009; April 15, 2009; May 29, 2009; July 24, 2009. During each survey, we searched for telemetered fish along the rock jetties that protrude 1.8 km from the shoreline and encompass the inlet (Figure 3.5). During several surveys, we also searched for fish in Cameron Loop (March, April, May 2009) and at a

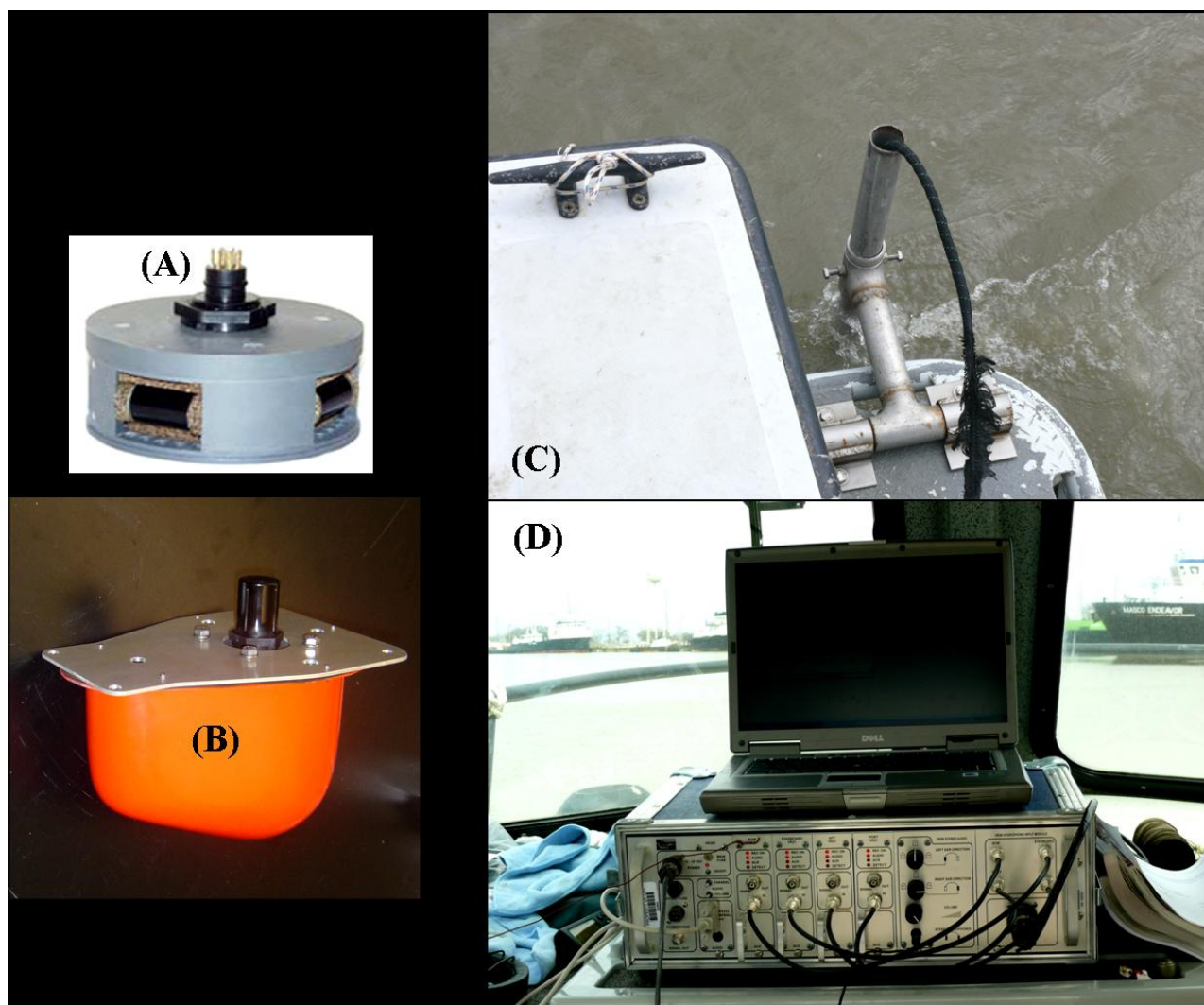


Figure 3.4. VR28 system used for manual telemetry surveys. The (A) hydrophone was enclosed within a (B) protective dome, which was attached to the bottom of an (C) aluminum pole towing assembly while in transit during surveys. (D) The computer-controlled receiver was housed in the cabin of the 9 m tracking vessel.



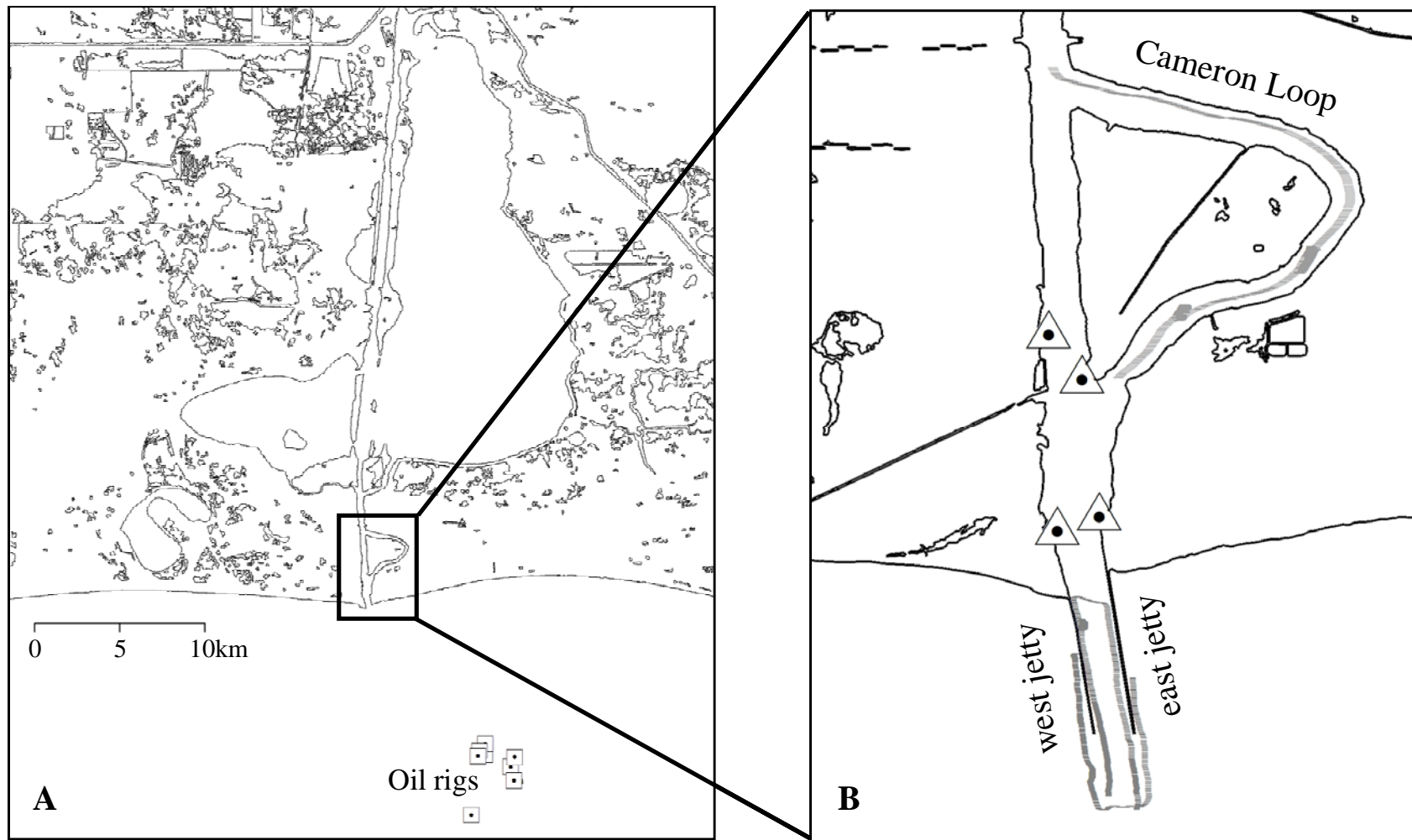


Figure 3.5. (A) Area searched during the VR28 manual telemetry surveys. (B) Vessel tracks (thick gray lines) for the May 2009 VR28 survey. The triangles depict the location of the four stationary receivers that comprised the terminal acoustic gate at the inlet. During each of seven surveys (July 2008–July 2009), I searched for telemetered fish along both sides of the rock jetties encompassing the tidal inlet. Cameron Loop was surveyed in March, April, and May 2009; a complex of oil rigs in the nearshore GOM (10–15 km offshore) was surveyed twice, in May and July 2009.

complex of oil rigs in the nearshore GOM (May, July 2009) (Figure 3.5). A vessel speed of two to three knots was maintained during surveys and only one engine was engaged (port, opposite the hydrophone) to reduce engine noise. If individual pings were heard through the audio output of the receiver, the engine was stopped, and the vessel was allowed to drift for five minutes (maximum transmitter delay) in an attempt to electronically detect the nearby telemetered fish. Successful electronic detection occurred when all eight pings of a given transmission sequence were received by the system. If no fish were detected within five minutes, the vessel was re-positioned to search the area from which the last audible ping(s) emanated. Directional information for each ping was provided as a bearing (in degrees) calculated from the relative signal strengths at each hydrophone element (e.g., port, starboard, bow, and aft). If a fish was successfully detected, the laptop recorded the associated date/time stamps and transmitter identification numbers. I streamed vessel position data (at 10 second intervals) from a hand-held GPS unit (Garmin GPS V) to the laptop computer used to control the VR28 receiver. The clock of the laptop was synchronized with the hand-held GPS; therefore, the time stamps of the two units could be cross-referenced to obtain the spatial position of fish detections. The average detection range of the VR28 was similar to that of the stationary VR2 and VR2W receivers (~250 m) reported in chapter 2.

I used detection data from the VR28 and a pair of buoyed VR2 receivers temporarily deployed at the south end of the jetties to evaluate the detection efficiency of the inlet gate. The VR2 receivers were only operational from May 9 to July 21, 2007 and December 6, 2007 to January 14, 2008, after which time they were retired due to excessive gear loss. Telemetered fish detected at the jetties by the VR28 or temporary VR2 receivers must have passed through the inlet gate to reach the jetties (Figure 3.5). Likewise, fish that returned to the estuary after

being detected at the jetties would also have to pass through the inlet gate. Accordingly, using methods similar to Melnychuk et al. (2007) and Welch et al. (2009), I calculated the detection efficiency of the inlet gate as the proportion of migration events (emigration, immigration) that were successfully recorded by the inlet gate (stations 47, 48, 50, Alpha). I also included in this analysis a telemetered fish that was recaptured in the nearshore GOM (2 km south of the jetties) and kept by the fisherman. This fish was considered to undergo a single emigration event for the purpose of this analysis.

### Conventional Tagging

I utilized conventional tagging data from a volunteer-based tagging program initiated by the CCA in 1987 that remains active today under the auspices of various participants (CCA, LDWF, LSU, and the United States Fish and Wildlife Service). Participating anglers were provided with a tagging kit consisting of plastic-tipped dart tags (HallPrint PDS series, 10 cm length), custom-made applicator needles, data cards, and an instruction sheet. The basic tagging instructions were to insert dart tags just below the dorsal fin between two fin spines (pterygiophores) and gently pull the tag to ensure it was locked in place. Several workshops were also held, mainly after 2004, to train anglers on proper tagging techniques. After tagging and releasing a fish, anglers completed data cards and mailed them to project personnel. Data cards requested the following information: tag number, species, fish length, tagging date and location, fish condition at the time of release, and the angler's identification number. When a tagged fish was recaptured, information (tag number, recapture location, etc.) could be reported to the tagging program by calling the phone number printed on tags. A small reward of \$2.50, indicated on the tag, was given to anglers who provided recapture information.

In the database furnished by project personnel, tagging and recapture locations were classified to the most precise spatial level possible based on information from anglers. The three spatial levels used, in order of increasing precision, were: 1) basin, 2) segment, and 3) latitude/longitude. Anglers supplied GPS coordinates for only 10% of all original records in the database (each fish/tag number was a record). They typically provided more general location information such as water bodies and nearby infrastructure (e.g., bridges, oil rigs/wellheads, and water control structures). Therefore, in an attempt to improve the spatial resolution of this historical data, mapping software (Topozone and Geolocate) was used to locate areas reported by anglers. If a reported tagging or recapture location could be determined within one statute mile, latitude and longitude coordinates were assigned to that record (A.M. Uzee O'Connell, University of New Orleans, personal communication). Otherwise, anglers were re-contacted and sent hardcopy maps to clarify location information. The maps contained one mile by one mile grids, and if an angler could pinpoint the tagging or recapture location within a particular grid, the center point of the grid was assigned as the spatial coordinates (latitude, longitude) for that record. For some records, latitude and longitude coordinates could not be assigned by either geo-referencing method (electronic mapping or re-contacting anglers), and locations for these records were classified to a broader spatial level of segment or basin (Figure 3.6). Spatial boundaries for segments and basins were adopted from the Louisiana Department of Environmental Quality. Basin-level location information was available for all records in the database, and spatial coordinates (latitude, longitude) were available for approximately half of the records. Segment-level information was available for 60% of all records.

I quantified movement distances of recaptured fish for the subset of records that had spatial coordinates for both tagging and recapture locations. Movement distances were

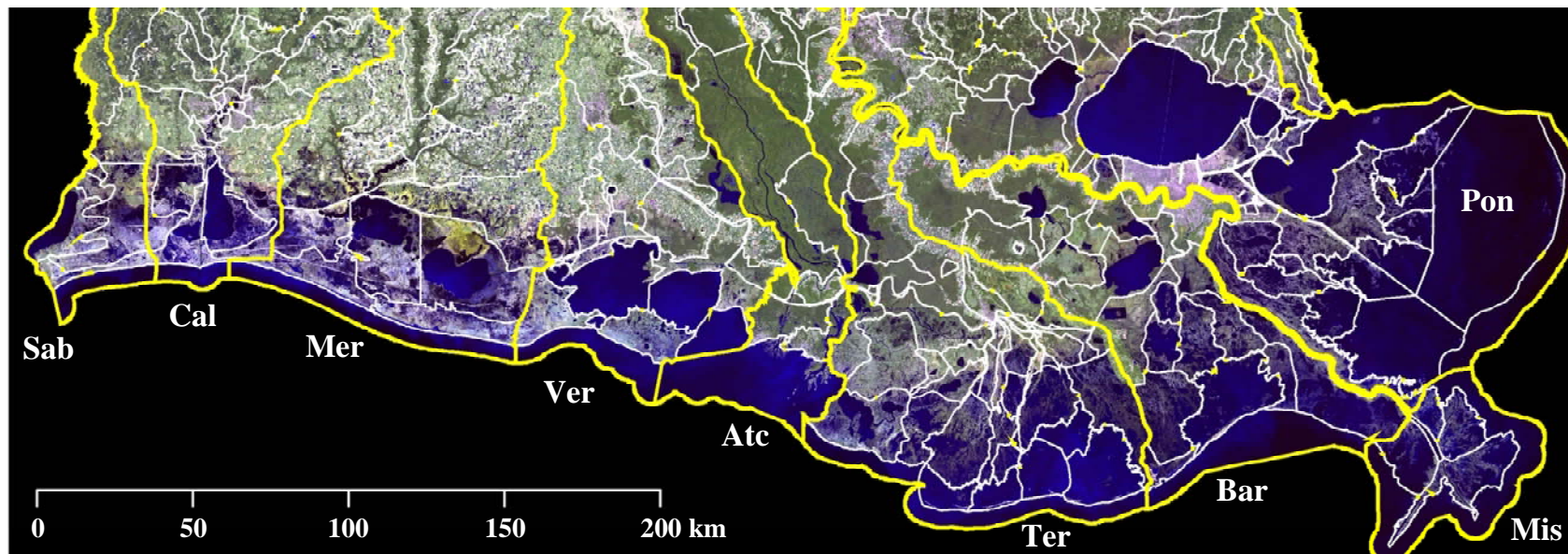


Figure 3.6. Spatial boundaries for basins (yellow) and segments (white) used to classify tagging and recapture locations of conventionally tagged spotted seatrout. Basin names are as follows: Sab = Sabine, Cal = Calcasieu, Ver = Vermilion, Atc = Atchafalaya, Ter = Terrebonne, Bar = Barataria, Mis = Mississippi River, Pon = Pontchartrain. Basin and segment delineations were adopted from the Louisiana Department of Environmental Quality.

calculated in ArcView (ArcMap, version 9.1) as the shortest distance (through water) between tagging and recapture points for each fish. The Louisiana coastline is extremely disarticulated, and this analysis was facilitated by the use high-resolution aerial maps (1 m x 1 m Digital Orthophoto Quarter Quadrangles) overlaid with point shapefiles of infrastructure locations (e.g., bridges, levees) from the United States Army Corps of Engineers and the Louisiana Department of Transportation and Development. To account for the potential spatial error (maximum=1 statute mile) in latitude and longitude coordinates gleaned from the tagging database, I assumed fish with calculated movement distances less than two statute miles (3.2 km) did not move and were recaptured at the same “site” at which they were tagged. As an example, if the distance between tagging and recapture points was calculated as two miles (3.2 km), the actual distance could have essentially been zero if the spatial errors of each coordinate were maximal (1 mile, 1.6 km) and of an opposite direction. Consequently, the minimum separation distance between two points (tagging, recapture) that could be validly interpreted as positive movement was 3.3 km (i.e., > 2 miles), which was greater than twice the maximum potential error for each spatial coordinate.

I performed statistical analyses to examine relationships between movement distance/incidence and days at liberty (DAL). I treated movement incidence as a binary response variable. If a fish moved, it received a positive incidence score of 1, otherwise it was scored as 0 (i.e., no movement). I calculated DAL as the number of days elapsed between tagging and recapture for records that had reliable date information. Date information was considered reliable if dates were available for both tagging and recapture events and the reported recapture date was after the tagging date. For fish recaptured on multiple occasions, I used the initial tagging and terminal recapture dates to calculate DAL as suggested by Patterson et al. (2001).

Similarly, I used initial tagging and terminal recapture locations to calculate movement incidence and distance for multiple recaptures. This method assured statistical independence in that data from the same fish were only included once in a given analysis. I performed negative binomial regression to evaluate the relationship between movement incidence and DAL. For this analysis, I tabulated the number of fish that moved in each of five DAL groups:  $\leq 30$  days, 31-60 days, 61-90 days, 91-150 days, and  $> 150$  days. It was necessary to group the data in this manner so that model fit could be assessed by deviance measures (Agresti, 1996). I chose the negative binomial model for this analysis because it provided a better fit to sample data than logistic or poisson regression. To test the association of movement distance with DAL, I used Spearman correlation because movement distances were not normally distributed. Further, I only included data from fish that moved to avoid a large number of ties (zero movement) in the correlation analysis.

I also tested for seasonal differences in movement incidence. Seasons were defined as follows: winter (December-February), spring (March-May), summer (June-August), and fall (September-November). To ensure that movement information could be assigned to a particular season, I only included data from fish that were tagged and recaptured within the same season (~90 day period). Logistic regression was used to compare movement incidence among seasons. I did not evaluate size effects on movement because data for large fish were sparse. Only 8% of recaptured fish were larger than 400 mm TL at the time of tagging.

## **Results**

### Telemetry

Some of the receivers comprising the inlet gate were lost between servicing trips during the course of this 2.5 year study (May 9, 2007 to October 25, 2009). Station Alpha was

inoperable from May 30 to June 20, 2007; station 47 was inactive from July 21 to September 19, 2007 and April 22 to May 29, 2008. Still, there was always at least one receiver line (Alpha/50 or 47/48) fully operational (i.e., both were receivers monitoring fish passage) at the inlet gate throughout the duration of this study, except for the period August 28 to October 1, 2008. During this period, all receivers in the array were inactive because they were removed from the estuary to prevent gear loss during Hurricanes Gustav and Ike. The acoustic gate at the GIWW was inoperable from September 19 to December 6, 2007 as both receivers constituting this gate (stations 26, 28A) were inactive during this period.

Of the 172 spotted seatrout implanted with transmitters, 146 (85%) were detected more than a week after being released and at multiple stations; thus, appeared to survive the tagging process (Figure 3.7). Of these 146 fish, 26 (17.8%) were last detected at the inlet gate and did not return to the estuary within the battery life of their transmitters. Accordingly, I assumed these 26 fish emigrated from the estuary. Telemetered fish only emigrated via the main tidal inlet, as there were no detections in the GIWW throughout the entire study. Most fish seemed to migrate rather quickly through the inlet gate as the time between initial and final detections was less than 24 hours for 85% of all emigrants. However, two fish were sporadically detected at the inlet gate for one to three weeks before emigrating.

Emigration rates for the 2007 spring and fall release groups were 19.4% (7 of 36 fish) and 18.2% (4 of 22 fish), respectively. For the 2008 spring and fall release groups, emigration rates were 21.8% (12 of 55 fish) and 9.1% (3 of 33 fish), respectively. Interestingly, emigration rates were significantly higher for males (28.9%, 13 of 45 fish) than females (11.3%, 9 of 80 fish) (exact logistic regression,  $p = 0.01$ ), but not significantly different among size classes (exact



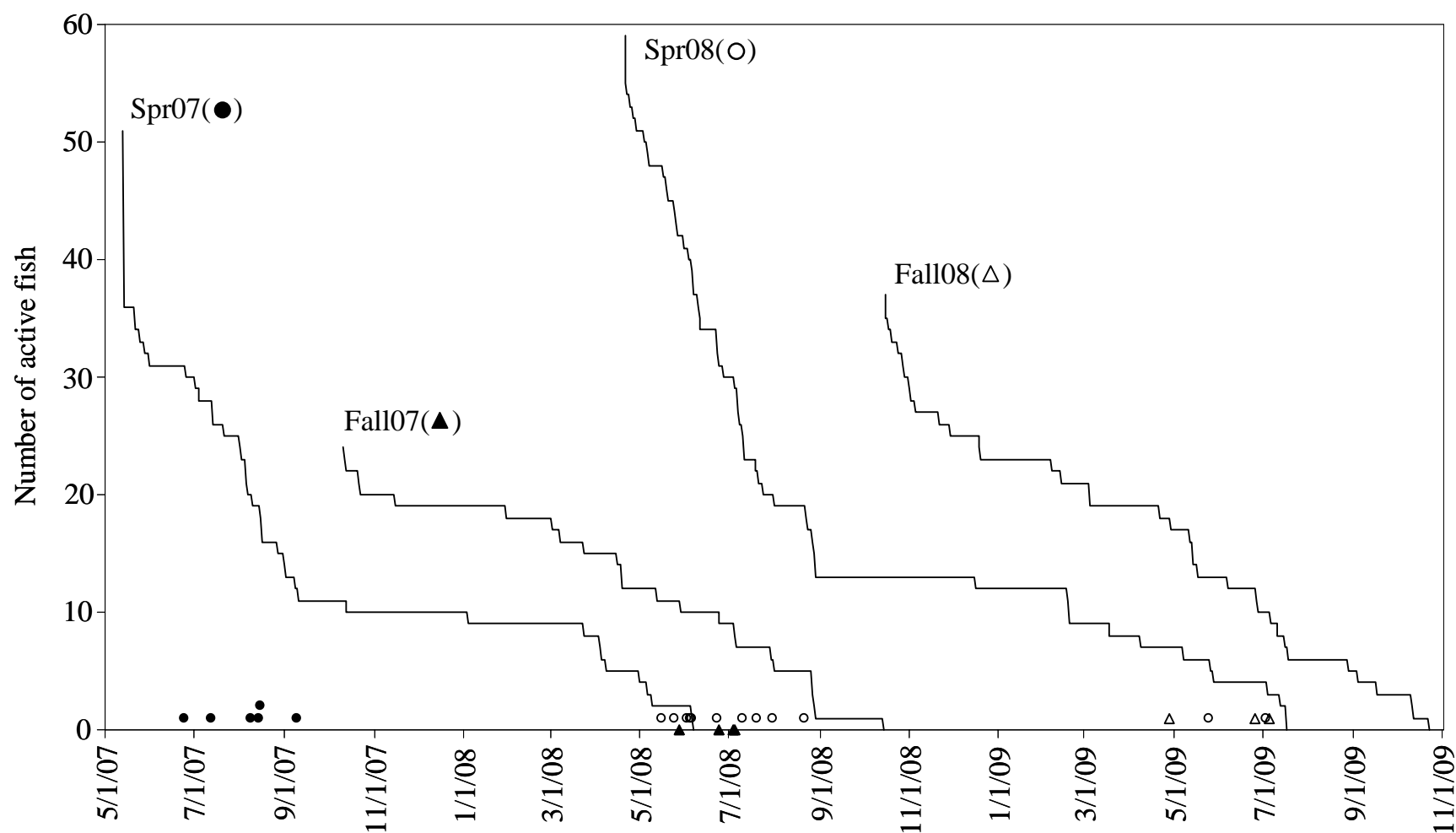


Figure 3.7. Chronology of the number of active fish by release group. A telemetered fish was considered ‘active’ until it was last detected by the stationary receiver array. For example, if a fish released in spring 2007 was last detected on July 15, 2007, it would be considered active only through July 15. The symbols along the x-axis represent the dates on which fish emigrated from the estuary; filled circles depict emigration dates for fish released in spring 2007, filled triangles the fall 2007 release group, open circles the spring 2008 release group, and open triangles the fall 2008 release group. Two fish from the spring 2007 release group emigrated from the estuary on the same day (August 15, 2007), but for all other emigration events, only one telemetered fish emigrated per day.

logistic regression,  $p = 0.30$ ). Based upon the logistic regression analysis, the odds of emigrating were four times higher for males than females (odds ratio = 4.0).

Emigration was highly seasonal and occurred exclusively during summer (late April to early September) across years (Figures 3.7, 3.8). Many fish were detected within the estuary during fall and winter, but surprisingly, no emigration occurred during this period (Figures 3.7, 3.8). For example, 34 fish from the fall release groups (2007, 2008 combined) were detected through the following spring (mid-April), but none of these fish emigrated during the fall or winter (Figure 3.7). Instead, they all appeared to over-winter in the estuary.

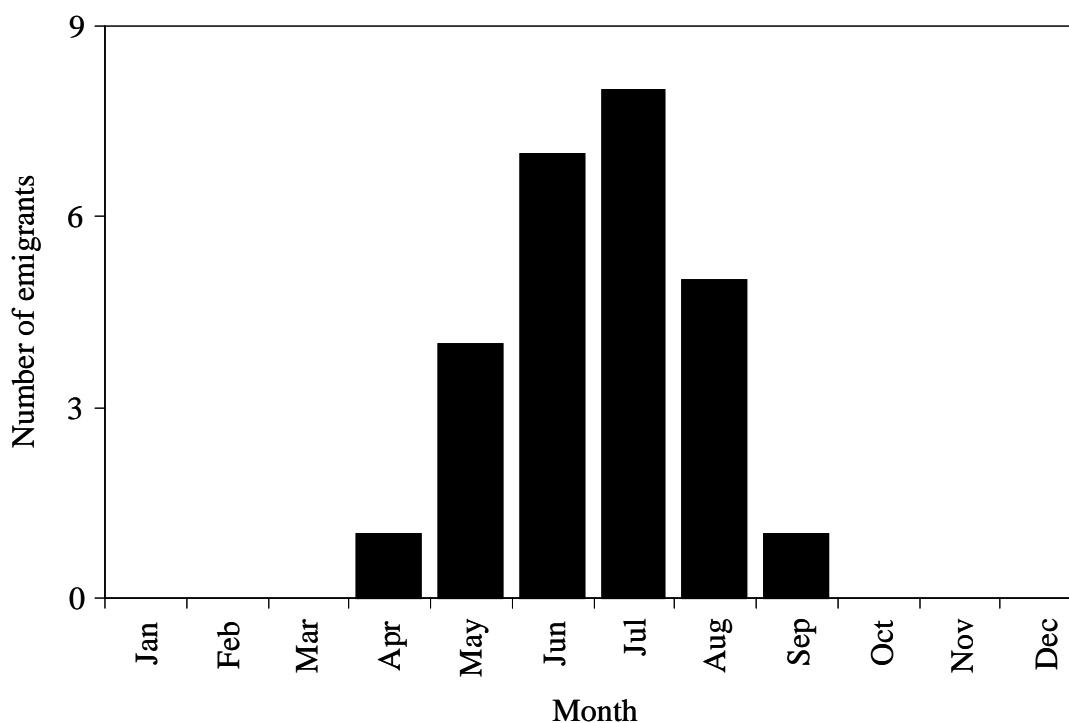


Figure 3.8. Number of spotted seatrout that emigrated from Calcasieu Lake per month. Data were pooled across all release groups ( $n = 146$  fish).

Only three fish were detected during the VR28 manual telemetry surveys. Two of these fish (fish 192, 194) emigrated from the estuary during summer 2008, returned to and remained in the estuary from fall 2008 through spring 2009, and re-emigrated in summer 2009. Both fish were detected at the jetties with the VR28 during summer 2008, and fish 194 was also detected at the jetties in summer 2009 (Figure 3.9). Specifically, fish 192, a 462 mm male, emigrated from the estuary in June 2008, was detected at the jetties with the VR28 in July and August 2008, and subsequently returned to the estuary in early October 2008. This fish re-emigrated from the estuary the following summer, as it was last detected (at the inlet gate) on July 3, 2009. Fish 194, a 477 mm female, emigrated from the estuary in June 2008, was detected at the jetties with the VR28 in August 2008, and subsequently returned to the estuary in early October 2008. This fish re-emigrated the following summer, as it was detected at the inlet gate on May 25, 2009. This individual was then detected four days later at the jetties during the May 29, 2009 survey with the VR28. For the purposes of the emigration analyses presented above, I assumed the emigration dates for fish 192 and 194 were July 3, 2009 and May 25, 2009, respectively. These two fish were exceptions to the general emigration pattern because they returned to the estuary after being detected at the inlet gate, then re-emigrated. Of the 28 fish detected at the inlet gate in this study, most (86%) were never again detected by the receiver array, and presumably left the system.

The other fish located with the VR28, fish 20, a 640 mm female, was found at the same location during each of the three VR28 surveys conducted in Cameron Loop (March, April, and May 2009) (Figure 3.9). I assumed this fish emigrated from the estuary the previous summer because it was last detected by the stationary receiver array (inlet gate, station 50) on July 30, 2008. However, the VR28 data suggested this female died in Cameron Loop (based on

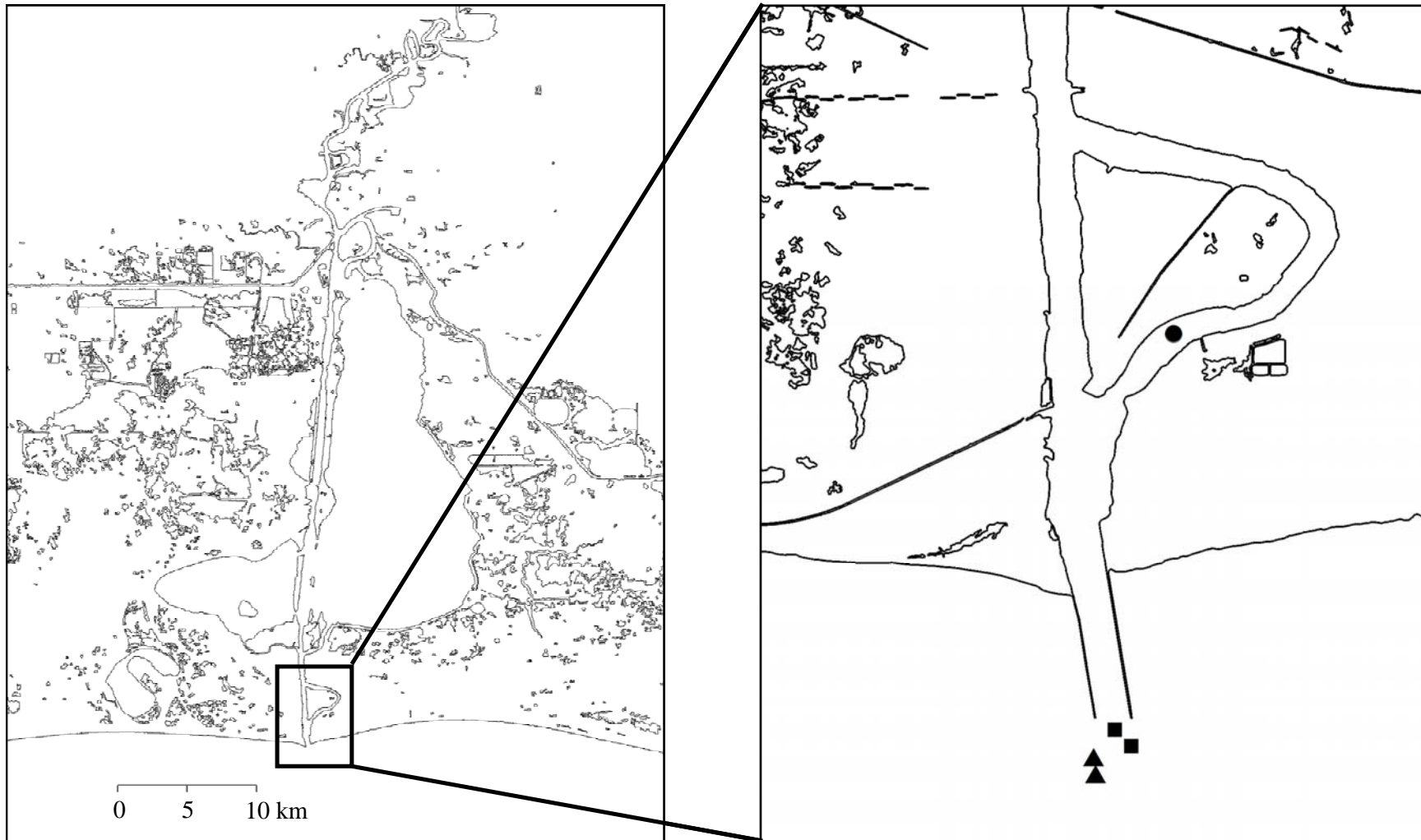


Figure 3.9. Locations of VR28 detections. Three fish were detected with the VR28 system; each symbol corresponds to an individual fish. Fish 20, a 640 mm female, was detected at the same location within Cameron Loop (dots) on three consecutive surveys and was presumed to have died at this location. Two other fish were detected at the jetties encompassing the tidal inlet. Fish 192, a 462 mm male, was detected (squares) at the jetties on July 18, 2008 and August 27, 2008. Fish 194, a 477 mm female, was detected (triangles) at the jetties on August 27, 2008 and May 29, 2009.

consecutive detections at the same location) rather than emigrating. The depth sensor on this transmitter malfunctioned and could not be used to confirm the fish (transmitter) was indeed lying dead on the bottom of the channel.

The overall detection efficiency of the inlet gate was 88% as seven of eight migration events, involving five fish, were successfully detected. Three fish undergoing migration events were implanted with V13s and two with V9s. All six of the migration events of V13-implanted fish were successfully detected and during each migration event, fish were detected at both receiver lines of the inlet gate. One of two migration events involving V9-implanted fish was successfully documented. The V9 migrant was detected at the southern receiver line (stations 47/48) despite the fact that only one receiver was active in this line (station 48) when the emigration occurred. Both receiver lines were fully operational when the V9-implanted fish that was not detected by the inlet gate emigrated from the estuary.

### Conventional Tagging

Across a 20-year period from 1988 to 2008, 29,246 spotted seatrout were tagged and released in Louisiana coastal waters as part of the cooperative tagging program. Tagged fish ranged in length from 150 to 715 mm TL, but most (85%) were between 250 and 375 mm TL (Figure 3.10). Tagging efforts were concentrated in the eastern half of the state; 94% of tagged fish were released from Terrebonne Bay to Chandeleur Sound (Table 3.2, Figure 3.11). Few fish were tagged in the freshwater-dominated Atchafalaya and Mermentau basins, and an intermediate number of fish (~1,600) were tagged in the western portion of the state in Calcasieu Lake (Table 3.2; Figures 3.6, 3.11).

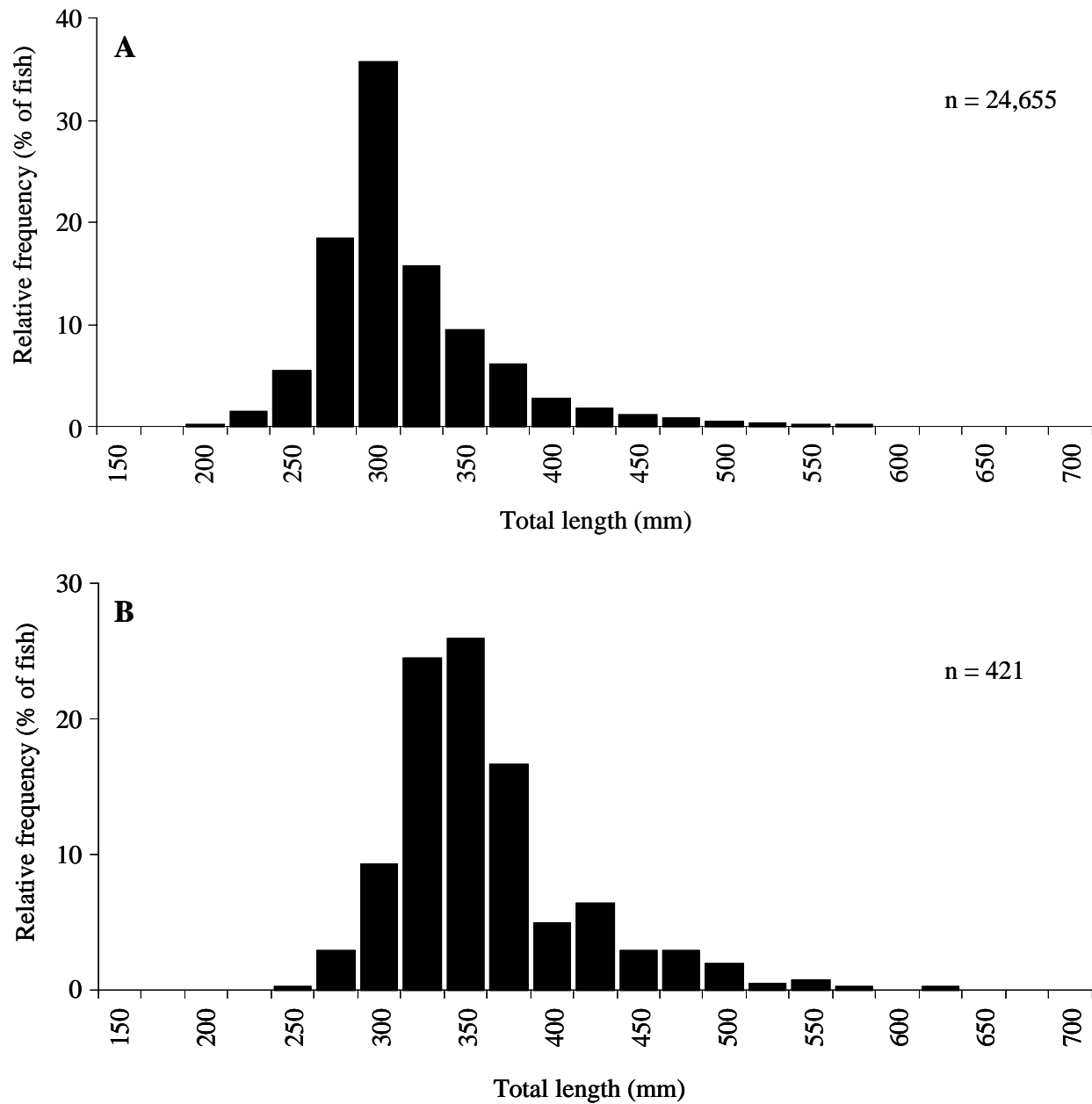


Figure 3.10. Length frequency distributions for (A) tagged and (B) recaptured spotted seatrout. Length information was not available for all fish. Of the 29,246 conventionally tagged spotted seatrout, lengths were available for 24,655 fish (84.3%). Of the 636 recaptures, lengths were available for 421 individuals (66.2%). Total length values along the x-axis correspond to the upper size limits for each 25 mm size bin (e.g., fish between 276 and 300 mm in length are included in the 300 mm bin).

Table 3.2. Total number of spotted seatrout conventionally tagged per basin (1988-2008). See Figure 3.6 for basin delineations.

Basin	Number of fish tagged	% of all tagged fish
Pontchartrain	8122	27.8
Miss. River	4650	15.9
Barataria	9372	32.0
Terrebonne	5346	18.3
Atchafalaya	4	0.01
Vermilion	9	0.3
Mermentau	74	0.03
Calcasieu	1598	5.5
Sabine	71	0.2

Only 2.2% of tagged fish (n=636, 240-610 mm TL) were reported as being recaptured, and five fish were recaptured twice. Few fish were at large for extended periods, as 60 and 80% of recaptures occurred within one and two months post-tagging, respectively (Figure 3.12). The maximum DAL was 385 days. Only one fish was recaptured in another state, a 300 mm individual that was tagged in Chandeleur Sound (LA) and recaptured six months later in nearby Mississippi Sound (MS).

Most fish (94% overall) were recaptured in the same estuarine basin in which they were tagged. Intra-basin recovery rates were 96% or higher for fish tagged in the Pontchartrain, Barataria, Terrebonne, and Calcasieu basins; slightly lower (85%) for fish tagged in the Mississippi River basin, which included the portion of the delta lying southward of Venice (Table 3.3; Figure 3.6). Intra-basin recovery rates were much lower for the Sabine and Vermilion basins (50%), but this was purely an artifact of sample size as only two fish tagged in each of those basins were subsequently recaptured (Table 3.3). One fish from each basin (Sabine, Vermilion) was recaptured in a different basin; hence, the intra-basin recovery rates for

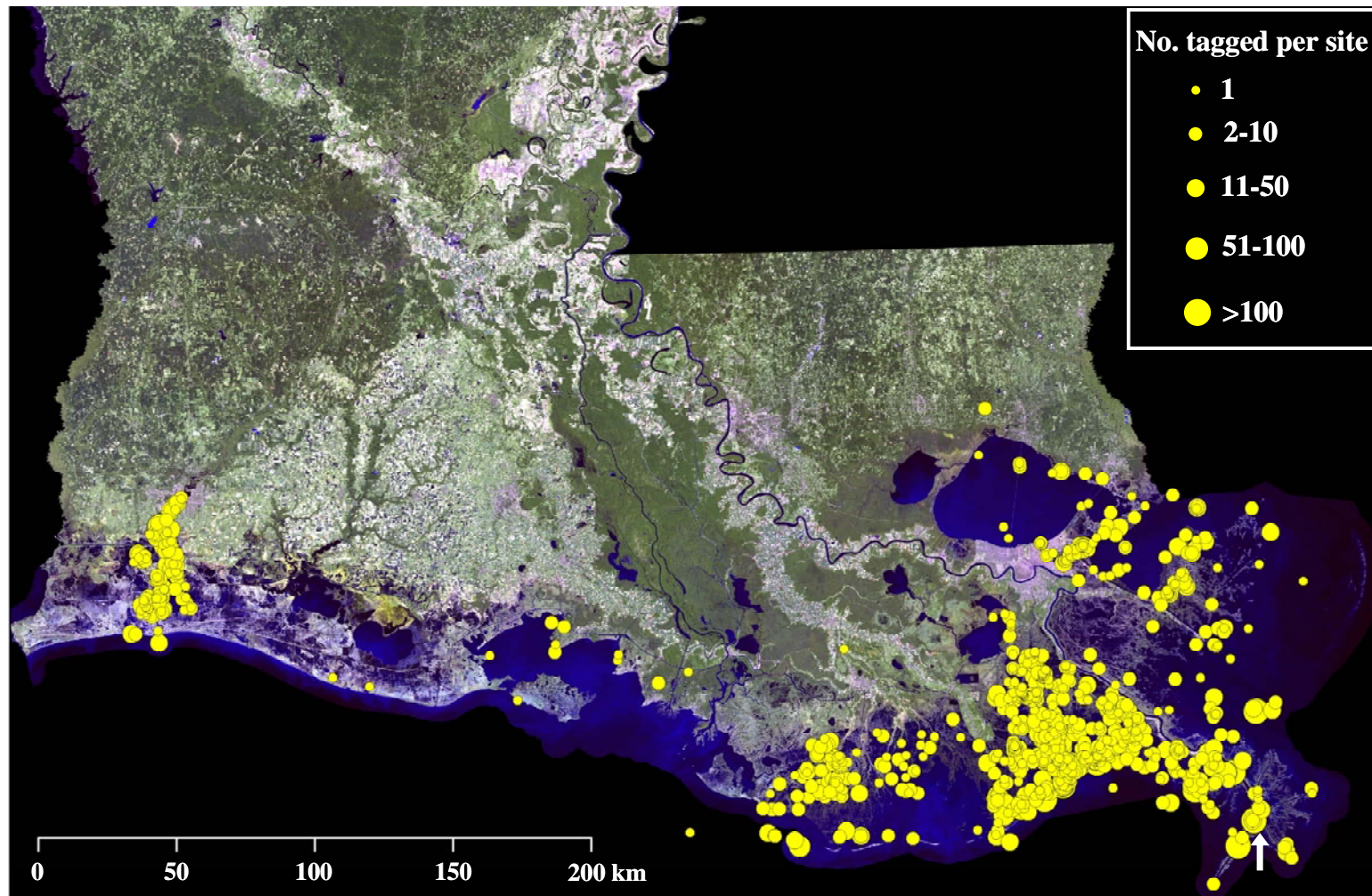


Figure 3.11. Tagging locations for conventionally tagged spotted seatrout. Each yellow dot represents a tagging site (unique spatial coordinates); the sizes of dots are a proxy for the number of fish tagged at each site as indicated in the legend. The site where the most fish were tagged ( $n=2,550$ ) was near the Southwest Pass of the Mississippi River delta and is indicated by the white arrow along the bottom-right corner of the map. Of the 29,246 spotted seatrout that were conventionally tagged, release coordinates (latitude, longitude) were available for 15,140 fish (51.8%).



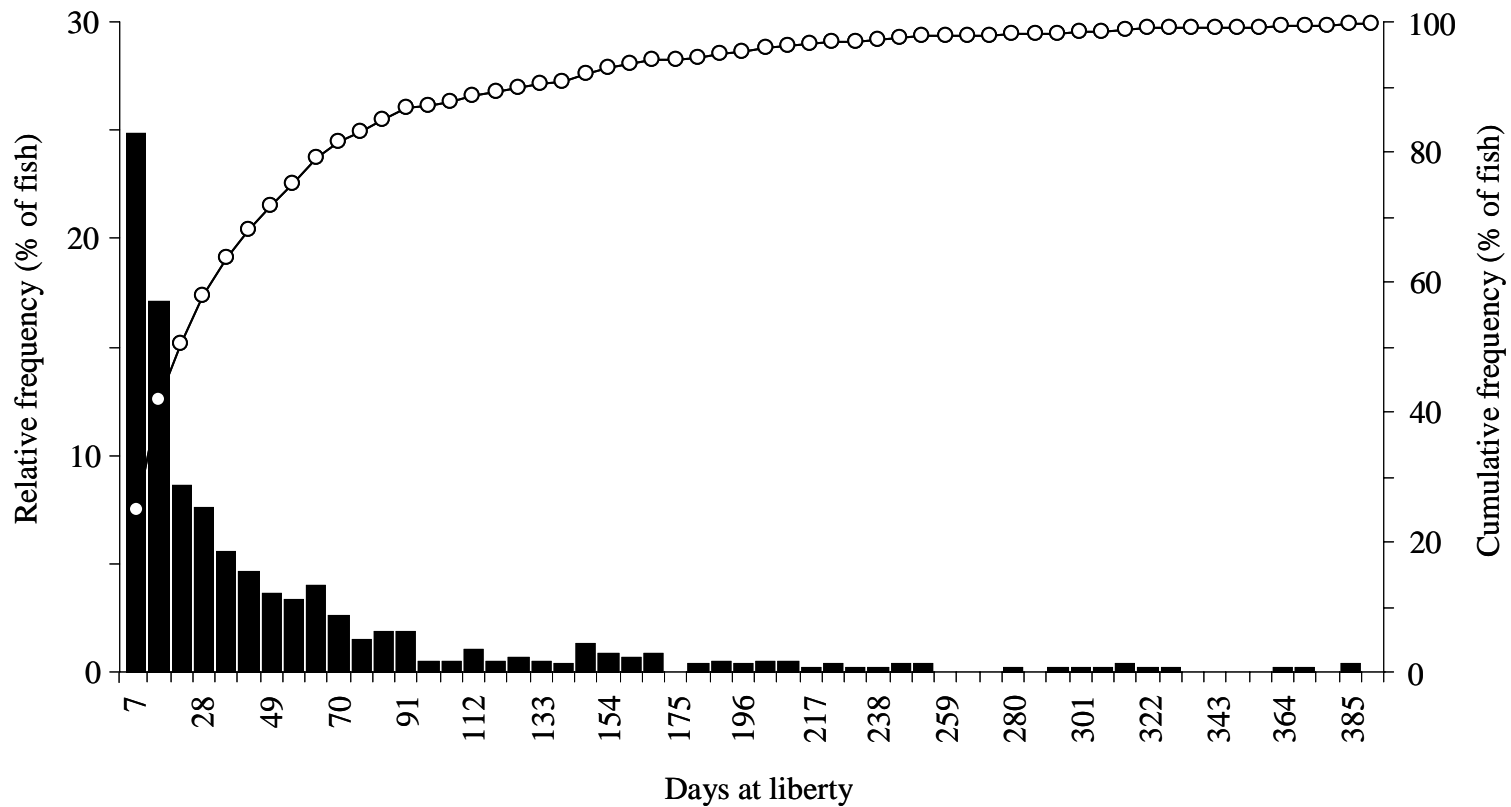


Figure 3.12. Days at liberty (DAL) for recaptured spotted seatrout. Bars illustrate relative frequencies for each 7-day DAL bin, and line with white dots depicts cumulative frequencies. DAL was calculated for the 608 of 636 total recaptures (95.6%) that had reliable date information for both tagging and recapture events.

Table 3.3. Matrix of tagging and recapture locations (basin-level) for the 636 fish reported as recaptures. Rows correspond to tagging basins and columns designate recapture basins. For example, of the 169 fish tagged in the Barataria basin that were later recaptured, 163 (96.4%) were recaptured in that same (Barataria) basin, three were recaptured in the Terrebonne basin (1.9%), two in the Pontchartrain basin (1.2%), and one in the Mississippi River basin (0.6%). Intra-basin recovery rates (along the diagonal of the matrix) are bolded for reference. See Figure 3.6 for basin delineations.

Tagging basin	Recapture basin							
	<u>Sabine</u>	<u>Calcasieu</u>	<u>Mermentau</u>	<u>Vermilion</u>	<u>Terrebonne</u>	<u>Barataria</u>	<u>Miss. River</u>	<u>Pontchartrain</u>
Sabine	1 (50%)	1 (50%)						
Calcasieu	1 (1.6%)	59 (96.7%)	1 (1.6%)					
Mermentau								
Vermilion		1 (50%)		1 (50%)				
Terrebonne					81 (98.8%)			1 (1.2%)
Barataria					3 (1.9%)	163 (96.4%)	1 (0.6%)	2 (1.2%)
Miss. River						16 (10.6%)	127 (84.7%)	7 (4.7%)
Pontchartrain						1 (0.6%)	2 (1.2%)	167 (98.3%)

Sabine and Vermilion were 50% (i.e., one of two fish). No inter-basin movement was observed for the five fish recaptured on multiple occasions.

Movement distances were quantified for the subset of 267 fish that had spatial coordinates (latitude, longitude) for both their tagging and recapture locations. The majority of fish (96%) moved less than 30 km (Figure 3.13). Movement distance was positively correlated with DAL ( $r_s=0.30$ ,  $p<0.0001$ ) (Figure 3.14). Movement incidence also significantly increased with DAL (Wald test,  $p=0.04$ ). Specifically, the negative binomial model predicted higher movement incidence for fish at large more than 90 days (45-75%) than those at large for shorter periods (30-35%). Movement incidence was slightly higher during spring (44%) and summer (30%) than fall and winter (both 17%), but these differences were not statistically significant (Wald test,  $p=0.10$ ).

Although movement appeared to be limited for most fish, several individuals ( $n=7$ , ~1%) moved in excess of 50 km. A 280 mm spotted seatrout tagged in Barataria Bay in March 2004 was recaptured 162 days later (September 2004) in Breton Sound, a distance of at least 120 km that involved an eastward migration across the Mississippi River delta (Figure 3.15). This fish exhibited the greatest movement (~120 km) observed in the study. Two other fish moved at least 100 km, a 550 mm individual that moved from Vermilion Bay to Calcasieu Lake in just sixteen days (June 1999) and a 280 mm fish that moved from Terrebonne Bay to the Pontchartrain basin (no DAL information). Only basin-level information was available for these fish; hence, their tagging and recapture locations are not provided in Figure 3.15. Three fish tagged in the vicinity of the Mississippi River delta moved 55 to 73 km (Figure 3.15). Two of these fish were tagged on the west side of the delta and recaptured 201 and 205 days later in lower Barataria Bay, and the other fish was tagged on the eastern side of the delta and recaptured in upper Breton Sound

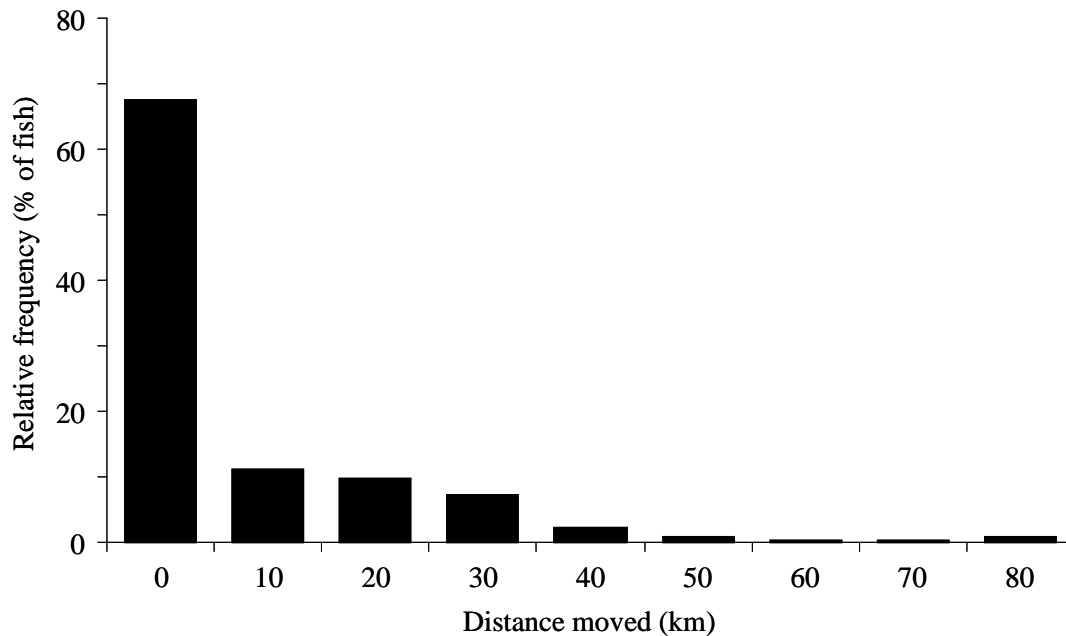


Figure 3.13. Movement distances of recaptured spotted seatrout. Values along the x-axis correspond to the upper size limits for each 10 km distance bin (e.g., fish that moved 11-20 km are included in the 20 km bin). Movement distances were only calculated for records that had spatial information (i.e., latitude and longitude coordinates) for both tagging and recapture locations (n=267 fish).

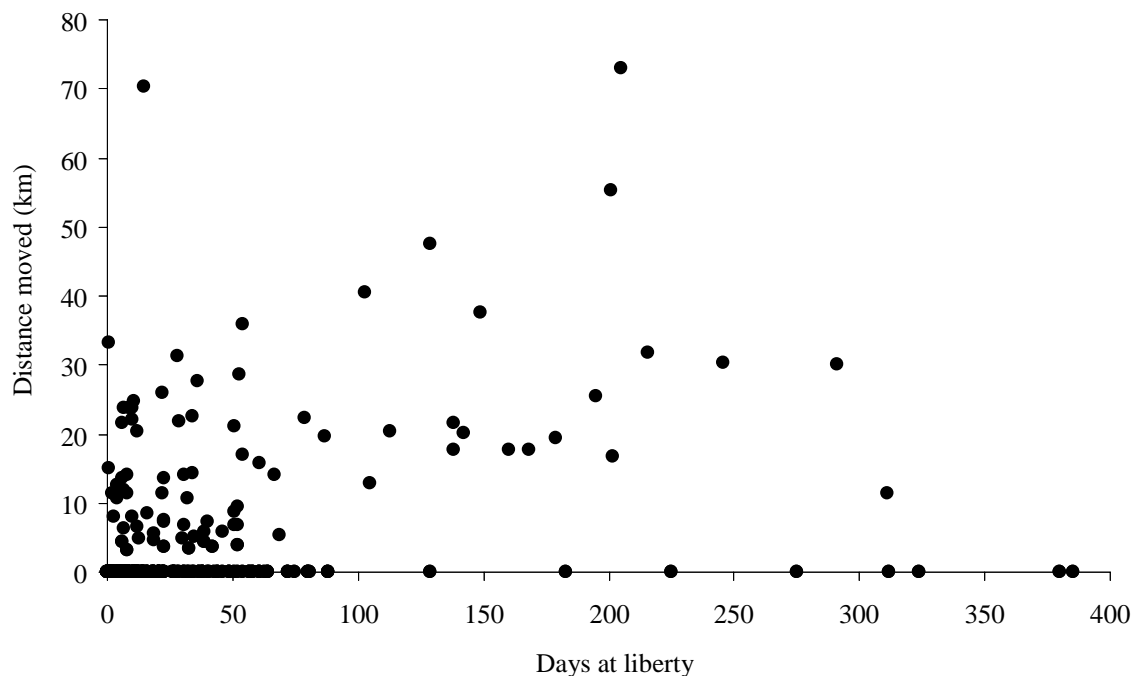


Figure 3.14. Movement distance versus days at liberty for recaptured spotted seatrout. Data is only shown for records that had spatial coordinates and reliable date information for both tagging and recapture events (n=256 fish).

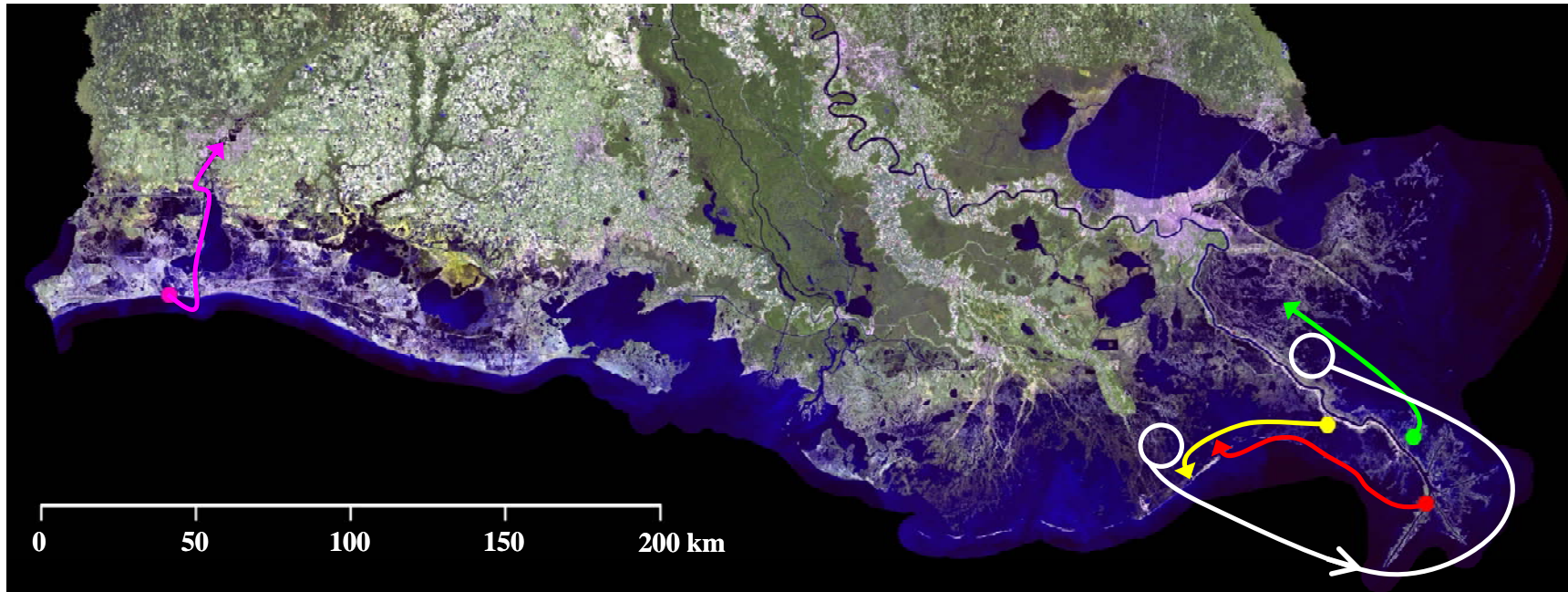


Figure 3.15. Tagging and recapture locations for conventionally tagged spotted seatrout that moved more than 50 km. Four fish had spatial coordinates for both tagging (filled dots) and recapture locations (heads of arrows). For the single fish with only segment-level location information, tagging and recapture segments are indicated by the open white circles; movement direction was east for this individual. See the main text for information on exact distances, days at liberty, and fish size.

(no DAL information) (Figure 3.15). Finally, a 280 mm spotted seatrout tagged in the nearshore GOM (August 1994) moved 70 km north to upper Calcasieu Lake in 15 days (Figure 3.15).

## **Discussion**

I conducted the first biotelemetry study on spotted seatrout in Louisiana coastal waters and analyzed conventional tagging data from the most intensive state tagging effort to date for this species. Results from these two approaches generally corroborated one another, but the telemetry technique in particular afforded novel information on the movement patterns of adult spotted seatrout. For instance, the telemetry study demonstrated that many adults were resident year-round within an individual estuarine system (Calcasieu Lake) that is indeed a very small portion ( $< 10\%$ ) of the Louisiana coast. Nevertheless, approximately 30% of males and 10% of females emigrated from the estuary during summer (across years) to the nearshore GOM and may have undertaken large-scale migrations to other areas within or beyond coastal Louisiana. Conventional tagging data indicated such large-scale movements ( $> 100$  km) were rare ( $< 1\%$  of tagged fish); however, tag return rates were disappointingly low ( $\sim 2\%$ ) and provided mostly short-term ( $< 2$  months) movement information. Collectively, my results indicate that spotted seatrout exhibit rather limited movements as adults, which despite their unknown natal and nursery origins, suggests that spatial (stock) structure occurs at a finer scale than is currently assumed in the assessment and management of this very important recreational species.

### **Conventional Tagging Data**

Conventional tagging data were of limited utility due to low return rates, mostly short-term recoveries, and dearth of data for larger fish. The fact that no spotted seatrout were recovered beyond 13 months post-tagging was surprising given that individuals to four years of age are common in coastal Louisiana (Wieting 1989; Nieland et al. 2002). Most tagged fish

were small (< 400 mm TL) and presumably only one or two years old, at least the females (Nieland et al. 2002). Accordingly, some tagged fish should have survived more than one year and been available for capture up to two to three years post-tagging. Instead, the temporal trend in tag returns (i.e., no fish recaptured beyond 385 days) suggested that total annual mortality was essentially 100%, which is obviously unrealistic. Even if total mortality neared 100% per annum for adult fish, tag return rates should have been much higher than 2% under such a scenario.

The mostly likely explanation for the short-term nature of tag recoveries is tag loss, which appeared to be a serious problem in this study. I provided direct evidence of tag loss in my holding experiment, in which c. 40% of fish shed their dart tags beginning at two weeks post-tagging (see chapter 1). These results are commensurate with the observed temporal trends in tag recoveries as 42% of all recoveries occurred within the first two weeks post-tagging, after which returns declined precipitously and were rare beyond 100 days (< 13% of all recaptures) (Figure 3.12). Hendon et al. (2002) observed a similar trend in tag returns from a cooperative tagging program in Mississippi that also utilized dart tags. In their study, 67% of spotted seatrout were recovered within one month post-tagging, and no recaptures occurred beyond 14 months (Hendon et al. 2002). Longer-term recoveries (i.e., days at large) and higher return rates have been reported for spotted seatrout tagged with internal (abdominal) anchor tags. Across studies, return rates for internal anchor tags ranged from 8 to 25% and recoveries of fish at large more than one year were common, with numerous individuals being recaptured two to three years later (Moffett 1961; Iversen and Moffett 1962; McEachron and Matlock 1980; Overstreet 1983; Baker et al. 1986; Woodward 1990; Baker and Matlock 1993). These results imply higher tag retention for internal anchor tags than dart tags. Nevertheless, all of the studies employing internal anchor tags were part of ‘scientific’ tagging programs in which scientists and biologists

from universities and governmental agencies inserted tags into fish. Meanwhile, both studies analyzing data from dart-tagged fish (this study and Hendon et al. 2002) were part of ‘cooperative’ tagging programs that relied on volunteer anglers (of varying skill levels) to apply tags. Hence, tag return statistics cannot be directly compared among studies to infer retention differences between tag types (i.e., dart tag vs. internal anchor tag) because tag type is confounded with tagger skill level. For instance, the apparent higher retention of internal anchor tags is probably due in part to the higher experience level of taggers in those studies. To unequivocally determine if internal anchor tags (or other tag types) have superior retention in spotted seatrout relative to dart tags, a long-term (at least six months) holding experiment should be coupled with a field-based double-tagging study to compare retention rates across tag types while controlling for tagger skill level. If tag retention is found to be substantially higher for a given tag type, the Louisiana Cooperative Marine Sportfish Tagging Program should consider adopting that tag type to improve the quality of data gleaned from its program. One complicating factor of switching to internal anchor tags may be the increased difficulty of inserting these tags as they require a small incision in the body wall of the fish. If this is an issue, a subset of more experienced and dedicated taggers (e.g., program participants who tag hundreds of fish per year) could be persuaded and trained to tag fish with internal anchor tags.

The movement potential of spotted seatrout was likely underestimated in this study due to the short-term nature of tag recoveries associated primarily with tag loss. Many fish reported as being recaptured were probably not at liberty for long enough periods to undertake long-distance movements (Fritsch et al. 2007; Righton et al. 2007). For example, at least 105 days would be required to traverse the entire Louisiana coastline (600 km) based on the maximum observed movement rate ( $5.7 \text{ km d}^{-1}$ ) of conventionally tagged fish. Yet, only 13% of tag recoveries



(n=76) occurred more than 100 days after tagging. Consequently, movement parameters based on the entire dataset are probably biased low, especially given the significant positive relationships between movement incidence/distance and days at liberty. Conditioning the dataset by only considering individuals that were theoretically at large for long enough periods (> 100 days) to move greater distances provides a more valid assessment of large-scale movement potential. For instance, of the 27 fish at liberty for more than 100 days whose movement distances could be quantified, only two fish (7.4%) moved more than 50 km (55 and 73 km). For the remaining 49 fish at large 100 days or more, only broader-level location information (basin, segment) was available. Still, only one of these individuals was recaptured in a basin non-adjacent to its tagging basin, a distance of approximately 120 km. While these results suggest minimal mixing of adults along the Louisiana coast, population-level inferences are tempered by the low sample size of fish at liberty for extended periods (n=76 total, maximum number per tagging basin=22).

Despite sample size issues, my results are very similar to previous tagging studies for spotted seatrout in Louisiana and other regions of the northern GOM. Of the 627 recaptures of fish tagged in Louisiana from the 1970s to mid-1980s, only two fish (0.3%) were recovered more than 50 km from their tagging sites (Rogillio 1975; Adkins 1979; Rogillio 1980; Rogillio 1985; Arnoldi 1985). Both of these fish moved from Calcasieu Lake to Vermilion Bay (Marsh Island), a distance of approximately 170 km (Arnoldi 1985). Similarly, in Mississippi, only 3 of 408 recaptured fish (0.7%) moved greater than 50 km (maximum=60 km) (Hendon et al. 2002). Likewise, in Texas and Florida, less than 5% of recaptured fish moved more than 50 km (230 and 413 total recaptures in TX and FL, respectively) (Moffett 1961; Iversen and Tabb 1962; Baker et al. 1986; Baker and Matlock 1993). Collectively, these tagging data indicate that

large-scale movements are rare for adult spotted seatrout inhabiting estuaries and coastal waters of the northern GOM as only 1.7% of all tag recoveries (34 of 1950 fish, across studies) occurred more than 50 km from tagging sites. Still, some individuals moved considerable distances (> 100 km) that would promote the exchange of adults among estuaries and coastal regions. For example, a spotted seatrout tagged in Apalachicola Bay, Florida was recaptured 233 days later at Grand Isle, Louisiana, a remarkable distance of 500 km which is the greatest movement distance recorded for this species (Moffett 1961). Precise quantification of the occurrence of such long-distance movements is necessary to delineate stock structure. Yet, movement distances and mixing rates (between areas) based upon conventional tagging data can be biased. Fishermen typically provide the majority of tag returns in a conventional tagging program (i.e., data are fishery-dependent). Therefore, if spatio-temporal differences in fishing effort or fisher reporting rates exist throughout the study area, movement rates can be biased (Hilborn 1990; Gillanders et al. 2001). For example, movement can be positively biased towards areas with higher fishing effort or angler reporting rates. Movement rates can be corrected for heterogeneous fishing effort (Hilborn 1990; Wang et al. 2007), but this requires reliable effort data, which was not available in this study, nor is it common for the diffuse recreational fisheries that were relied upon to provide tag returns. Green et al. (1983) found that tag-reporting rates for spotted seatrout in Texas were typically 35-40% and exhibited little spatio-temporal variation; however, no such information is available for Louisiana waters. Thus, it was not possible to correct tagging data for differential fishing effort or reporting rates. More importantly, conventional tagging is a cross-sectional (vs. longitudinal) approach in that fish positions are only known at two discrete points in time, tagging and recapture. A fish could be tagged and recaptured at the same location, but undergo substantial movement during the interim, especially if the fish is at

liberty for extended periods (Klimley et al. 1998; Bolle et al. 2005). Accordingly, conventional tagging data may underestimate the degree of fish movement.

#### Emigration from Calcasieu Lake

A major advantage of remote acoustic telemetry over conventional tagging is the ability to continuously monitor the movements and behavior of aquatic organisms. I used this technology to quantify fish emigration from Calcasieu Lake, an estuarine system in southwest Louisiana. This system is rather unique, at least in the northern GOM, because there are only two narrow exit points from the estuary. I deployed acoustic receivers (gates) at these two exit routes to continuously monitor emigration dynamics. To undergo a long-distance migration, a fish must obviously leave its current area before reaching another destination (e.g., another estuary or coastal region of the northern GOM). Therefore, all telemetered fish that emigrated from Calcasieu Lake and potentially moved substantial distances should have been detected at one of the terminal acoustic gates as they left the estuary.

Overall emigration rates were rather low (~18%), yet strong seasonal and sex trends were evident whereby emigration occurred exclusively during summer and males showed a greater tendency to emigrate than females. The fact that emigration was seasonally confined could simply be due to higher activity levels during the summer associated with spawning and feeding. Spotted seatrout spawn from April through September in Louisiana (Helser et al. 1993; Saucier and Baltz 1993; Nieland et al. 2002). Energetic costs are highest during the summer spawning season because routine metabolic rates are at a maximum (due to warm temperatures) and reproductive costs are high (e.g., egg development in females and drumming behavior in males) (Vetter 1982). Thus, fish probably feed more often in the summer to fuel this higher energetic demand in addition to making excursions to spawning sites. It is possible the emigration

observed in this study was due to such behavior, whereby in the process of seeking more optimal foraging and/or spawning habitats, fish passed through the lower ship channel and arrived in the nearshore GOM, where they may have remained, upon finding suitable habitat, or otherwise, moved to another estuarine system (e.g., Sabine Lake or Vermilion Bay). In addition, males may be more ‘exploratory’ than females and spawn at numerous locations within the same spawning season. This proclivity for exploration could explain the three-fold higher emigration rates for males (~30%) relative to females (~10%).

Spotted seatrout do not appear to undertake a seasonal migration from estuarine waters to the nearshore GOM in the fall or winter to escape cold water temperatures as hypothesized by previous researchers (Arnoldi 1985; Baker et al. 1986). In my 2.5 year study, no emigration occurred during fall or winter, yet fish were frequently detected in the estuary during winter. Thus, my results suggest that adult spotted seatrout primarily over-winter in inshore estuarine waters, not the nearshore GOM, and this may be true in other systems of the northern GOM which lie along the same latitudinal band as Calcasieu Lake (i.e., western Florida to eastern Texas). During a 15-year period from 1997 to 2011, mean winter (December-February) water temperatures in Calcasieu Lake were 13.8°C, and temperatures were generally above 10°C (93% of all daily measurements, <http://waterdata.usgs.gov/nwis>). Hence, winter temperatures in northern GOM estuaries are probably consistently warm enough such that spotted seatrout inhabiting this region have not evolved a seasonal migration (i.e., fall/winter emigration to the more thermally stable, warmer waters of the nearshore GOM) as part of their life history strategy. The tendency for spotted seatrout to remain and over-winter in inshore waters may explain the mortalities of this species that are often observed in estuaries during abnormally cold winters and episodic hard-freezes (McEachron et al. 1994). Winter emigration is probably more

common for spotted seatrout occurring in the northern portion of their range in estuaries and coastal regions of the Mid-Atlantic Bight (Cape Cod to Cape Hatteras) where winter temperatures are much colder and frequently below 5°C (Mercer 1984; Able and Fahay 1998; Able and Grothues 2007). If so, cyclic migrations to more suitable (warmer) over-wintering grounds that are geographically disparate from summer feeding areas could facilitate the mixing of adults between the Mid- and South-Atlantic Bights and lead to larger stock boundaries than in the northern GOM where extensive seasonal migrations do not appear to be common for this species.

I made several assumptions in calculating emigration rates, the violation of which could bias rate estimates. The key assumption in this study was that all emigrants were detected at a terminal acoustic gate as they left the estuary. To test this assumption, I calculated the detection efficiency of the acoustic gate at the inlet using opportunistic data from telemetered fish that were known to have passed through this gate. Although this analysis was based on just eight migration events, it suggested the overall detection efficiency of the inlet gate was quite high (88%). Extensive range testing also indicated the inlet gate was highly efficient (85%) in detecting towed transmitters (see chapter 2). Thus, it seems likely that the majority of emigrants were detected by the inlet gate as they left the estuary. Emigration rates could be negatively biased if some fish left the estuary when the terminal acoustic gates were inactive. The inlet gate was inactive for one month (September 2008) during the passages of Hurricanes Gustav and Ike. However, there did not appear to be a ‘permanent’ mass emigration due to these two hurricanes, one of which (Ike) made landfall as a strong category two storm in nearby Galveston Bay, Texas. As evidence, 13 of the 19 telemetered fish from the spring 2008 release group that were detected through August 21 (one week before receivers were removed) were also detected in the estuary

after the receiver array was re-deployed in early October (Figure 3.7). The terminal acoustic gate in the GIWW was inactive for a 2.5 month period (September 19 to December 6, 2007), but this area did not appear to be an important migration corridor as there were no fish detections at this gate during the 789 days its receivers were active.

The possible slight underestimation of emigration rates due to the above scenarios may have been partially offset by several factors that caused emigration to be overestimated. I assumed all telemetered fish that were last detected at a terminal acoustic gate emigrated from the estuary. However, some fish, instead of emigrating, may have remained (undetected) in areas just interior to the terminal acoustic gates for the remainder of their battery lives, in which case emigration rates would be positively biased. For instance, some fish detected at the inlet gate may have remained in the lower ship channel between the inlet gate and the nearest estuarine receivers, a distance of approximately 7 km that lacked receiver coverage (see Figure 2.2). Furthermore, it is possible that some transmitters detected at a terminal acoustic gate were in the stomachs of predators that consumed telemetered fish and had not yet excreted the ingested transmitter. In this situation, predator movement would be misinterpreted as emigration of a study subject, causing emigration rates to be overestimated. Interestingly, the temperature transmission from one presumed emigrant as it passed through the inlet gate was 8°C above the ambient water temperature (37.3 vs. 29°C) and matched the reported stomach temperature of marine mammals (~37°C, Bendall and Moore 2008). Hence, this transmitter was probably in the stomach of a bottlenose dolphin, a common marine mammal in Calcasieu Lake.

#### Stock Structure and Management Implications

Dispersal potential is likely highest during the adult stage in spotted seatrout. Adults have increased swimming capabilities and a much longer stage duration (years) than eggs (< 24

hours), larvae (2-3 weeks), and juveniles (6-12 months); and thus, possess a greater opportunity for dispersal. Significant larval dispersal could result from spawning in offshore waters of the GOM. For example, larvae spawned in offshore waters (e.g., 5-30 km from shore) west of the delta could be passively advected 120 km alongshore in the westward-flowing Louisiana Coastal Current assuming a mean current speed of  $10 \text{ cm s}^{-1}$  (Shaw et al. 1985; Wiseman et al. 1997; Zavala-Hidalgo et al. 2003) and an average larval stage duration of two weeks (Fable et al. 1978; Peebles and Tolley 1988). However, most spawning is thought to occur within or in close proximity to estuaries (Peebles and Tolley 1988; Walters et al. 2009), the progeny from which are probably retained in estuarine habitats rather than being transported long distances. Intense spawning activity has been found at tidal inlets (passes) that connect estuaries to the nearshore GOM (Saucier and Baltz 1993; Lowerre-Barbieri et al. 2009). Larvae spawned in the vicinity of these habitats (tidal inlets) should generally experience net landward transport (i.e., towards the estuary vs. the GOM), regardless of tidal state at the time of spawning, because the duration of flood tides is typically 1.5 to 2 times longer than ebb tides in estuaries along the northern GOM, especially in bottom waters where spawning is reported to occur (Lyczkowski-Shultz et al. 1990). Thus, most estuarine recruits (larvae, juveniles) probably originate from local versus distant spawning.

Despite their mobility and capacity for dispersal, I found little evidence of large-scale movements of adult spotted seatrout. Annual emigration rates from Calcasieu Lake were low and ranged from 9 to 22% across release groups. Hence, most fish (80-90%) remained in the estuary for extended periods rather than emigrating. Many individuals (non-emigrants) disappeared (i.e., were last detected) within the estuary before their transmitter batteries hypothetically expired (i.e., < 300 days post-release) (Figure 3.7). These fish were presumably

harvested (and not reported), died of natural causes (e.g., predation, senescence), or remained alive, but utilized areas of the estuary without receiver coverage. Still, some individuals were known to be alive (based on movement patterns) for nearly the entire life of their transmitters. For instance, 32 fish were active for 293 to 457 days and never emigrated from the estuary, providing unprecedented evidence of long-term (annual) residence of adults within an individual estuarine system in the northern GOM. It is unknown if spotted seatrout exhibit high annual residency in other Louisiana estuaries which are generally too large and geomorphologically complex (many entry/exit points) to feasibly conduct investigations of migration dynamics using currently available biotelemetry technology, with the exception of Sabine Lake and possibly Lake Pontchartrain. Nevertheless, the high intra-basin recovery rates ( $> 96\%$ ) and limited movements (98% of fish moved  $< 50$  km) indicated by the state-wide conventional tagging data support the notion that estuarine residency (fidelity) is similarly high in other systems throughout coastal Louisiana.

Although the movement range of adults appears to be limited, genetic divergence (isolation-by-distance) in spotted seatrout has only been found at large spatial scales of 500 to 1,000 km in the northern GOM (Ramsey and Wakeman 1987; King and Pate 1992; Gold and Richardson 1998; Ward et al. 2007; Anderson and Karel 2009). This disparity can be explained by the fact that historical exchange of just a few spawning individuals among areas on a generational time scale can lead to genetic homogeneity across large sampling domains. For example, if 1 to 5% of adults move to and spawn in non-natal estuaries, this low exchange rate would be sufficient to preclude genetic divergence (Ward 2000; Jennings et al. 2001). Hence, the low inter-basin exchange rates I observed in this study ( $\sim 2\text{-}4\%$ , based on conventional tagging data) would be theoretically sufficient to promote genetic homogeneity in spotted



seatrout throughout coastal Louisiana. This example highlights a common limitation in using genetic data to delineate practical management units for coastal and marine fisheries because significant spatial structure often exists across geographic areas from which samples are deemed genetically similar (Pawson and Jennings 1996; Thorrold et al. 2001). Specifically, the low mixing rates (i.e., < 10%) rendering putative subpopulations genetically homogenous are negligible from a pragmatic management standpoint because under such limited exchange subpopulations would be demographically independent and thus should be considered separate management units (stocks) (Palsboll et al. 2006).

While the available genetic data for spotted seatrout in the northern GOM has limited utility in delineating stock structure, it does provide important insight on a likely mechanism of large-scale movement and associated gene flow, namely sex-biased dispersal. Interestingly, genetic divergence in spotted seatrout collected from the same geographic area (the Texas coast) has only been found with mtDNA markers (Gold and Richardson 1998; Anderson and Karel 2009) and not microsatellites (Gold et al. 2003; Ward et al. 2007). Microsatellites are paternally inherited (from both parents), whereas mtDNA is only maternally inherited and is therefore indicative of female gene flow (Wirgin and Waldman 2005). Accordingly, one plausible explanation for the higher genetic diversity in mtDNA versus microsatellite sequences is that gene flow in spotted seatrout occurs predominantly via male dispersal or ‘straying’ (i.e., adult males moving to and spawning in non-natal habitats) rather than female or larval dispersal (Gold et al. 2001; Gold et al. 2003). My telemetry data support this idea as emigration rates from Calcasieu Lake were three-fold higher for males (~30%) than females (~10%). The ultimate fate of emigrants was unknown, with the exception of one individual that was recaptured (and kept) by a fisher near the jetties. Still, it seems reasonable to assume that a few emigrants moved

considerable distances (i.e., > 100 km and to another estuary) of which this species is indeed capable as evidenced by conventional tagging data. In another study, I attempted to use otolith microchemistry to investigate the tendency of adults to remain within or near their nursery (and probable natal) estuaries and whether movement away from nursery estuaries was sex- or age-related. This study would have afforded a test of the hypothesis of male-biased dispersal in spotted seatrout. However, elemental and isotopic concentrations of juvenile otoliths were too similar at estuarine- and regionally-specific spatial scales to develop fingerprints that could be used to assign the nursery origins of adults with high accuracy (>80%). Future movement studies on this species should determine the sex of fish upon release (using the methods I presented in chapter 1) as behavior and movement patterns appear to differ substantially between sexes (also see chapter 4). In fact, any movement studies, regardless of species, should attempt to determine the sex of study fish (if possible) as sex-biased dispersal may be a fairly common and important phenomenon, but has received little attention (Pardini et al. 2001; Hutchings and Gerber 2002; Croft et al. 2003).

The spatial structure of spotted seatrout in Louisiana may best be viewed as a metapopulation, without the strict requirement of extinction and recolonization events that are implicit in classical metapopulation models (Smedbol et al. 2002; Kritzer and Sale 2004; Jones 2006). An important distinction between the concepts of ‘metapopulation’ and ‘stock’ is that connectivity (or exchange) among areas and variation in migratory behaviors (e.g., straying) are essential for metapopulation structure but considered a nuisance in the traditional stock concept which is rooted in ideals of closed populations, life cycles, and uniform seasonal migration circuits (Cadrin and Secor 2009). I hypothesize that each major estuary in Louisiana harbors a subpopulation of spotted seatrout and that exchange among areas (estuaries) occurs principally

by the straying of male adults, and to a lesser degree by female and larval dispersal. Further, I would argue that, based on my movement data, the overall exchange rates among estuaries are generally low enough ( $< 10\%$ , *sensu* Palsboll et al. 2006) such that subpopulations are demographically independent, with the possible exception of those occurring in geographically proximate estuaries (e.g., Barataria and Terrebonne Bays). Many fish may remain within or near their recruitment (and likely natal) estuaries for the majority of their life, yet some vagility no doubt occurs, albeit at a seemingly low magnitude.

My proposed model of spatial population structure has important implications for the assessment and management of spotted seatrout in Louisiana. Anthropogenic effects such as fishing mortality, habitat loss, hydrologic alteration, and pollution likely differ across Louisiana's estuaries. Subpopulations, due to their demographic independence, would be expected to differentially respond to these varying levels of anthropogenic impacts. Consequently, subpopulations may exhibit different (i.e., independent) abundance and/or biomass trajectories over time. Yet, important differences in subpopulation trajectories may go unnoticed under the current state-wide stock assessment methodology that pools data for assessment metrics across all estuaries (and putative subpopulations). As an example, females may be especially vulnerable to localized (high) fishing pressure because they appear to exhibit higher estuarine residency and are exposed to fishing mortality for a greater portion of their lifespan than males. Growth rates of females are significantly higher than males, presumably to maximize fecundity. As a corollary, females recruit to the fishery (305 mm minimum size limit) more than one year before males (age 1 for females, ages 2.5-3 for males) and the majority of the recreational catch in Louisiana is comprised of females (Nieland et al. 2002; E.J. Chesney, LUMCON, personal communication). A common consequence of high fishing mortality is

age-truncation, which recent research suggests can manifest in impaired population resiliency to environmental changes and anthropogenic perturbations, especially when old (large) females become rare in populations (Berkeley et al. 2004; Hsieh et al. 2010). Older females typically spawn at different times and/or locations and produce more eggs per capita (that are often of a higher quality) than younger fish; both of these processes, bet hedging and maternal effects, may increase the survival of early life history stages (Berkeley et al. 2004). Thus, age-truncation of females (over time) may be an important indicator that a subpopulation is either overfished or on the brink of becoming overfished (due to decreased population resiliency), in which case fishing mortality should be reduced. However, such effects (e.g., age-truncation) may only be recognized if stock assessments are conducted at an appropriate (finer) spatial scale.

The most prudent approach to assessing the status of spotted seatrout in Louisiana may be to conduct each stock assessment at a hierarchy of spatial scales: state-wide, regional (i.e., adjacent estuaries combined), and estuarine-specific, if data are sufficient. Hence, a given assessment would yield metrics (e.g., fishing mortality, recruitment, and spawning potential ratios) at each of three spatial scales. Output metrics could then be compared across the different spatial scales to determine if there are any indications of small-scale overexploitation of subpopulations. For example, if small-scale trends (i.e., on an estuarine- or regionally-specific basis) diverge from state-wide trends in a manner suggesting overexploitation, spatially-explicit regulations (e.g., reduced bag limits or rotating seasonal closures in regions X/Y) could be considered as a management option. A similar spatially-explicit (regional) assessment and management protocol is used to evaluate the status and set regulations for spotted seatrout in Texas and Florida.

Interestingly, Louisiana recently adopted (in 2006) a spatially-explicit management plan for Calcasieu Lake. The premise of this management decision, which included a reduction in daily bag limits and imposition of a slot limit, was to ‘preserve’ the renowned trophy-fishery for spotted seatrout in Calcasieu Lake. However, the decision to enact this regulation was based exclusively on socio-economic factors, rather than the biological status of the subpopulation. In fact, no formal stock assessment was conducted as part of the decision-making process. Thus, the status of the subpopulation (stock) was largely unknown (i.e., overfished or not?) at the time regulations were changed. While perhaps setting a bad precedent for fisheries management (i.e., making a decision based purely on socioeconomic reasons), this situation affords a unique opportunity to evaluate the response of spotted seatrout to a spatially-explicit (estuarine-scale) regulations change (i.e., adaptive management, *sensu* Hilborn and Walters 1992). For example, the response of the stock to the more stringent regulations could be examined by analyzing fisheries independent monitoring data and conducting periodic, formal stock assessments (e.g., every five years). Obviously, response dynamics would largely depend on the status of the stock when regulations were changed, which could be gleaned from the assessment. If the stock was truly overfished at the time of the regulations change, response trajectories in the following period might provide some indication as to whether the regulations were indeed stringent enough to have a positive (re-building) effect. If no stock response is observed, this could indicate a different type of management regulation (e.g., ‘input controls’ such as seasonal closures vs. ‘output controls’ such as bag limits) may be more effective. Finally, if the stock was considered healthy at the time of the regulations change, subsequent abundance and biomass trajectories could provide important clues to potential density-dependence processes in spotted seatrout. For instance, an important question may be whether spotted seatrout are able to significantly increase

their abundance (when fishing pressure is relaxed) to a degree that allows them to exert higher top-down predation pressure on other species in the ecosystem. As we move towards the future in fisheries science and attempt to implement ecosystem-based fisheries management, questions as these become important because seemingly conservative management actions for one species (e.g., a reduction in fishing mortality) can often have unforeseen (negative) consequences on other species within the ecosystem due to complex species and fisheries interactions (Pine et al. 2009).

This study demonstrated that adult spotted seatrout exhibit limited movements in coastal Louisiana. The telemetry study provided strong evidence of high annual residency of adults within an individual estuary (Calcasieu Lake), especially females (~90%). Furthermore, conventional tagging data indicated large-scale movements in excess of 50 km were rare (< 2%), albeit most tag recoveries occurred within two months post-release. Based on these results, I hypothesized the spatial structure of spotted seatrout may best be represented as a metapopulation comprised of subpopulations in each major estuary that were genetically similar (primarily due to male straying), yet demographically independent due to seemingly low inter-estuarine exchange rates (< 4%). Finally, I proposed an alternative stock assessment technique (spatially-hierarchical models) that could be considered as a management tool to enhance and promote the sustainability of Louisiana's most sought after sportfish.

## **References**

- Able, K.W., M.P. Fahay. 1998. The first year in the life of estuarine fishes in the Middle Atlantic Bight. Rutgers University Press, Brunswick, New Jersey.
- Able, K.W., and T.M. Grothues. 2007. An approach to understanding habitat dynamics of flatfishes: advantages of biotelemetry. *Journal of Sea Research* 58:1-7.

- Adkins, G.A., P. Bowman, and B. Savoie. 1979. A study of the commercial finfish in coastal Louisiana. Louisiana Department of Wildlife and Fisheries, Technical Bulletin 29, Baton Rouge, Louisiana.
- Agresti, A. 1996. An introduction to categorical data analysis. John and Wiley Sons, New York.
- Anderson, J.D., and W.J. Karel. 2009. A genetic assessment of current management strategies for spotted seatrout in Texas. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 1:121-132.
- Arnoldi, D.C. 1985. Aspects of the biology of spotted seatrout, *Cynoscion nebulosus*, in Calcasieu Lake, Louisiana, with management implications. *Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies* 38(1984):1-18.
- Baker, Jr., W.B., and G.C. Matlock. 1993. Movement of spotted seatrout tagged in Trinity Bay, Texas. *Northeast Gulf Science* 13(1):29-34.
- Baker, Jr. W.B., G.C. Matlock, L.W. McEachron, A.W. Green, and H.E. Hegen. 1986. Movement, growth and survival of spotted seatrout tagged in Bastrop Bayou, Texas. *Contributions in Marine Science* 22:91-101.
- Bendall, B., and A. Moore. 2008. Temperature-sensing telemetry – possibilities for assessing the feeding ecology of marine mammals and their potential impacts on returning salmonid populations. *Fisheries Management and Ecology* 15:339-345.
- Berkeley, S.A., M.A. Hixon, R.J. Larson, and M.S. Love. 2004. Fisheries sustainability via protection of age structure and spatial distribution of fish populations. *Fisheries* 29(8):23-32.
- Bolle, L.J., E. Hunter, A.D. Rjinsdorp, M.A. Pastoors, J.D. Metcalfe, and J.D. Reynolds 2005. Do tagging experiments tell the truth? Using electronic tags to evaluate conventional tagging data. *ICES Journal of Marine Science* 62:236-246.
- Bortone, S.A. 2003. Introduction. Pages 1-4 *in* S.A. Bortone, editor. *Biology of the Spotted Seatrout*. CRC Press, Boca Raton, Florida.
- Brown-Peterson, N.J. 2003. The reproductive biology of spotted seatrout. Pages 99-133 *in* S.A. Bortone, editor. *Biology of the Spotted Seatrout*. CRC Press, Boca Raton, Florida.
- Cadrin, S.X., D.H. Secor. 2009. Accounting for spatial population structure in stock assessment: past, present, and future. Pages 405-425 *in* R.J. Beamish and B.J. Rothschild, editors. *The Future of Fisheries Science in North America*. Springer, New York.

- Croft, D.P., B. Albanese, B.J. Arrowsmith, M. Botham, M. Webster, and J. Krause. 2003. Sex-biased movement in the guppy (*Poecilia reticulata*). *Oecologia* 137:62-68.
- Derr, R.E. 2000. Performing exact logistic regression with the SAS system. Proceedings of the 25<sup>th</sup> Annual SAS Users Group International Conference. SAS Institute, Inc., Cary, North Carolina.
- Dunn, M.R., and M.G. Pawson. 2002. The stock structure and migrations of plaice populations on the west coast of England and Wales. *Journal of Fish Biology* 61:360-393.
- Fable, Jr., W.A., T.D. Williams, and C.R. Arnold. 1978. Description of reared eggs and young larvae of the spotted seatrout, *Cynoscion nebulosus*. *Fishery Bulletin* 76:65-71.
- Fritsch, M., Y. Morizur, E. Lambert, F. Bonhomme, and B. Guinand. 2007. Assessment of sea bass (*Dicentrarchus labrax*, L.) stock delimitation in the Bay of Biscay and the English Channel based on mark-recapture and genetic data. *Fisheries Research* 83:123-132.
- Fromentin, J.M., and J.E. Powers. 2005. Atlantic bluefin tuna: population dynamics, ecology, fisheries, and management. *Fish and Fisheries* 6:281-306.
- Gillanders, B.M., D.J. Ferrell, and N.L. Andrew. 2001. Estimates of movement and life history parameters of yellowtail kingfish (*Seriola lalandi*): how useful are data from a cooperative tagging programme? *Marine and Freshwater Research* 52:179-192.
- Gold, J.R., and L.R. Richardson. 1998. Mitochondrial DNA diversification and population structure in fishes from the Gulf of Mexico and western Atlantic. *The Journal of Heredity* 89(5):404-414.
- Gold, J.R., C.P. Burrige, and T.F. Turner. 2001. A modified stepping-stone model of population structure in red drum, *Sciaenops ocellatus* (Sciaenidae), from the northern Gulf of Mexico. *Genetica* 111:305-317.
- Gold, J.R., L.B. Stewart, and R. Ward. 2003. Population structure of spotted seatrout (*Cynoscion nebulosus*) along the Texas Gulf coast, as revealed by genetic analysis. Pages 17-29 in S.A. Bortone, editor. *Biology of the Spotted Seatrout*. CRC Press, Boca Raton, Florida.
- Green, A.W., G.C. Matlock, and J.E. Weaver. 1983. A method for directly estimating the tag-reporting rate of anglers. *Transactions of the American Fisheries Society* 112:412-415.
- Helser, T.E., R.E. Condrey, and J.P. Geaghan. 1993. Spotted seatrout distribution in four coastal Louisiana estuaries. *Transactions of the American Fisheries Society* 122:99-111.
- Hendon, J.R., J.R. Warren, J.S. Franks, and M.V. Buchanan. 2002. Movements of spotted seatrout (*Cynoscion nebulosus*) in Mississippi coastal waters based on tag-recapture. *Gulf of Mexico Science* 20(2):91-97.



- Hilborn, R. 1990. Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. *Canadian Journal of Fisheries and Aquatic Sciences* 47:635-643.
- Hilborn, R. and C.J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Kluwer Academic Publishers, Boston.
- Hsieh, C., A. Yamauchi, T. Nakazawa, and W. Wang. 2010. Fishing effects on age and spatial structures undermine population stability of fishes. *Aquatic Sciences* 72:165-178.
- Hutchings, J.A., and L. Gerber. 2002. Sex-biased dispersal in a salmonid fish. *Proceedings of the Royal Society of London B* 269:2487-2493.
- Hyndman, K.A., and D.H. Evans. 2009. Short-term low-salinity tolerance by the longhorn scuplin, *Myoxocephalus octodecimspinous*. *Journal of Experimental Zoology* 311A:45-56.
- Iversen, E.S., and A.W. Moffett. 1962. Estimation of abundance and mortality of a spotted seatrout population. *Transactions of the American Fisheries Society* 91:395-398.
- Iversen, E.S., and D.C. Tabb. 1962. Subpopulations based on growth and tagging studies of spotted seatrout, *Cynoscion nebulosus*, in Florida. *Copeia* 3:544-548.
- Jennings, S., M.J. Kaiser, and J.D. Reynolds. 2001. Marine fisheries ecology. Blackwell Science Ltd., Oxford.
- Jones, C.M. 2006. Estuarine and diadromous fish metapopulations. Pages 119-154 in J.P. Kritzer and P.F. Sale, editors. *Marine Metapopulations*. Elsevier Academic Press, Burlington, Massachusetts.
- King, T.L., and H.O. Pate. 1992. Population structure of spotted seatrout inhabiting the Texas Gulf coast: an allozymic perspective. *Transactions of the American Fisheries Society* 121:746-756.
- Klimley, A.P., F. Voegeli, S.C. Beavers, and B.J. Le Boeuf. 1998. Automated listening stations for tagged marine fishes. *Marine Technology Society Journal* 32(1):94-101.
- Kritzer, J.P., and P.F. Sale. 2004. Metapopulation ecology in the sea: from Levins' model to marine ecology and fisheries science. *Fish and Fisheries* 5(2):131-140.
- Lee, K.M., T. Kaneko, and K. Aida. 2005. Low-salinity tolerance of juvenile fugu *Takifugu rubripes*. *Fisheries Science* 71:1324-1331.
- Lowerre-Barbieri, S.K., N. Henderson, J. Llopiz, S. Walters, J. Bickford, and R. Muller. 2009. Defining a spawning population (spotted seatrout *Cynoscion nebulosus*) over temporal, spatial, and demographic scales. *Marine Ecology Progress Series* 394:231-245.

- Lyczkowski-Shultz, J., D.L. Ruple, S.L. Richardson, and J.H. Cowan, Jr. 1990. Distribution of fish larvae relative to time and tide in a Gulf of Mexico barrier island pass. *Bulletin of Marine Science* 46(3):563-577.
- McEachron, L.W., and G.C. Matlock. 1980. Movement of spotted seatrout, *Cynoscion nebulosus*, tagged in Bastrop Bayou, Texas. *Annual Proceedings of the Texas Chapter of the American Fisheries Society* 3:64-82.
- McEachron, L.W., G.C. Matlock, C.E. Bryan, P. Unger, T.J. Cody, and J.H. Martin. 1994. Winter mass mortality of animals in Texas bays. *Northeast Gulf Science* 13(2):121-138.
- Melnychuk, M.C., D.W. Welch, C.J. Walters, and V. Christensen. 2007. Riverine and early ocean migration and mortality patterns of juvenile steelhead trout (*Oncorhynchus mykiss*) from the Cheakamus River, British Columbia. *Hydrobiologia* 582:55-65.
- Mercer, L.P. 1984. A biological and fisheries profile of spotted seatrout, *Cynoscion nebulosus*. North Carolina Department of Natural Resources and Community Development, Special Scientific Report Number 40, Morehead City, North Carolina.
- Metcalf, J.D. 2006. Fish population structuring in the North Sea: understanding processes and mechanisms from studies of the movements of adults. *Journal of Fish Biology* 69 (Supplement C):48-65.
- Moffett, A.W. 1961. Movements and growth of spotted seatrout, *Cynoscion nebulosus* (Cuvier), in west Florida. Florida State Board of Conservation, University of Miami Marine Laboratory Technical Series 36:1-35.
- Nieland, D.L., R.G. Thomas, and C.A. Wilson. 2002. Age, growth, and reproduction of spotted seatrout in Barataria Bay, Louisiana. *Transactions of the American Fisheries Society* 131:245-259.
- Overstreet, R.M. 1983. Aspects of the biology of the spotted seatrout, *Cynoscion nebulosus*, in Mississippi. *Gulf Research Reports* (Supplement 1):1-43.
- Palsboll, P.J., M. Berube, and F.W. Allendorf. 2006. Identification of management units using population genetic data. *Trends in Ecology and Evolution* 22(1):11-16.
- Pardini, A.T., C.S. Jones, L.R. Noble, B. Kreiser, H. Malcolm, B.D. Bruce, J.D. Stevens, G. Cliff, M.C. Scholl, M. Francis, C.A.J. Duffy, and A.P. Martin. 2001. Sex-biased dispersal of great white sharks. *Nature* 412:139-140.
- Patterson, W.F., J.C. Watterson, R.L. Shipp, and J.H. Cowan, Jr. 2001. Movement of tagged red snapper in the northern Gulf of Mexico. *Transactions of the American Fisheries Society* 130:533-545.

- Pawson, M.G., and S. Jennings. 1996. A critique of methods for stock identification in marine capture fisheries. *Fisheries Research* 25:203-217.
- Peebles, E.B., and S.G. Tolley. 1988. Distribution, growth and mortality of larval spotted seatrout, *Cynoscion nebulosus*: a comparison between two adjacent estuarine areas of southwest Florida. *Bulletin of Marine Science* 42(3):397-410.
- Pine, W.E., S.D. Martell, C.J. Walters, and J.E. Kitchell. 2009. Counterintuitive responses of fish populations to management actions: some common causes and implications for predictions based on ecosystem modeling. *Fisheries* 34(4):165-180.
- Ramsey, P.R., and J.M. Wakeman. 1987. Population structure of *Sciaenops ocellatus* and *Cynoscion nebulosus* (Pisces: Sciaenidae): biochemical variation, genetic subdivision and dispersal. *Copeia* 3:682-695.
- Righton, D., V.A. Quayle, S. Hetherington, and G. Burt. 2007. Movements and distribution of cod (*Gadus morhua*) in the southern North Sea and English Channel: results from conventional and electronic tagging experiments. *Journal of the Marine Biological Association of the United Kingdom* 87:599-613.
- Rogillio, H.E. 1975. An estuarine sportfish study in southeastern Louisiana. Louisiana Wildlife and Fisheries Commission, Fisheries Bulletin Number 14, Baton Rouge, Louisiana.
- Rogillio, H.E. 1980. Movement and migration of the spotted seatrout in southeast Louisiana. Louisiana Department of Wildlife and Fisheries, Federal Aid in Sportfish Restoration, Project F-33, Final Report, Baton Rouge, Louisiana.
- Rogillio, 1982. Movement study of estuarine sportfish. Louisiana Department of Wildlife and Fisheries, Federal Aid in Sportfish Restoration, Project F-41, Final Report, Baton Rouge, Louisiana.
- Rooker, J.R., J.R. Alvarado Bremer, B.A. Block, H. Dewar, G. De Metrio, A. Corriero, R.T. Kraus, E.D. Prince, E. Rodriguez-Marin, and D.H. Secor. 2007. Life history and stock structure of Atlantic bluefin tuna (*Thunnus thynnus*). *Reviews in Fisheries Science* 15:265-310.
- Saucier, M.H., and D.M. Baltz. 1993. Spawning site selection by spotted seatrout, *Cynoscion nebulosus*, and black drum, *Pogonias cromis*, in Louisiana. *Environmental Biology of Fishes* 36:257-272.
- Serafy, J.E., K.C. Lindeman, T.E. Hopkins, and J.S. Ault. 1997. Effects of freshwater canal discharge on fish assemblages in a subtropical bay: field and laboratory observations. *Marine Ecology Progress Series* 160:161-172.

- Shaw, R.F., W.J. Wiseman, Jr., R.E. Turner, L.J. Rouse, Jr., and R.E. Condrey. 1985. Transport of larval gulf menhaden *Brevoortia patronus* in continental shelf waters of western Louisiana: a hypothesis. *Transactions of the American Fisheries Society* 114:452-460.
- Smedbol, R.K., A. McPherson, M.M. Hansen, and E. Kenchington. 2002. Myths and moderation in marine 'metapopulations'?. *Fish and Fisheries* 3:20-35.
- Stephenson, R.L. 1999. Stock complexity in fisheries management: a perspective of emerging issues related to population sub-units. *Fisheries Research* 43:247-249.
- Stokes, M.E., C.S. Davis, and G.G. Koch. 2000. Categorical data analysis using the SAS system, 2<sup>nd</sup> edition. SAS Institute, Cary, North Carolina.
- Tabb, D.C. 1966. The estuary as a habitat for spotted seatrout, *Cynoscion nebulosus*. American Fisheries Society, Special Publication 3, Bethesda, Maryland.
- Thorrold, S.R., C. Latkoczy, P.K. Swart, and C.M. Jones. 2001. Natal homing in a marine fish metapopulation. *Science* 291:297-299.
- Vetter, R.D. 1982. Seasonal metabolic compensation in sympatric seatrout: adaptation to the estuary. *Transactions of the American Fisheries Society* 111:193-198.
- Walters, S., S. Lowerre-Barbieri, and J. Bickford. 2009. Using a passive acoustic survey to identify spotted seatrout spawning sites and associated habitat in Tampa Bay, Florida. *Transactions of the American Fisheries Society* 138:88-98.
- Wang, H.Y., E.S. Rutherford, H.A. Cook, D.W. Einhouse, R.C. Haas, T.B. Johnson, R. Kenyon, B. Locke, and M.W. Turner. 2007. Movement of walleyes in Lakes Erie and St. Clair inferred from tag return and fisheries data. *Transactions of the American Fisheries Society* 136:539-551.
- Ward, R.D. 2000. Genetics in fisheries management. *Hydrobiologia* 420:191-201.
- Ward, R., K. Bowers, R. Hensley, B. Mobley, and E. Belouski. 2007. Genetic variability in spotted seatrout (*Cynoscion nebulosus*), determined with microsatellite DNA markers. *Fishery Bulletin* 105:197-206.
- Welch, D.W., M.C. Melnychuk, E.R. Rechiksy, A.D. Porter, M.C. Jacobs, A. Ladouceur, R.S. McKinley, and G.D. Jackson. 2009. Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. *Canadian Journal of Fisheries and Aquatic Sciences* 66:736-750.
- Wieting, D.S. 1989. Age, growth, and fecundity of spotted seatrout (*Cynoscion nebulosus*) in Louisiana. Master's thesis. Louisiana State University, Baton Rouge, Louisiana.

- Wirgin, I., and J.R. Waldman. 2005. Use of nuclear DNA in stock identification: single-copy and repetitive sequence markers. Pages 331-370 *in* S.X. Cadrin, K.D. Friedland, and J.R. Waldman, editors. Stock identification methods applications in fishery science. Elsevier Academic Press, Burlington, Massachusetts.
- Wiseman, Jr., W.M., N.N. Rabalais, R.E. Turner, S.P. Dinnel, and A. MacNaughton. 1997. Seasonal and interannual variability within the Louisiana coastal current: stratification and hypoxia. *Journal of Marine Systems* 12:237-248.
- Woodward, A.G., J.M. Pafford, and N. Nicholson. 1990. Exploitation, movement, and growth of spotted seatrout in coastal Georgia. Georgia Department of Natural Resources, Coastal Resources Division, Federal Aid in Sport Fish Restoration, Project F-31, Final Report, Brunswick, Georgia.
- Zavala-Hidalgo, J., S.L. Morey, and J.J. O'Brien. 2003. Seasonal circulation on the western shelf of the Gulf of Mexico using a high-resolution numerical model. *Journal of Geophysical Research* 108(C12):1-19.

## **CHAPTER 4: EFFECTS OF METEOROLOGICAL EVENTS ON THE DISTRIBUTION OF SPOTTED SEATROUT IN A LOUISIANA ESTUARY**

### **Introduction**

Meteorological events often result in abrupt changes in abiotic conditions in both the terrestrial and aquatic realm. Organisms inhabiting environments frequently disturbed by weather events have likely evolved behaviors to cope with such rapidly changing conditions (Mallin and Corbett 2006; Langtimm et al. 2006; Heupel and Simpfendorfer 2008). For example, mobile organisms may simply move to more suitable areas. As a case in point, numerous studies have illustrated storm-related distribution shifts of adult fishes and invertebrates in coastal and marine environments (Walsh 1983; Knott and Martore 1991; Jury et al. 1995; Watterson et al. 1998; Heupel et al. 2003; Sackett et al. 2007).

Knowledge of movement and distribution responses to weather events can improve stock assessments. The accessibility of fish to both harvest and scientific sampling changes if species undergo distribution shifts due to weather disturbances (Fréon et al. 1993; Jones and Rogers 1998). For instance, catches in typically productive or routinely sampled areas (e.g., shallower water) may be low directly after a storm event because fish moved to another region (e.g., deeper water) and have not yet returned to their preferred habitats. In this case, reduced catches would be due to fish behavior (movement), not necessarily a decline in abundance (mortality). Accordingly, a better understanding of fish responses to weather events, and abiotic variables in general, can aid interpretations of catch data that are used to assess abundance trends of important fishery species (Smith 1990; Bigelow et al. 1999; Brill and Lutcavage 2001; Shepherd et al. 2002; Hobday et al. 2009).

Remote acoustic telemetry is an evolving technique well-suited for investigations of event-scale movement responses of fishes in coastal and marine environments. High-resolution

technology allows continuous monitoring of study areas. Such capability is extremely useful for assessing the effects of meteorological events which can be frequent but unpredictable in their timing, at least to the extent that generally precludes opportunistic sampling via conventional methods (i.e., taking point samples before and after events of interest). Continuously monitoring a study area for an extended period of time (months, years) ensures that regularly occurring weather events will be encountered and thus sampled. Moreover, chronologies of fish locations can be linked to continuously-recorded environmental variables to yield a detailed picture of movement and distribution responses to weather events. For example, the distribution of telemetered fish can be compared across time periods (i.e., before, during, and after a defined event) to determine whether fish change their distribution; if so, when they return to impacted areas (Sakabe and Lyle 2010; Kawabata et al. 2010). Also, the timing of movements can be related to environmental conditions to gain insight into the abiotic variables most important in triggering movement (Heupel et al. 2003; Sackett et al. 2007; Childs et al. 2008).

In this study, I used remote acoustic telemetry to investigate the effects of meteorological events on the movement and distribution of adult spotted seatrout in a Louisiana estuary, Calcasieu Lake. The responses of spotted seatrout to weather events is largely unknown as movement information for this important recreational species is limited to a few low resolution mark-recapture studies (Rogillio 1980; Baker et al. 1986; Hendon et al. 2002) and anecdotal reports from fishermen. Herein, I address this important knowledge gap by examining the effects of both regularly occurring (cold fronts, heavy rainstorms) and less frequent, but more severe weather phenomena (tropical storms) encountered in coastal Louisiana (Moeller et al. 1993; Schroeder and Wiseman 1999; Solis and Powell 1999). Specifically, I anticipated that spotted seatrout would: 1) avoid areas in which salinities were low ( $< 5$  psu) as a result of

freshets following heavy rain events and 2) mainly utilize calmer regions of the estuary during periods of high winds associated with the passages of cold fronts and tropical storms.

## **Methods**

### Study Area

Calcasieu Lake is an estuarine system ( $\sim 300 \text{ km}^2$ ) located in the Chenier Plain of southwestern Louisiana (see Figure 2.1). The majority of this estuary is shallow, as the maximum depth of the estuary proper is only 2.5 m. However, a relatively deep ( $\sim 15 \text{ m}$ ) and narrow (300-500 m) ship channel spans 60 km from the main tidal inlet to Lake Charles (see Figure 2.1). Natural meandering channels and marsh creeks of 4 to 8 m depth are also present in the system.

Freshwater input to this system is largely pulsed. Only when the floodgates of the Saltwater Barrier (hereafter “SW Barrier”) are open can freshwater from the Calcasieu River enter the estuary. This water control structure is located approximately 4 km north of Lake Charles (see Figure 2.1). The floodgates of the SW Barrier are generally closed to prevent saltwater intrusion into the Calcasieu River watershed. These gates are only opened for flood control, typically following heavy rains.

### Fish Tagging

Following methods described in chapters 1 and 3, I surgically implanted acoustic transmitters (VEMCO V9-2Hs and V13TP-1Hs) into 172 adult spotted seatrout (300-725 mm total length, TL) and released the fish during four tagging events (spring and fall of both 2007 and 2008). Transmitter battery lives were approximately one year. Only the V13TP-1H transmitters implanted into larger fish ( $> 430 \text{ mm TL}$ , 700 g) contained temperature and pressure (depth) sensors. During the tagging process, fish were also measured (TL, nearest mm), weighed



(nearest gram), sexed, and externally marked with a dart tag (HallPrint PDS series, 10 cm length).

### Receiver Array

To monitor the movements and distribution of telemetered fish, I deployed a stationary array of 60 remote acoustic receivers (VEMCO VR2s and VR2Ws) throughout the Calcasieu Lake system (see Figure 2.2). Details of receiver deployment and operation principles for this telemetry system were presented in chapter 2. Briefly, if a transmitter (fish) emitted a signal while within the detection range of a receiver (~250 m), the receiver recorded and stored the transmitter ID number, date and time of the detection, and any transmitter sensor data (temperature, depth). I serviced and downloaded data from receivers at approximately six week intervals during the course of this 2.5 year study (May 2007 to October 2009). During downloading, I also measured physico-chemical water variables (temperature, salinity, and dissolved oxygen) at each receiver station (surface and bottom) with a 600R YSI sonde.

### Processing of Telemetry Data

I censored all downloaded receiver data for spurious detections, namely false detections and transmissions from dead fish. False detections arise when two or more transmitters at the same location simultaneously emit a signal (i.e., collide) and occasionally create a hybrid transmission that is comprised of a valid ping sequence, but whose ID number does not match any of the transmitters present in the area. This situation can result in a false positive detection if the receiver's error-checking algorithm fails to recognize that the sequence arose from two different transmitters. False detections are easily recognized and removed when isolated detections have ID numbers that do not match those of deployed transmitters. However, this is

not always the case; therefore, formal rejection criteria must be used to remove false detections (D.G. Pincock, VEMCO, personal communication).

I based my rejection criteria for removing false detections on simulations performed by VEMCO. The shortest average delay for the transmitters used in my study was 120 seconds, and rarely were more than five telemetered fish detected at the same receiver on a given day (~6% of all data). Under this scenario (five resident transmitters with an average delay of 120 seconds) VEMCO simulations showed that the mean time between successive false detections was 88 hours, with most (> 90%) separated by 24 hours or more. Accordingly, in my study, I used the criterion that a given transmitter must have been detected at least twice within a 24 hour period at the same receiver to be considered valid. Thus, an isolated detection, or single detection of an individual at a given receiver within a 24 hour period, was deemed false or invalid. The one exception to this criterion occurred when a fish detected only once at a particular receiver was also detected (within the same 24 hour period) at a nearby receiver (< 1 km distant). In this case, if successive detections of the individual (at adjacent stations) were temporally separated by at least twice the maximum transmitter delay (to ensure they were from separate transmissions), I assumed they represented valid detections. Using these criteria, I removed all apparent false detections from receiver data. It should be noted that I assumed false detections were negligible for emigration analyses in chapter 3 because rarely were multiple fish detected at the inlet gate on the same day. Thus, the possibility for collisions and associated false detections was minimal.

Several telemetered fish (n=5) appeared to die in the vicinity of receivers. These individuals were continuously detected at the same station for at least five months with no corresponding detections elsewhere in the receiver array during the remainder of their transmitter battery lives. To ensure detections of these presumably dead fish were excluded from data

analyses, I removed detections of each individual starting with the day they began to be continuously detected. After removing spurious detections from raw receiver data, all remaining (valid) detections (study total = 644,058) were imported into a database management system.

### Environmental Data

The main objective of this study was to evaluate the movement and distribution responses of spotted seatrout to meteorological events. I assumed that meteorological effects would be realized most during extreme events. Therefore, I chose to investigate the effects of the most extreme events observed during the course of the study. Specifically, I examined the effects of the two largest freshets, the two strongest fall cold fronts, and the only tropical cyclone (Tropical Storm Edouard, hereafter “TS Edouard”) that directly impacted the study area while the receiver array was operational. I defined the ‘largest’ freshets as those with the highest river discharge that consequently led to the greatest reductions in estuarine salinities. The frontal system with the highest maintained wind speeds in the fall of each year (October-November 2007/2008) was classified as the ‘strongest’ cold front.

I used environmental data from continuously recording instruments to identify and characterize the most extreme weather events. To identify freshets, river discharge data were obtained from the United States Geological Survey (USGS) station at Kinder, LA, approximately 40 km upstream of the SW Barrier (see Figure 2.12). Salinity data used to characterize freshets were gleaned from the three USGS stations within the estuary as well as a multi-parameter YSI sonde (6620 V2) deployed in the lower portion of the bay (see Figure 2.12). I identified cold frontal passages using methods described in chapter 2. Meteorological data for cold front identification and characterization (wind velocity, air temperature, and barometric pressure) were obtained from the National Oceanic and Atmospheric Administration (NOAA) station at

Cameron, LA and the Lake Charles airport (LCH) (see Figure 2.12). Additionally, I viewed surface weather maps from NOAA's Hydrometeorological Prediction Center archive to confirm the passage of cold fronts (Feng and Li 2010). For TS Edouard, wind velocity and water level data were obtained from the USGS station at Cameron and barometric pressure from the Lake Charles airport. Additional storm statistics such as the timing/location of landfall and local precipitation data were obtained from a tropical cyclone report from NOAA's National Hurricane Center (Franklin 2008).

### Data Analyses

The general approach I used for data analyses was to compare the movement and distribution of telemetered fish across a time period that included the meteorological event of interest. To assess the effects of freshets, I examined the relationship between fish use/presence and salinity in a particular region of the estuary and also evaluated system-wide patterns of fish distribution before, during, and after freshet events. For the fish use/presence analyses, I focused on the upper portion of estuary proper (hereafter referred to as the 'upper bay') for two reasons. First, only in the upper bay were salinities consistently low ( $< 5$  psu) following large freshets. Secondly, there were numerous receivers ( $n=9$ ) in this region in close proximity ( $< 5$  km) to a USGS station that provided continuous salinity data (Figure 4.1). I assumed salinities recorded at this USGS station were representative of those experienced at upper bay receivers because temporally-matched salinity measurements (based on point samples from receiver downloading trips) indicated the average salinity difference between the USGS and upper bay receiver stations was minimal (1.6 psu). The time periods I chose for all freshet analyses were based on salinity dynamics in the upper bay. Each 'freshet period' began on the date salinities in the upper bay



Figure 4.1. (A) Region of the estuary designated as the “upper bay”. (B) Receiver stations in the upper bay (grey circles with corresponding station numbers). The black square depicts the location of the USGS station in the upper bay at which salinity was measured hourly.

started to decline from relatively high values (15-20 psu) preceding the freshet and terminated on the date salinities increased to 15-20 psu following the freshet.

To examine the relationship between daily fish presence and salinity in the upper bay, I performed logistic regression analyses. I conducted these analyses on a sex-specific basis for each freshet. If at least one fish (of a given sex) was detected at any of the receivers in the upper bay on a particular day, presence was scored positive for that day, otherwise it was scored as 0. Daily mean salinities were categorized into one of four groups:  $< 5$ , 5-10, 10-15, and  $> 15$  psu. It was necessary to group data in this manner to evaluate goodness-of-fit via deviance measures (Agresti 1996). The main response variable was the proportion of days fish were present within each salinity class (e.g., males were present on 15 of the 20 days during which mean salinities were 10-15 psu). I used a generalized linear model with a binomial response and logit link to test the relationship between fish presence and salinity. I treated salinity as a quantitative explanatory variable in the model by using within-group means as salinity values (Agresti 1996).

I also evaluated fish use of the upper bay during freshet periods. The metric I developed to quantify fish use of the upper bay was the sex-specific total daily number of detections. Due to the close proximity of some receivers in the upper bay ( $< 1$  km apart), a given tag transmission was occasionally detected at more than one receiver. Thus, in generating this metric, it was necessary to account for such 'duplicate detections'. I assumed a duplicate detection occurred when the interval between recorded detection times of the same transmitter at two or more receivers was less than the minimum transmitter delay. Theoretically, a given tag transmission should be detected first by the nearest receiver, assuming no multipath propagation or differences in receiver clock drift (Klimley et al. 2001). Hence, for duplicate detections, I assigned the detection to only one receiver, that with the earliest recorded detection time of a given

transmission. Based upon data censored for duplicate detections, I calculated the daily fish use metric via the following equation:

$$DD_{s,d} = \sum_{i=1}^9 r_{i,s,d} \quad (\text{Equation 4.1})$$

where DD = the total number of detections in the upper bay from fish of a given sex (s) on a particular day (d), and  $r_i$  = the number of detections of fish of a given sex by a particular receiver (i, 1 of 9) in the upper bay during a given day (d). As an example calculation, if there were 300 unique detections of females recorded across the nine receivers in the upper bay on day X, the metric would take on a value of 300 that day for females. This metric of daily fish use was related to daily mean salinities in the upper bay throughout the entire freshet period.

To further evaluate freshet effects, I compared estuarine-wide patterns of fish distribution among pre-, peak, and post-freshet periods. ‘Peak’ conditions were defined as the period when daily mean salinities in the upper bay were consistently less than 5 psu. ‘Pre’ and ‘post’ conditions were defined as the periods (days) preceding and following ‘peak’ conditions during which daily mean salinities were consistently greater than 5 but less than 20 psu. To quantify fish distribution, I calculated for each period (pre, peak, post) the sex-specific relative frequency of detections recorded at each operational receiver in the array. As described above, I accounted for duplicate detections in this analysis (for all receivers in the array). As an example calculation: if 1,000 detections of females were recorded across all operational receivers during the pre-freshet period with 300 of those recorded at station X, the sex-specific relative frequency of detections at station X (for females) would be 30%.

To assess the movement responses of fish to cold fronts and TS Edouard, I created abacus plots of hourly detections for select individuals across the time period spanning 72 hours before to 72 hours after ‘peak’ frontal/storm conditions. I defined ‘peak’ conditions as the time period

when wind speeds were consistently greater than  $8 \text{ ms}^{-1}$  (~15 knots). For this analysis, I only included fish that were detected before ( $< 72$  hrs), during, and after ( $< 72$  hours) peak conditions for the event of interest.

I also compared fish depths between periods of peak and non-peak winds based on depth data from sensor transmitters. “Peak” detections were depths recorded when winds speeds exceeded  $8 \text{ ms}^{-1}$  during a particular event, and “non-peak” detections were those recorded during the three days before and after peak winds. I only included depth data from the seven sensor-equipped fish that were detected before, during, and after events of interest. I employed a Wilcoxon rank sum test to compare fish depths between peak and non-peak wind conditions because depth data were non-normally distributed. For this analysis, depth detections were pooled across events (two cold fronts, TS Edouard) and individuals within each wind class (i.e., peak, non-peak).

## **Results**

### Freshets

The two largest freshets occurred in late winter 2008 and spring 2009. Both freshets were due to heavy rains in the Calcasieu River watershed, where total precipitation during the week preceding each freshet was 8 cm (2008) and 14 cm (2009). Heavy rainfall and associated runoff caused a dramatic increase in the discharge of the Calcasieu River, which peaked on February 22, 2008 and April 22, 2009 (Figure 4.2). The gates of the SW Barrier remained open during these peak discharge events, thus allowing large pulses of freshwater from the river (freshets) to penetrate the estuary (Figure 4.2). These freshets considerably reduced salinities in the estuary (Figure 4.3). Salinities in the upper bay remained low ( $< 5$  psu) for 10 and 29 consecutive days following the 2008 and 2009 freshets, respectively. Although salinities in the



Figure 4.2. Daily discharge of the Calcasieu River (thick black line) during the study period, May 2007 to October 2009. The major discharge peaks on February 22, 2008 and April 22, 2009 represent the two largest freshets observed during the study. Discharge data were obtained from the USGS station at Kinder (see Figure 2.12). The thin grey line shows the number of hours per day the floodgates of the Saltwater Barrier were open. Freshwater from the Calcasieu River only enters the estuary when these gates are open. The break in the x-axis corresponds to the one-month study gap (September 2008) due to Hurricanes Gustav and Ike.

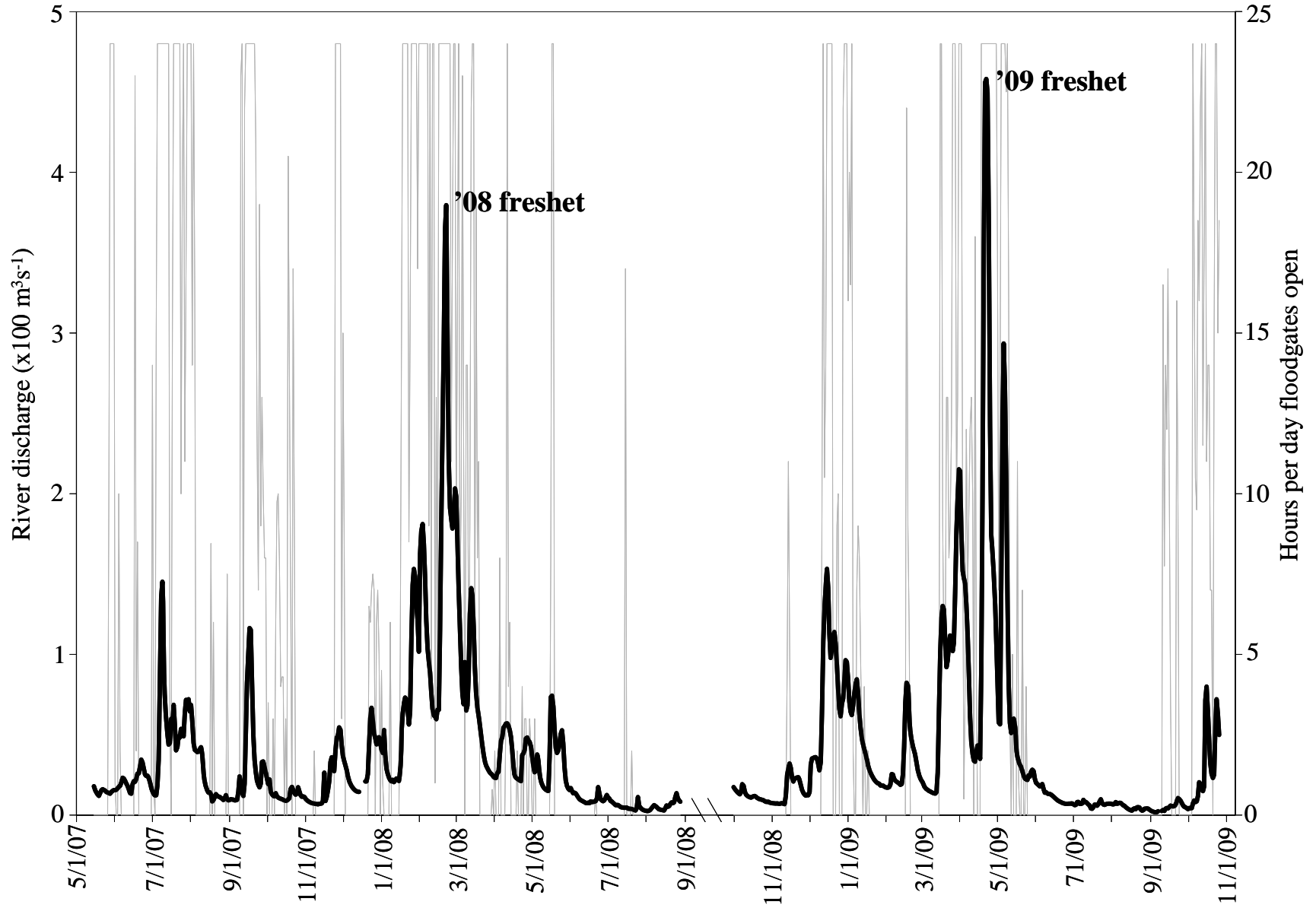
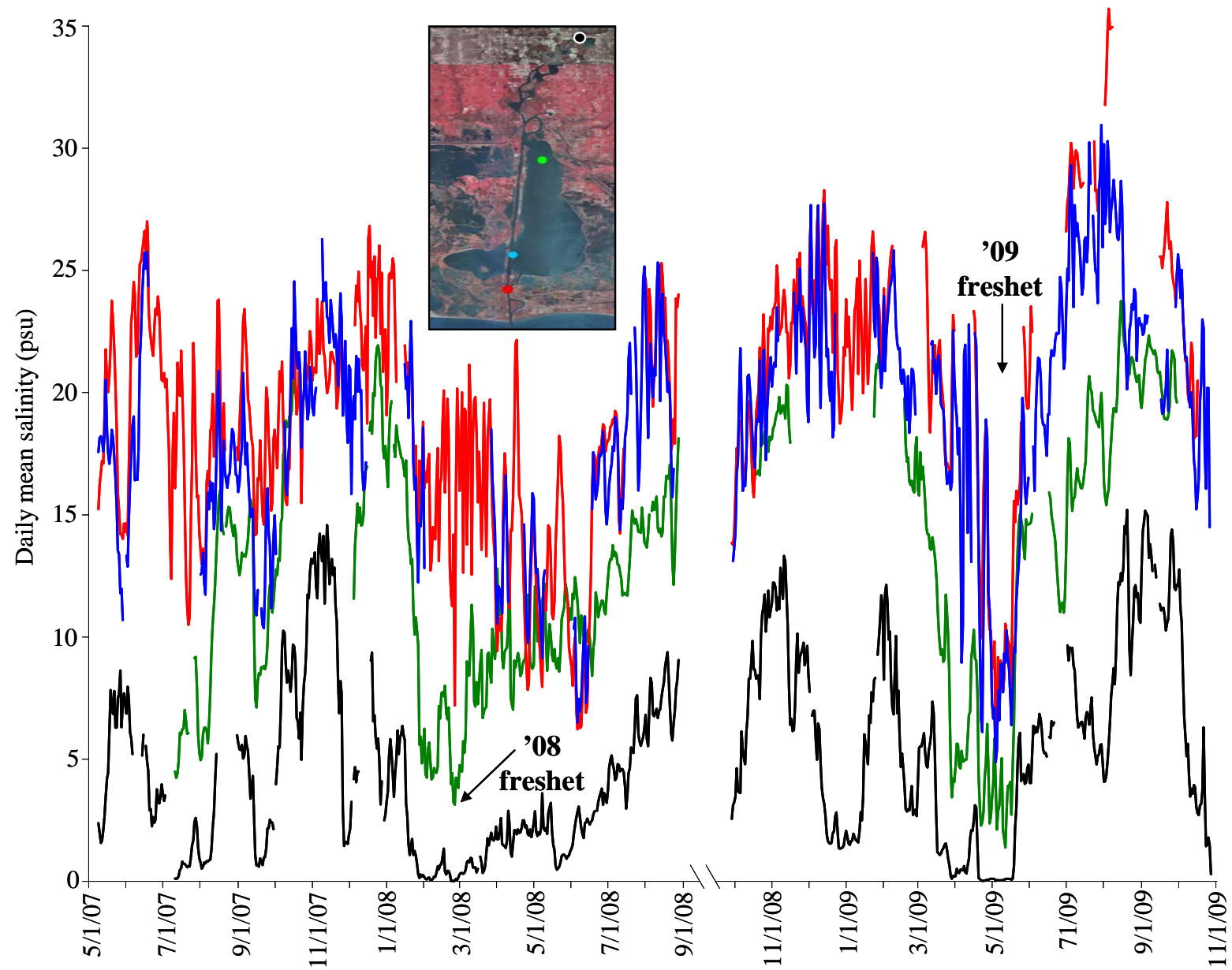


Figure 4.3. Estuarine salinities throughout the study period, May 2007 to October 2009. Colored lines represent the daily mean salinities at each of four long-term monitoring stations (map inset depicts color-coded station locations). Daily mean salinities were only calculated (and shown) for days during which stations were operational for 24 hours. Major freshet periods are indicated by arrows. The one month gap in salinity data during September 2008 was due to the passage of Hurricanes Gustav and Ike, during which time salinity stations were not operational.



lower bay were also reduced, they remained above 5 and ranged from 7-20 psu (2008) and 6-19 psu (2009) (Figure 4.3).

Interestingly, the behavioral response of spotted seatrout to these low salinity events was strongly sex-specific. Females were virtually absent from the upper bay when salinities there were low ( $< 5$  psu), but heavily utilized this area when salinities were higher ( $> 5$  psu) (Figures 4.4, 4.5). Yet, males continued to utilize the upper bay throughout low salinity periods and surprisingly were present when salinities were as low as 1 to 2 psu (Figures 4.6, 4.7). Additionally, most female detections (91-96%) during peak freshet conditions occurred in the lower bay where salinities were slightly higher (Figures 4.8, 4.9). On the contrary, males were distributed fairly evenly throughout the estuary during peak freshet conditions and exhibited a similar distribution among pre, peak, and post freshet periods (Figures 4.10, 4.11).

Logistic regression analyses corroborated this sex-specific response whereby only females seemed to avoid low salinities. For both freshets, the daily presence of females exhibited a significant positive relationship with salinity ( $p < 0.002$  across tests), but male presence was not significantly related to salinity ( $p > 0.3$  across tests). The odds of at least one female being present in the upper bay were 15-fold higher when the daily mean salinity therein exceeded 5 psu.

### Cold Fronts

The strongest fall cold fronts passed over the study area on October 22, 2007 and November 15, 2008 (Figures 4.12, 4.13). Prior to frontal passages ( $< 3$  days), wind speeds averaged  $5 \text{ ms}^{-1}$ . When cold fronts passed over the study area, indicated by a sharp drop in air temperature and rise in barometric pressure, there was a rapid switch in wind direction (S to NNW) and concomitant increase in wind speed ( $8\text{-}15 \text{ ms}^{-1}$  maintained, with gusts to  $19 \text{ ms}^{-1}$ )

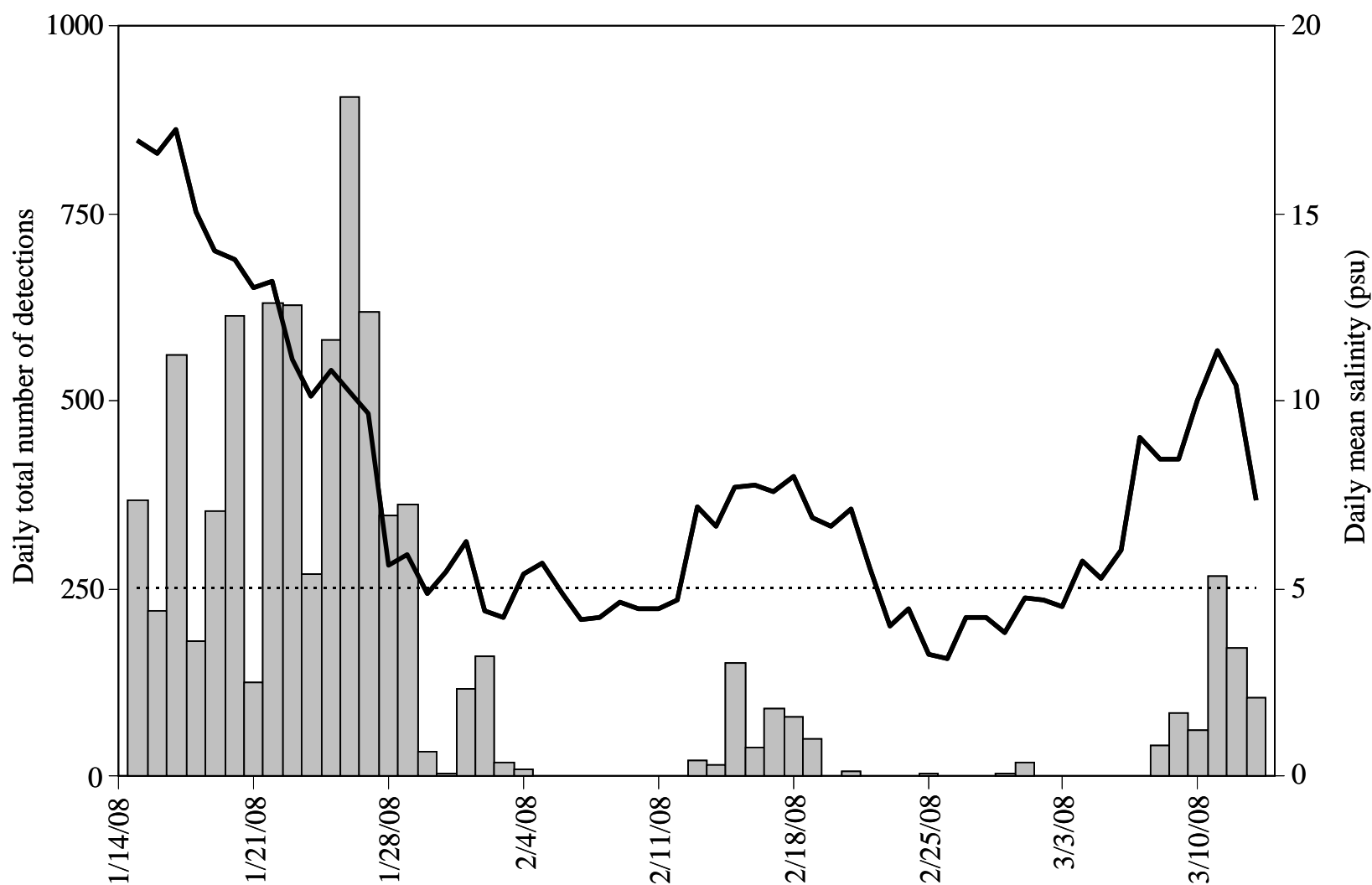


Figure 4.4. Female use of the upper bay in relation to salinities therein for the period January 15 to March 13, 2008. The grey bars represent the daily total number of detections (of females) recorded across all nine receivers in the upper bay. Salinity, shown by the thick black line, was measured at the USGS station in the upper bay (see Figure 4.1). The dashed line is a reference for salinity = 5 psu. The extended period of low salinities (< 5 psu) from February 23 to March 3, 2008 was due to a freshet.

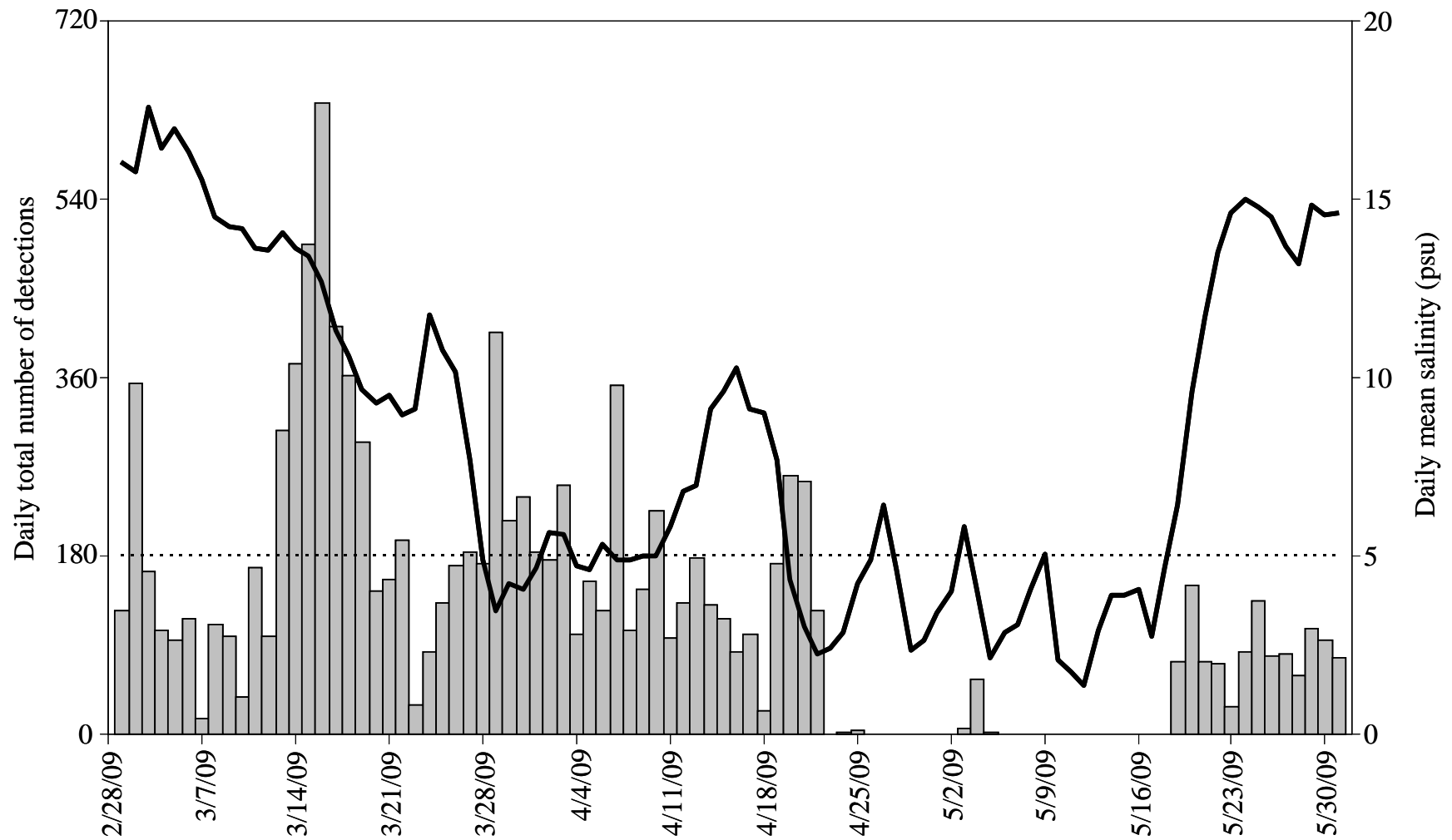


Figure 4.5. Female use of the upper bay in relation to salinities therein for the period March 1 to May 31, 2009. The grey bars represent the daily total number of detections (of females) recorded across all nine receivers in the upper bay. Salinity, shown by the thick black line, was measured at the USGS station in the upper bay (see Figure 4.1). The dashed line is a reference for salinity = 5 psu. The extended period of low salinities (< 5 psu) from April 20 to May 18, 2009 was due to a freshet.

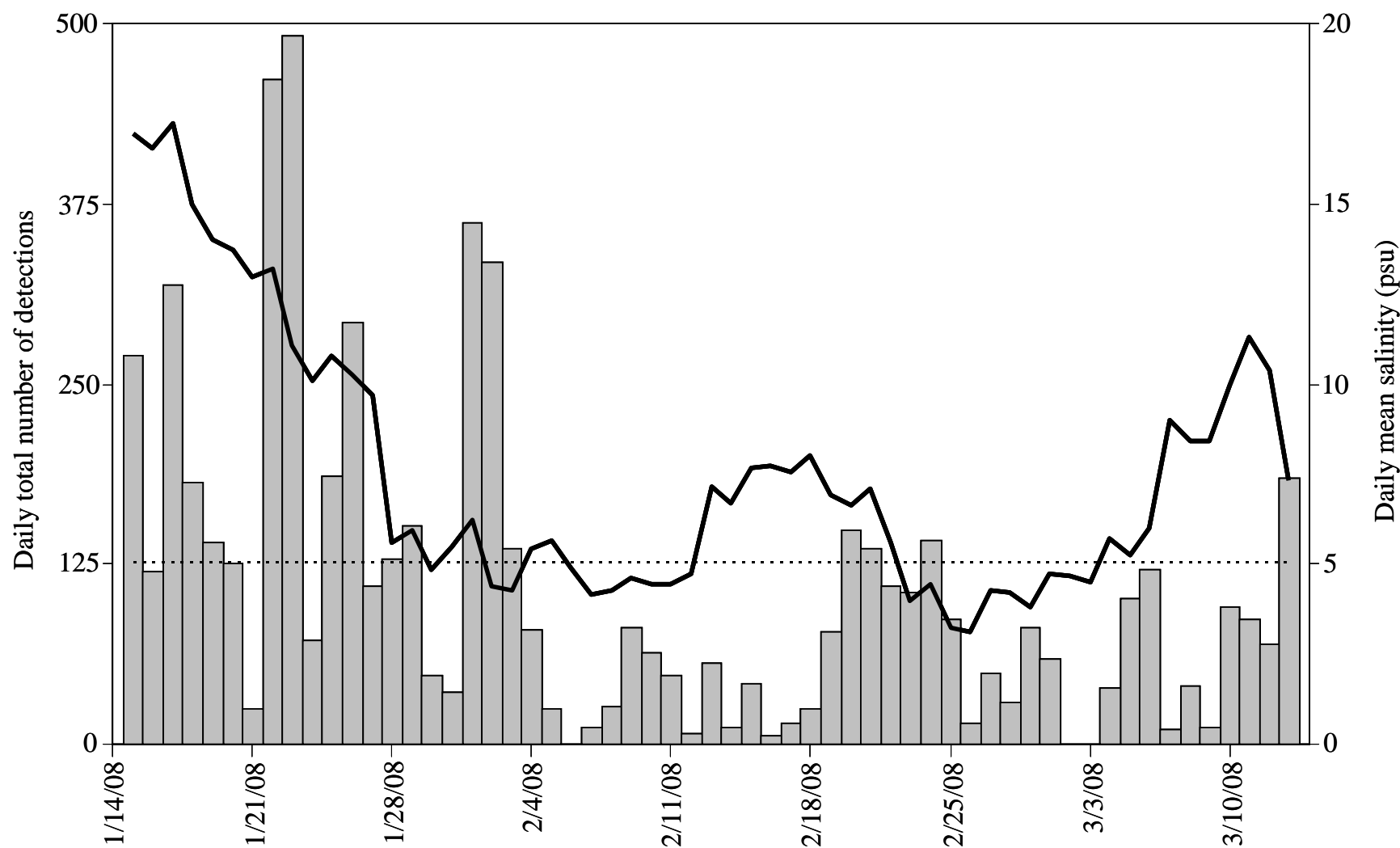


Figure 4.6. Male use of the upper bay in relation to salinities therein for the period January 15 to March 13, 2008. The grey bars represent the daily total number of detections (of males) recorded across all nine receivers in the upper bay. Salinity, shown by the thick black line, was measured at the USGS station in the upper bay (see Figure 4.1). The dashed line is a reference for salinity = 5 psu. The extended period of low salinities (< 5 psu) from February 23 to March 3, 2008 was due to a freshet.



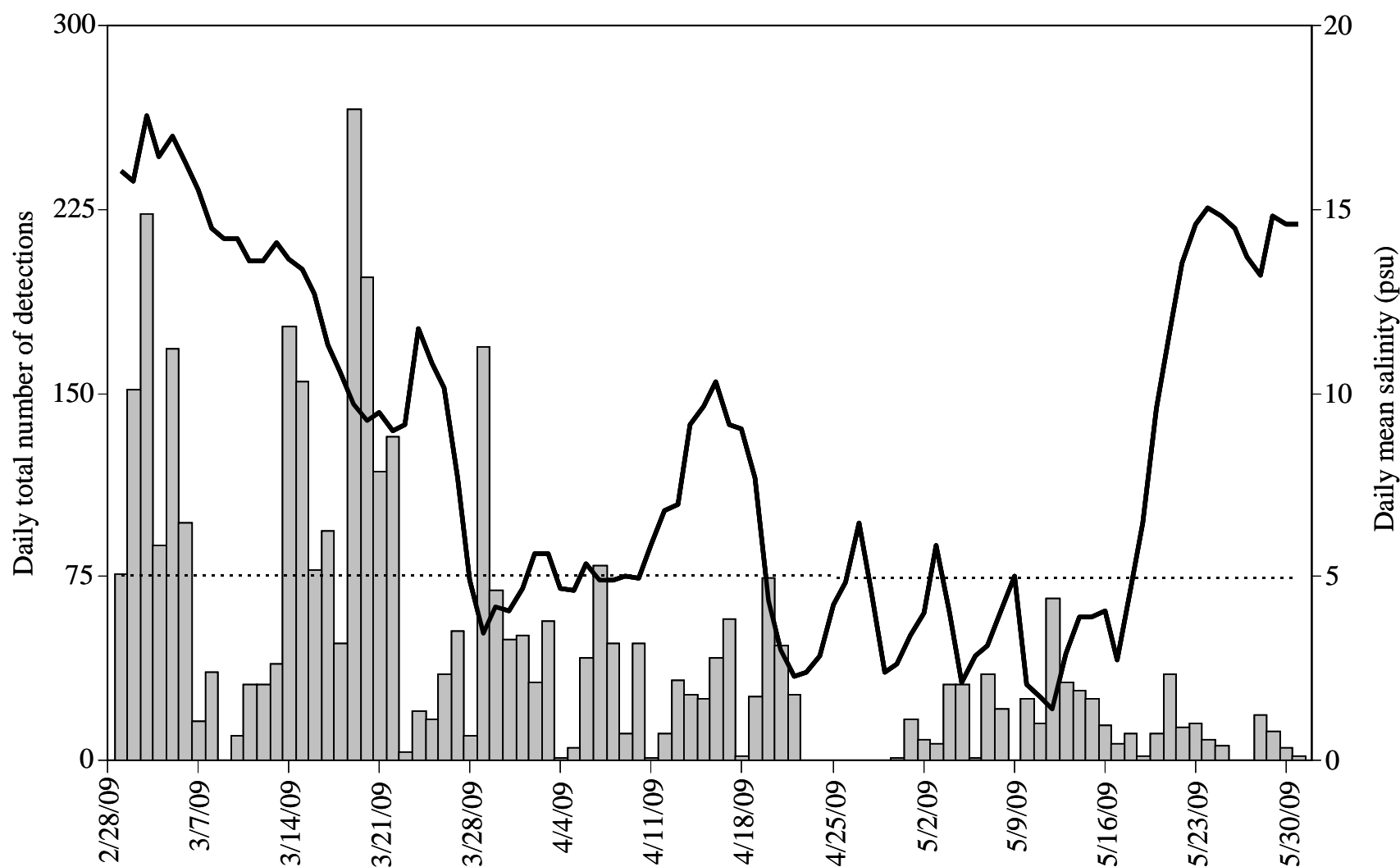


Figure 4.7. Male use of the upper bay in relation to salinities therein for the period March 1 to May 31, 2009. The grey bars represent the daily total number of detections (of males) recorded across all nine receivers in the upper bay. Salinity, shown by the thick black line, was measured at the USGS station in the upper bay (see Figure 4.1). The dashed line is a reference for salinity = 5 psu. The extended period of low salinities (< 5 psu) from April 20 to May 18, 2009 was due to a freshet.

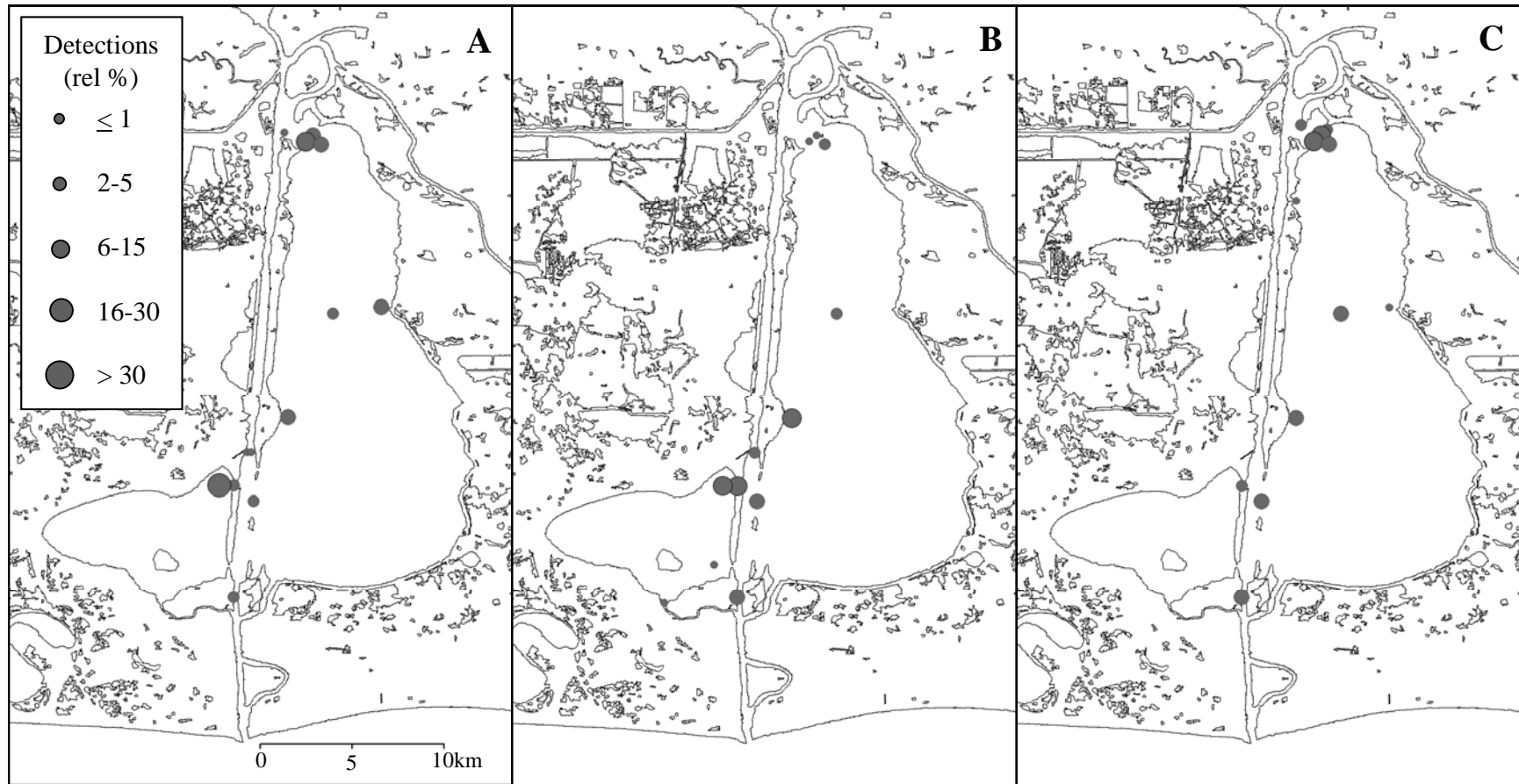


Figure 4.8. Distribution of female spotted seatrout (A) before, (B) during, and (C) after the 2008 freshet. Salinities in the upper bay were less than 5 psu during the peak freshet period (February 23 to March 3, 2008) and greater than 5 psu during the pre- and post-freshet periods: February 13-22, 2008 and March 4-13, 2008; respectively. Bubbles depict the relative frequency (%) of detections recorded at each receiver station within each period (pre, peak, post). Bubble sizes are positively scaled to this metric as indicated in the legend.

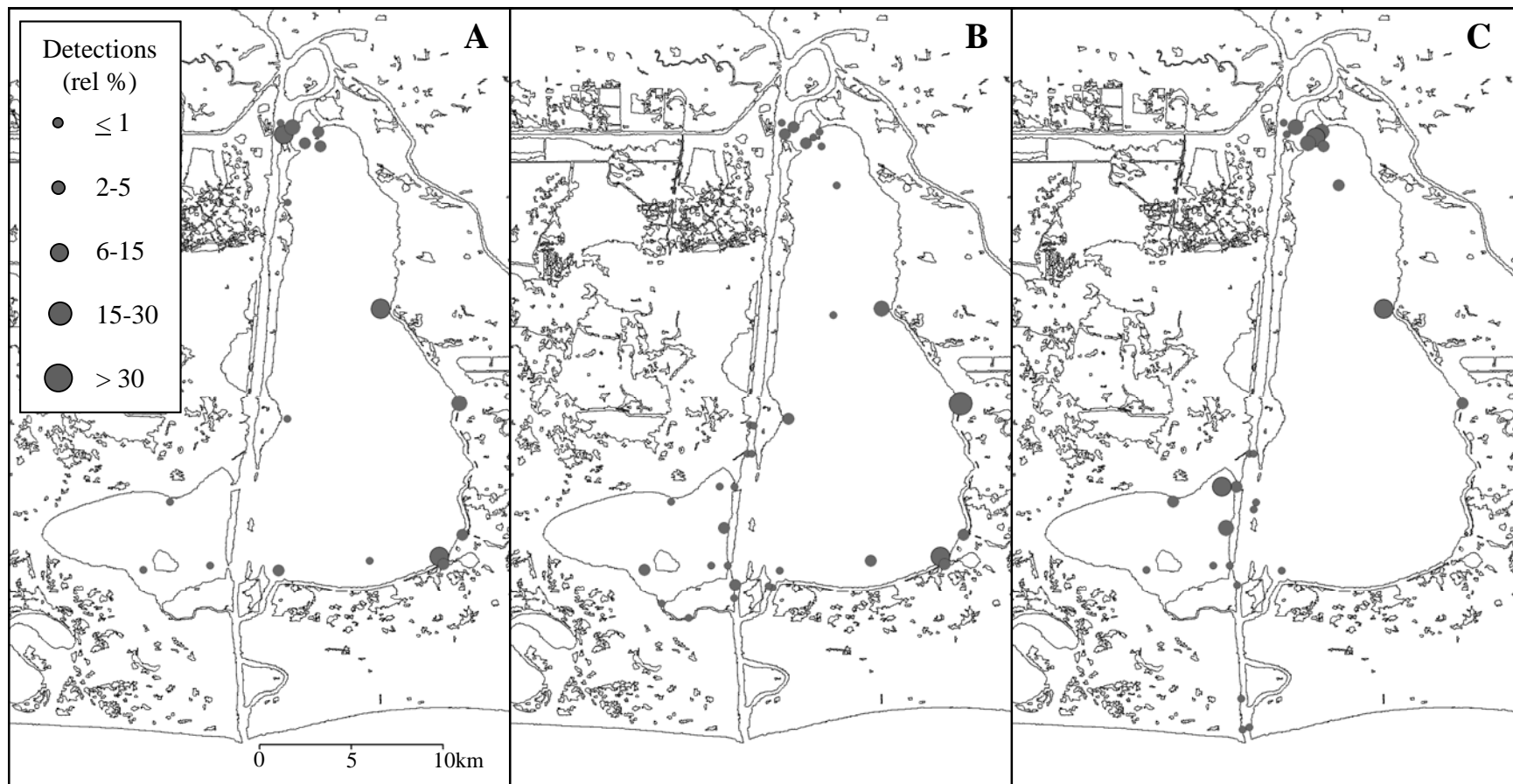


Figure 4.9. Distribution of female spotted seatrout (A) before, (B) during, and (C) after the 2009 freshet. Salinities in the upper bay were less than 5 psu during the peak freshet period (April 20 to May 18, 2009) and greater than 5 psu during the pre- and post-freshet periods: April 11-19, 2009 and May 19-31, 2009; respectively. Bubbles depict the relative frequency (%) of detections recorded at each receiver station within each period (pre, peak, post). Bubble sizes are positively scaled to this metric as indicated in the legend.

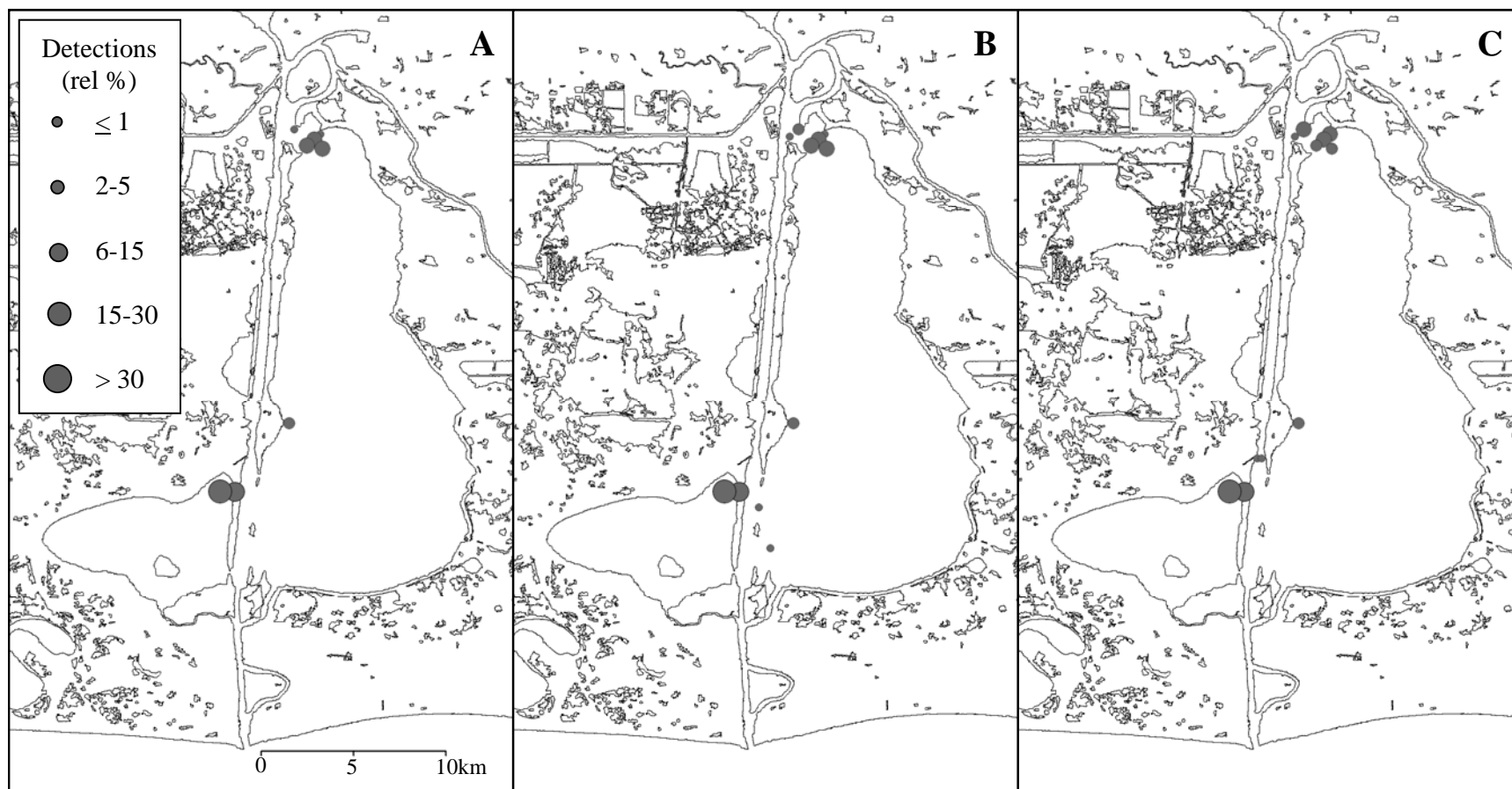


Figure 4.10. Distribution of male spotted seatrout (A) before, (B) during, and (C) after the 2008 freshet. Salinities in the upper bay were less than 5 psu during the peak freshet period (February 23 to March 3, 2008) and greater than 5 psu during the pre- and post-freshet periods: February 13-22, 2008 and March 4-13, 2008; respectively. Bubbles depict the relative frequency (%) of detections recorded at each receiver station within each period (pre, peak, post). Bubble sizes are positively scaled to this metric as indicated in the legend.

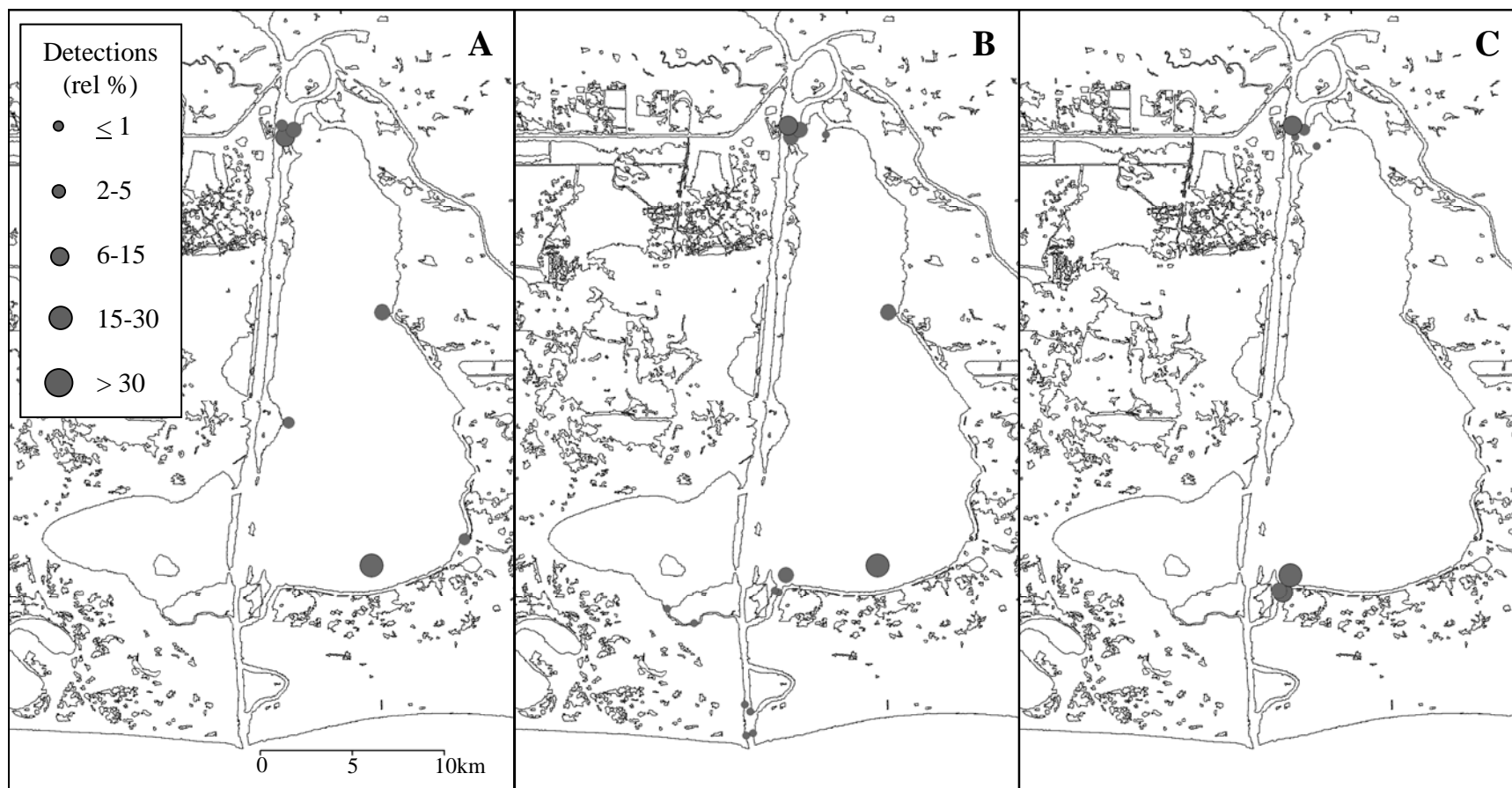


Figure 4.11. Distribution of male spotted seatrout (**A**) before, (**B**) during, and (**C**) after the 2009 freshet. Salinities in the upper bay were less than 5 psu during the peak freshet period (April 20 to May 18, 2009) and greater than 5 psu during the pre- and post-freshet periods: April 11-19, 2009 and May 19-31, 2009; respectively. Bubbles depict the relative frequency (%) of detections recorded at each receiver station within each period (pre, peak, post). Bubble sizes are positively scaled to this metric as indicated in the legend.

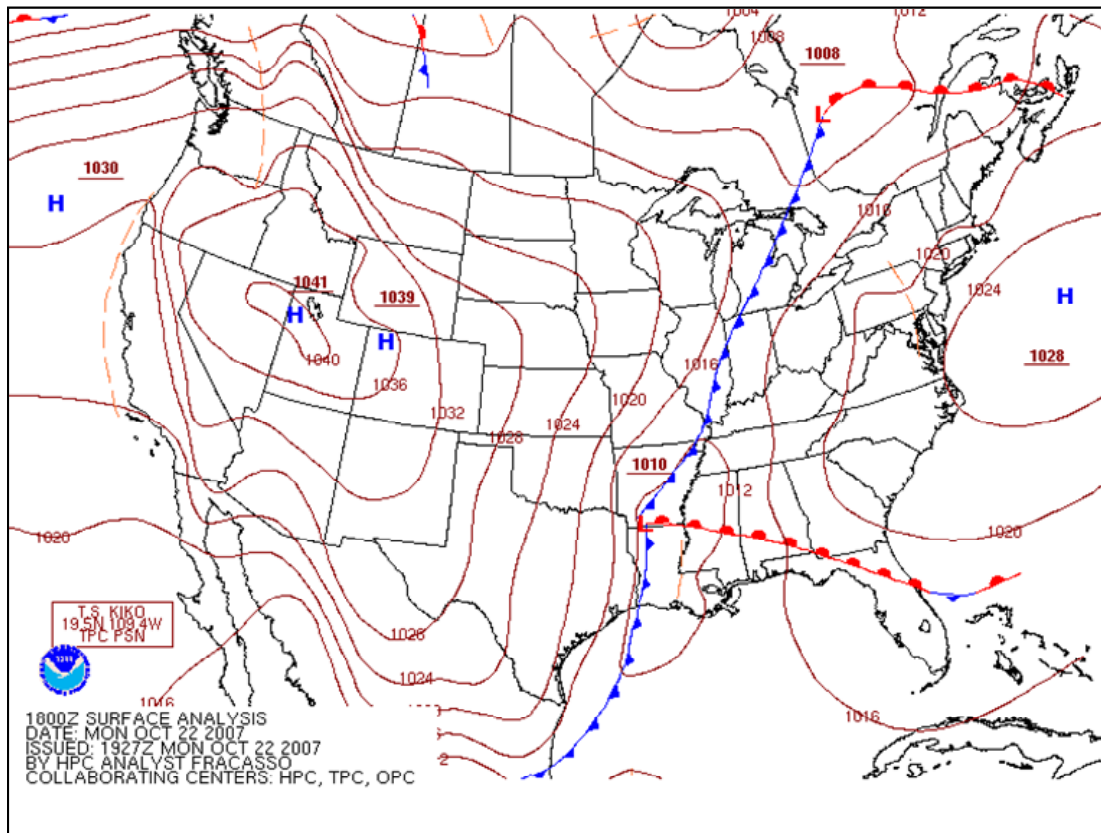


Figure 4.12. Surface weather map illustrating the passage of a cold front across the study area on October 22, 2007. Image is from the Hydrometeorological Prediction Center of the National Oceanic and Atmospheric Administration. [http://www.hpc.ncep.noaa.gov/html/sfc\\_archive.shtml](http://www.hpc.ncep.noaa.gov/html/sfc_archive.shtml)

(Figures 4.14, 4.15). Peak frontal conditions (wind speeds  $> 8 \text{ ms}^{-1}$ ) persisted for 27 and 20 consecutive hours during the 2007 and 2008 fronts, respectively. After the passage of fronts ( $< 3$  days), winds were generally light ( $< 4 \text{ ms}^{-1}$ ) and northerly (Figures 4.14, 4.15).

Seven fish were detected before, during, and after peak frontal conditions and thus used for movement analyses. Three of these individuals were detected in shallow water during the pre-frontal period, but moved to and utilized deeper water during peak frontal conditions. Specifically, two fish (32, 6115) present in West Cove (depth  $< 1.5 \text{ m}$ ) during the pre-frontal period were detected in the ship channel shortly after the October 2007 front reached the study area (Figures 4.16, 4.17). These individuals appeared to remain in the ship channel during the

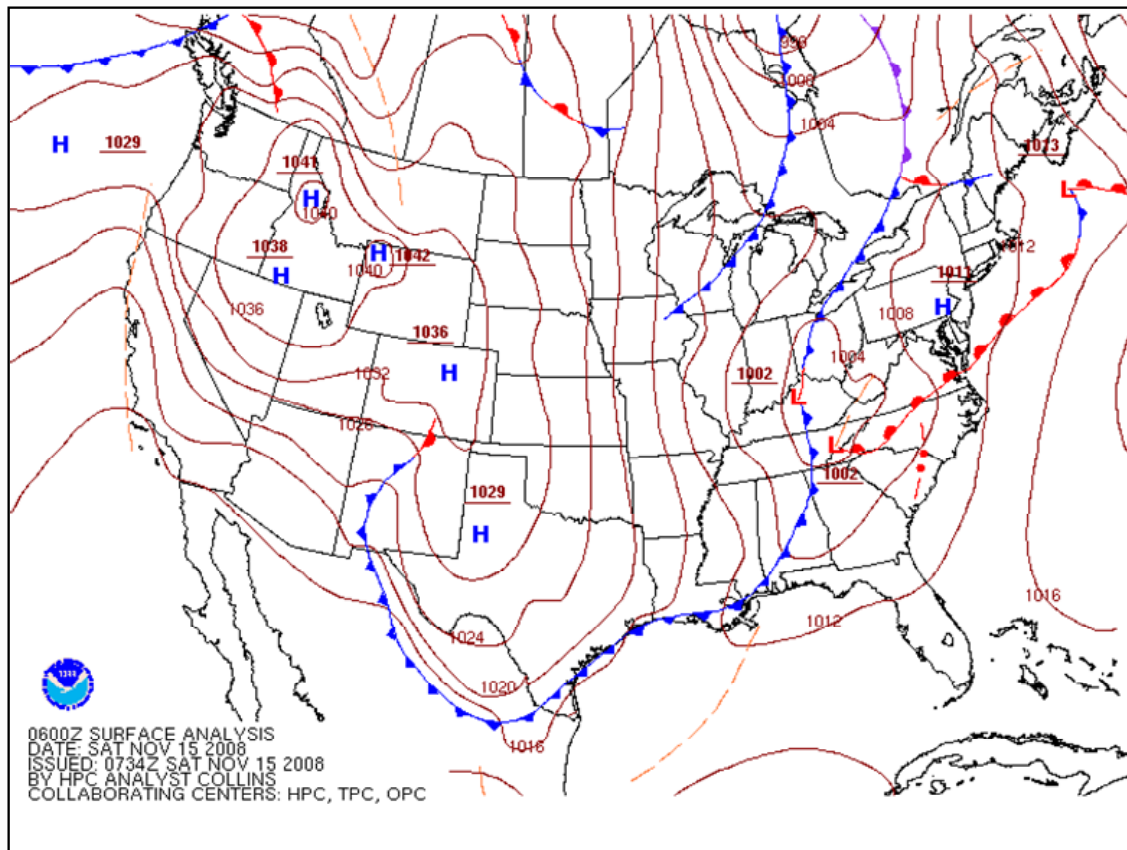


Figure 4.13. Surface weather map illustrating the passage of a cold front across the study area on November 15, 2008. Image is from the Hydrometeorological Prediction Center of the National Oceanic and Atmospheric Administration. [http://www.hpc.ncep.noaa.gov/html/sfc\\_archive.shtml](http://www.hpc.ncep.noaa.gov/html/sfc_archive.shtml)

peak frontal period, after which they moved back to shallower water (Figures 4.16, 4.17).

Additionally, fish 341 exhibited a shift from the shoreline to a deeper (2.5 m) mid-portion of the estuary proper during peak frontal conditions (Figure 4.18). After the front passed and winds subsided, this fish returned to shallower regions of the estuary (Figure 4.18). Four fish (46, 156, 353, and 7826) were present in channel habitats before the fronts passed and appeared to remain there during peak conditions (Figures 4.19-4.22). After the fronts passed, fish 46 moved into the estuary proper, whereas the other individuals (156, 353, 7826) remained in the vicinity of deeper habitats, either the ship channel (fish 353 and 7826) or a sheltered marsh creek (Fish 156) (Figures 4.19-4.22).

Figure 4.14. Meteorological conditions during the passage of the strongest cold front in fall 2007. The time period shown is from three days before to three days after peak frontal conditions. The dashed vertical lines encompass peak frontal conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . Vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Hourly wind data were obtained from the NOAA station near Cameron (see Figure 2.12). Hourly data for air temperatures and barometric pressure were obtained from the Lake Charles airport (see Figure 2.12).



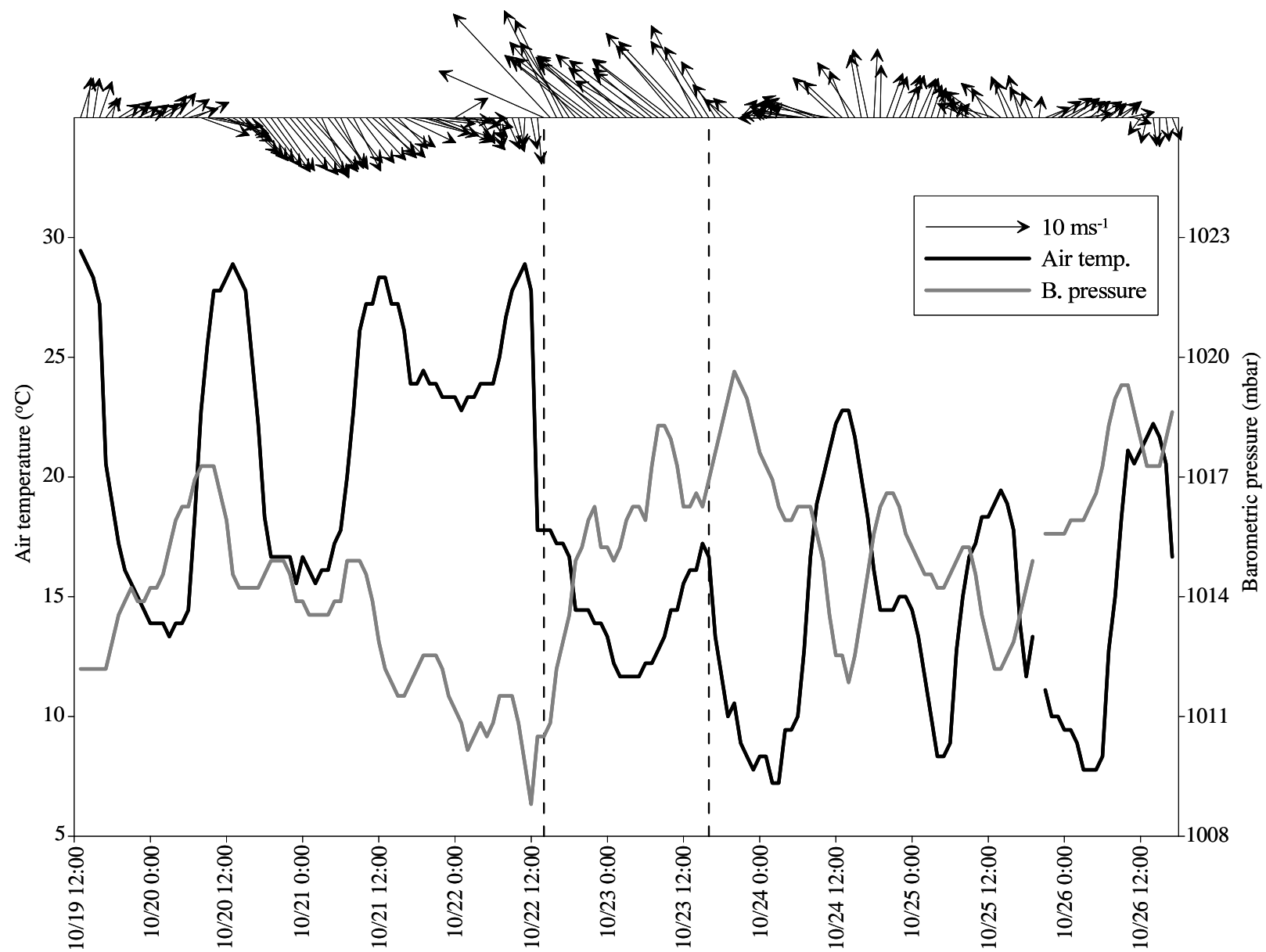
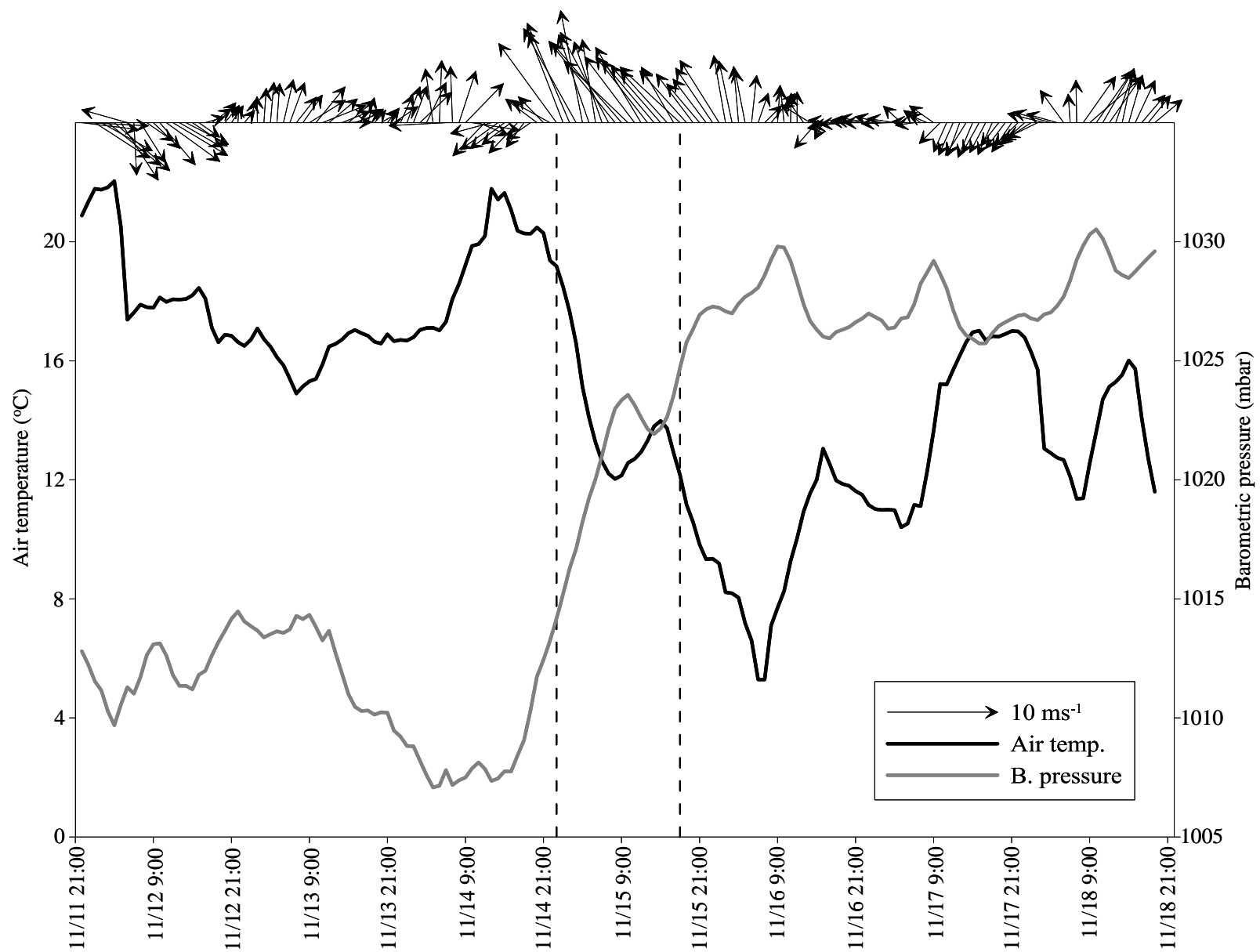


Figure 4.15. Meteorological conditions during the passage of the strongest cold front in fall 2008. The time period shown is from three days before to three days after peak frontal conditions. The dashed vertical lines encompass peak frontal conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . Vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Hourly data for all variables were obtained from the NOAA station near Cameron (see Figure 2.12).



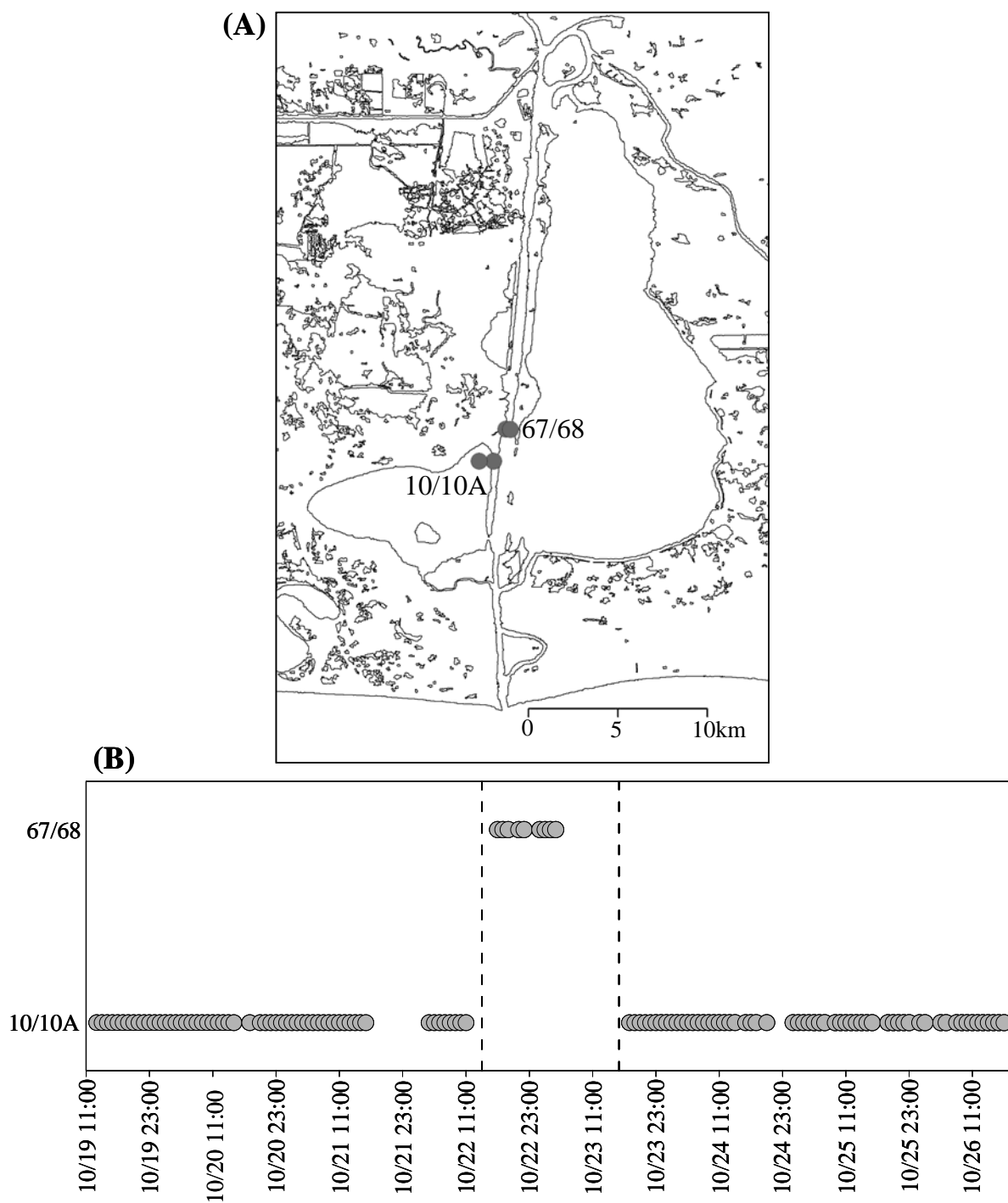


Figure 4.16. **(A)** Receiver stations (grey circles) where fish 32, a 430 mm female, was detected during a week-long period encompassing the three days before and after the passage of a cold front in October 2007. **(B)** Hourly detection chronology of fish 32 during this week-long span. The dashed vertical lines designate the peak frontal period, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

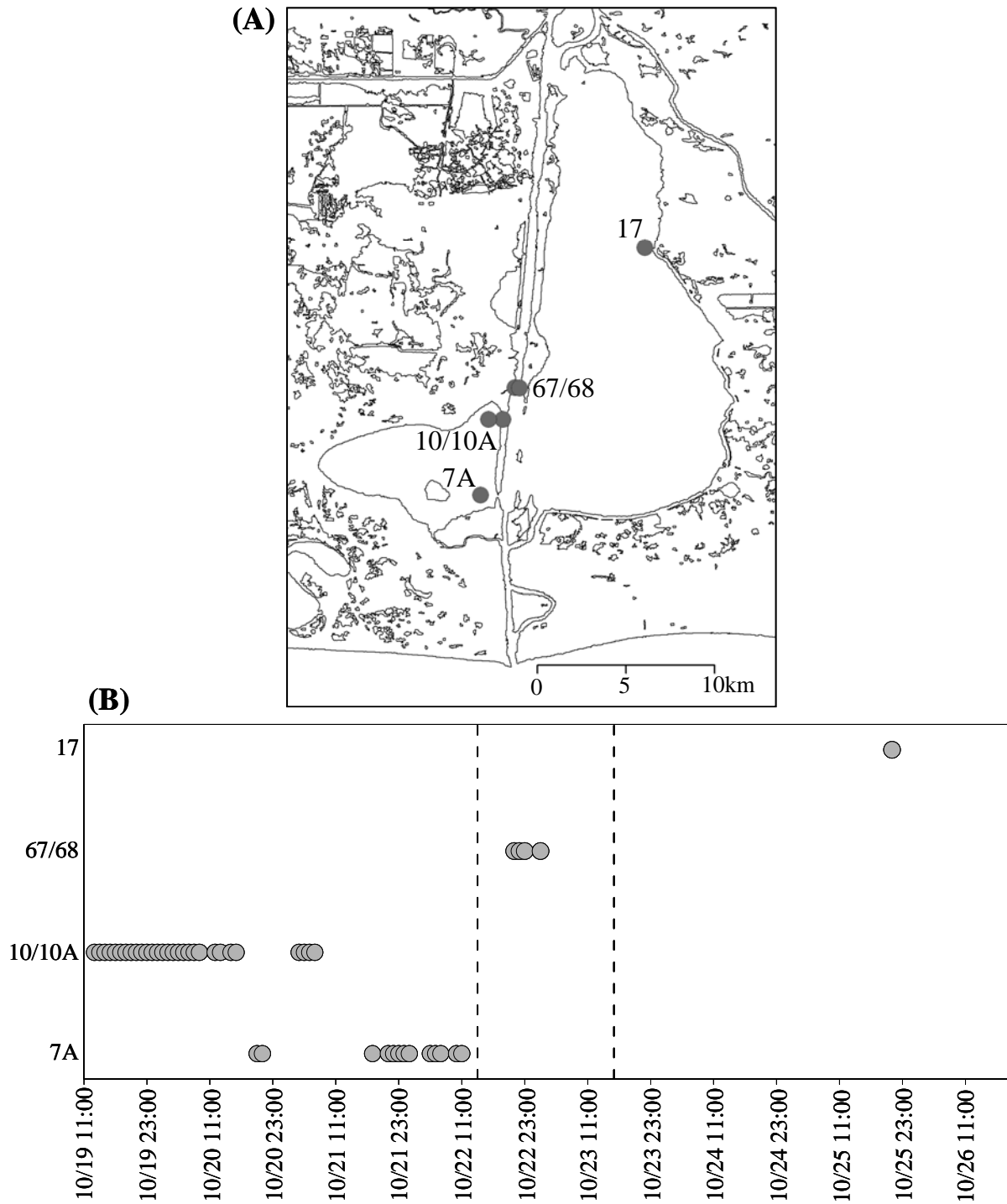


Figure 4.17. (A) Receiver stations (grey circles) where fish 6115, a 372 mm female, was detected during a week-long period encompassing the three days before and after the passage of a cold front in October 2007. (B) Hourly detection chronology of fish 6115 during this week-long span. The dashed vertical lines designate the peak frontal period, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

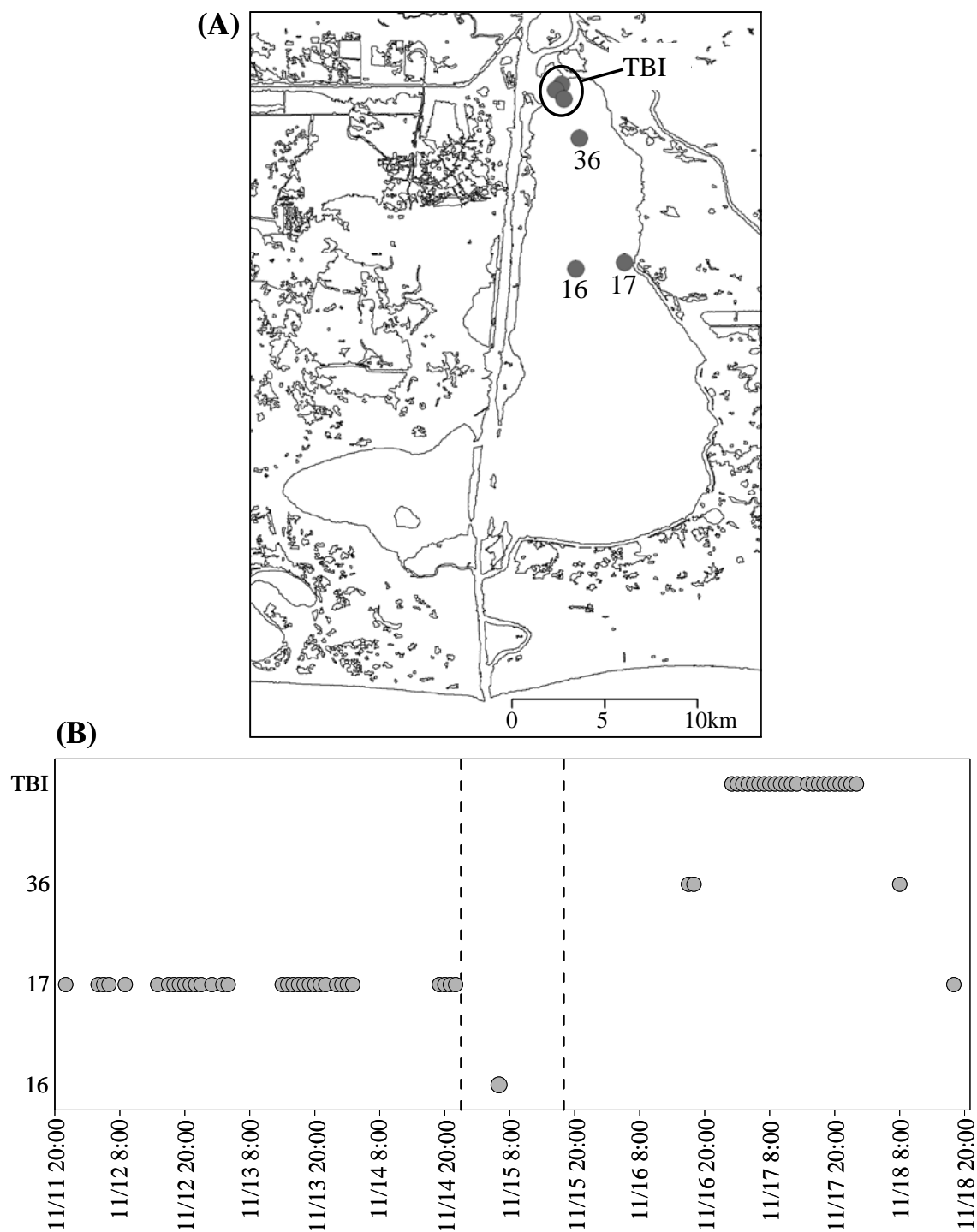


Figure 4.18. **(A)** Receiver stations (grey circles) where fish 341, a 364 mm female, was detected during a week-long period encompassing the three days before and after the passage of a cold front in November 2008. **(B)** Hourly detection chronology of fish 341 during this week-long span. The dashed vertical lines designate the peak frontal period, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).



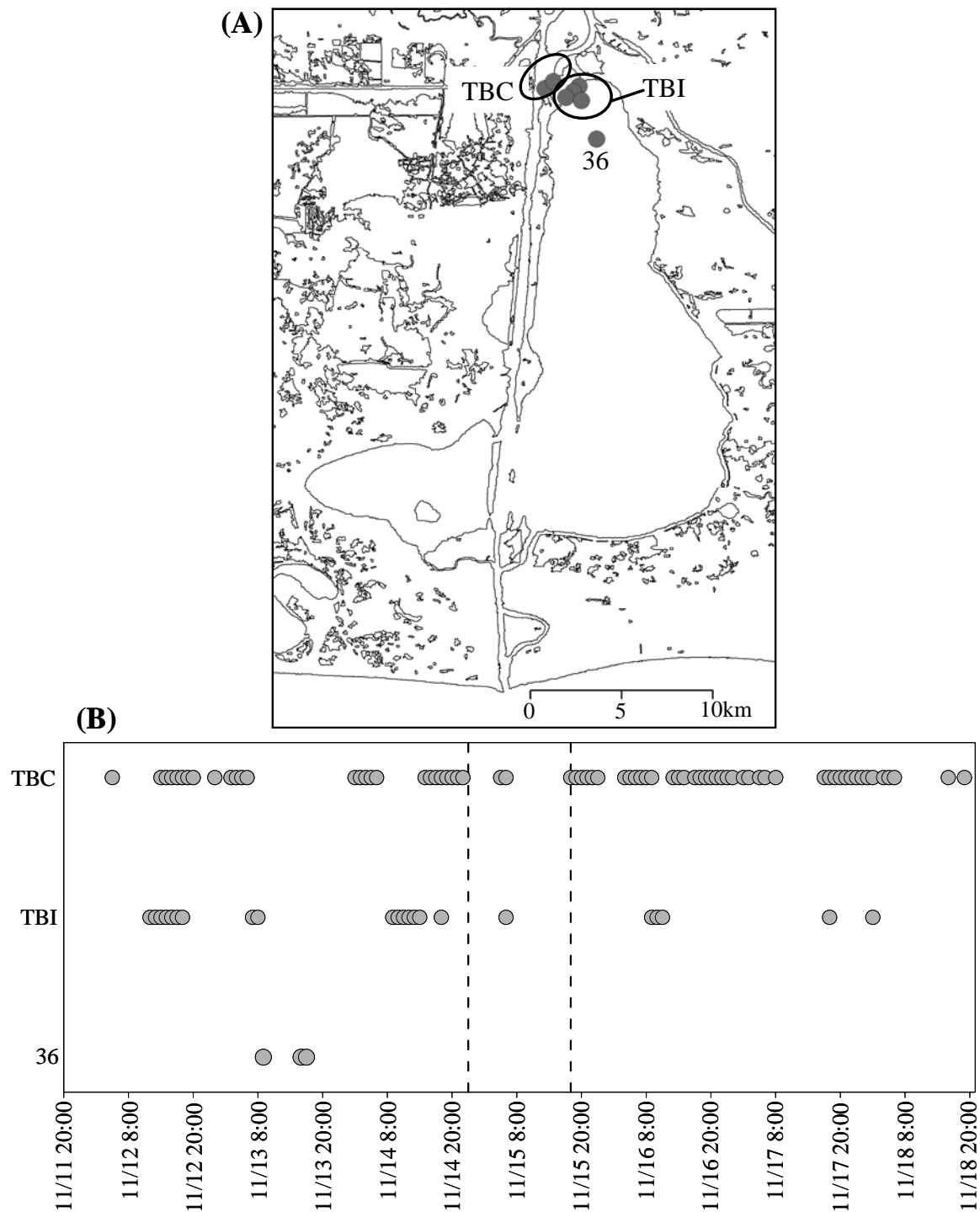


Figure 4.20. **(A)** Receiver stations (grey circles) where fish 353, a 389 mm female, was detected during a week-long period encompassing the three days before and after the passage of a cold front in November 2008. **(B)** Hourly detection chronology of fish 353 during this week-long span. The dashed vertical lines designate the peak frontal period, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).



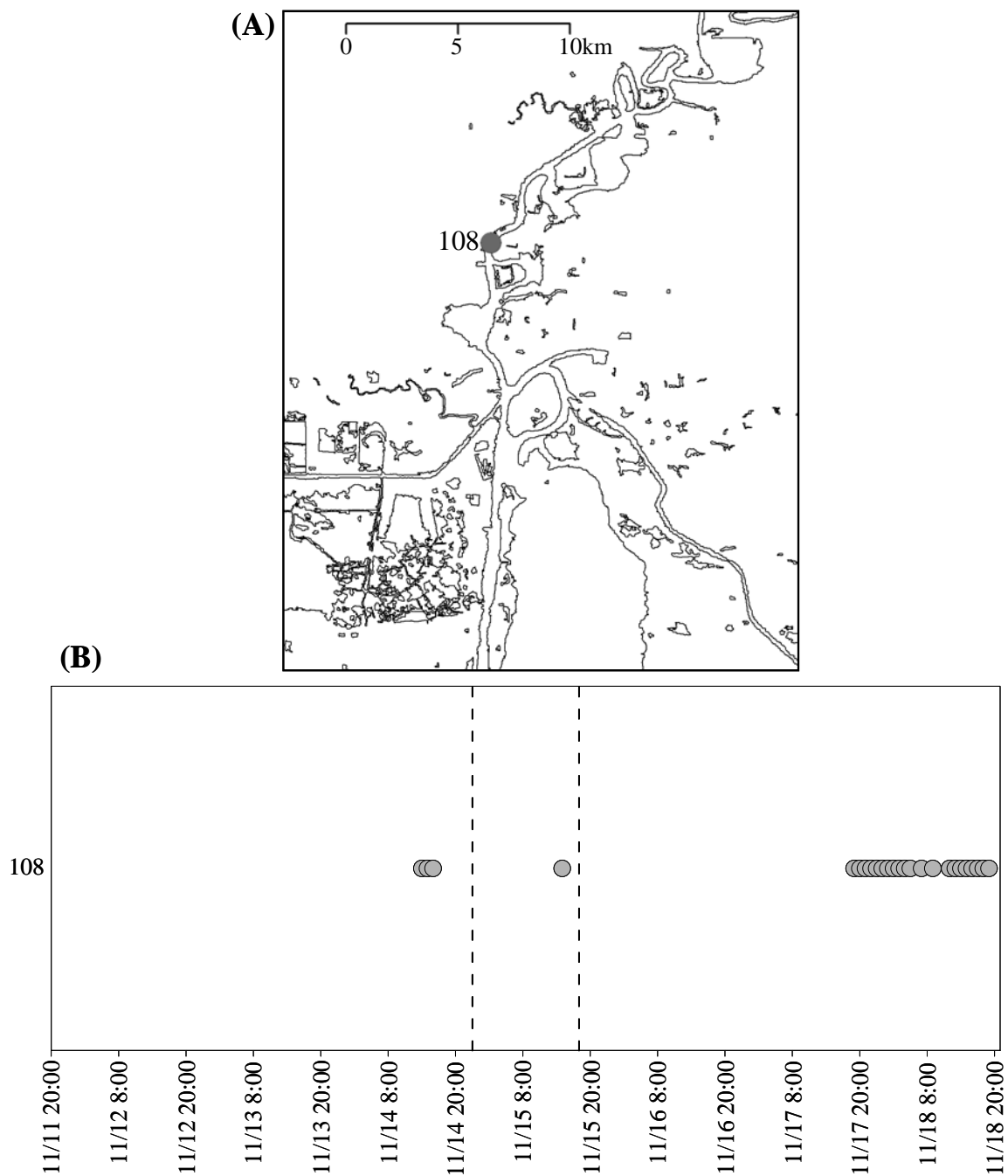


Figure 4.21. **(A)** Receiver stations (grey circles) where fish 7826, a 300 mm male, was detected during a week-long period encompassing the three days before and after the passage of a cold front in November 2008. **(B)** Hourly detection chronology of fish 7826 during this week-long span. The dashed vertical lines designate the peak frontal period, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

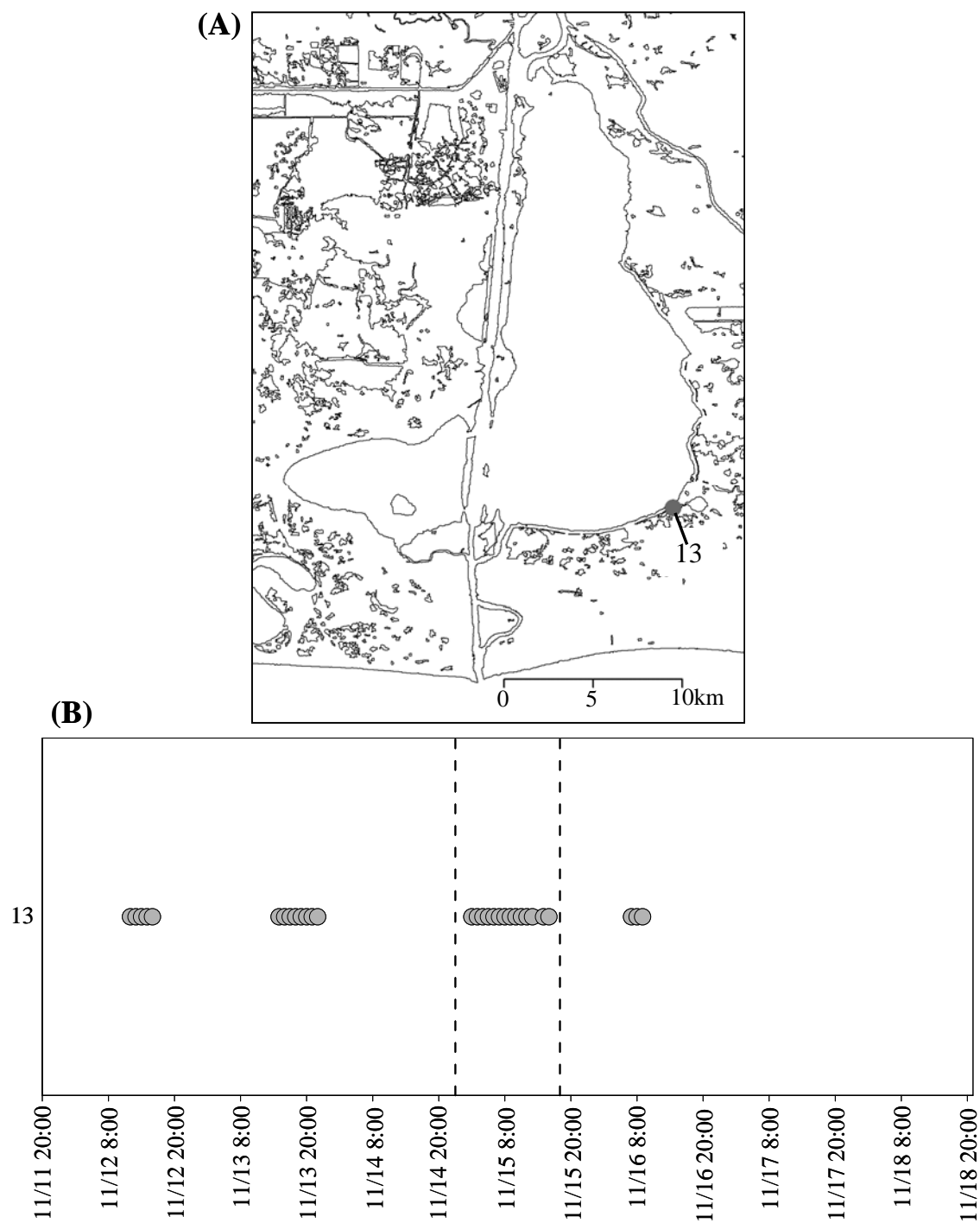


Figure 4.22. **(A)** Receiver stations (grey circles) where fish 156, a 455 mm female, was detected during a week-long period encompassing the three days before and after the passage of a cold front in November 2008. **(B)** Hourly detection chronology of fish 156 during this week-long span. The dashed vertical lines designate the peak frontal period, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

### Tropical Storm Edouard

Tropical Storm Edouard made landfall along the Louisiana-Texas border (~60 km west of the study area) on August 5, 2008 at 0700 (Figure 4.23). The heaviest bands of wind and rain from this cyclone directly impacted the study area (Figure 4.23). Winds were initially NNE and switched to SSE as the storm passed over the study area with maximum sustained winds of 25  $\text{ms}^{-1}$  (Figure 4.24). Storm surge was minimal at approximately 1 m and local precipitation from the storm totaled 10 cm.

Six fish were detected before, during, and after peak storm conditions and thus used for movement analyses. Four of these individuals were present in the estuary proper before the storm hit and moved to and utilized either deeper water or leeward shorelines during peak storm conditions. Specifically, fish 184 and 198 moved to the ship channel where they appeared to remain during the height of the storm and afterwards returned to shallower waters of the estuary (Figures 4.25, 4.26). Fish 172 and 6115 were detected in the windward (western) portion of the estuary before and after the storm, but along the leeward (eastern) shoreline during peak conditions (Figures 4.27, 4.28). Two fish (156, 168) were already utilizing channel habitats before the storm made landfall and appeared to remain there during peak conditions (Figures 4.29, 4.30). After the storm passed, fish 156 remained in the vicinity of a sheltered marsh creek and fish 168 moved into a shallow-water cove (~1 m depth) along the western margin of the ship channel (Figures 4.29, 4.30).

### Depth Distribution

Interestingly, telemetered fish occupied significantly greater depths during periods of peak versus non-peak winds (Wilcoxon rank sum test,  $p < 0.0001$ ). Approximately 80% of all fish depths recorded during non-peak wind conditions (wind speeds  $< 8 \text{ ms}^{-1}$ ) were less than 1 m

(Figure 4.31). Yet, the majority (75%) of fish depths recorded during peak wind conditions (wind speeds  $> 8 \text{ ms}^{-1}$ ) exceeded 1 m, indicating that fish avoided surface waters (upper 1 m of the water column) during peak frontal/storm conditions (Figure 4.31).

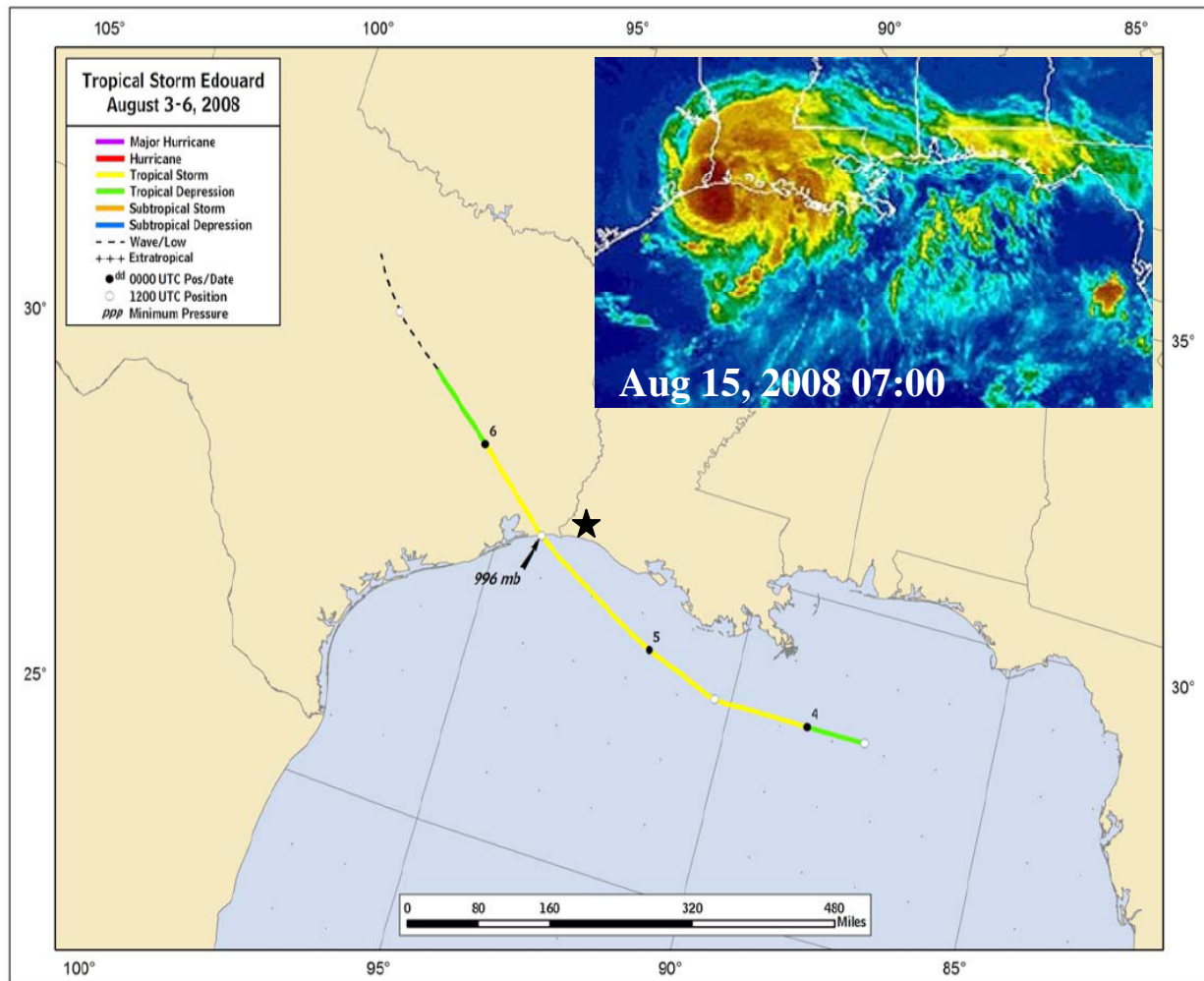
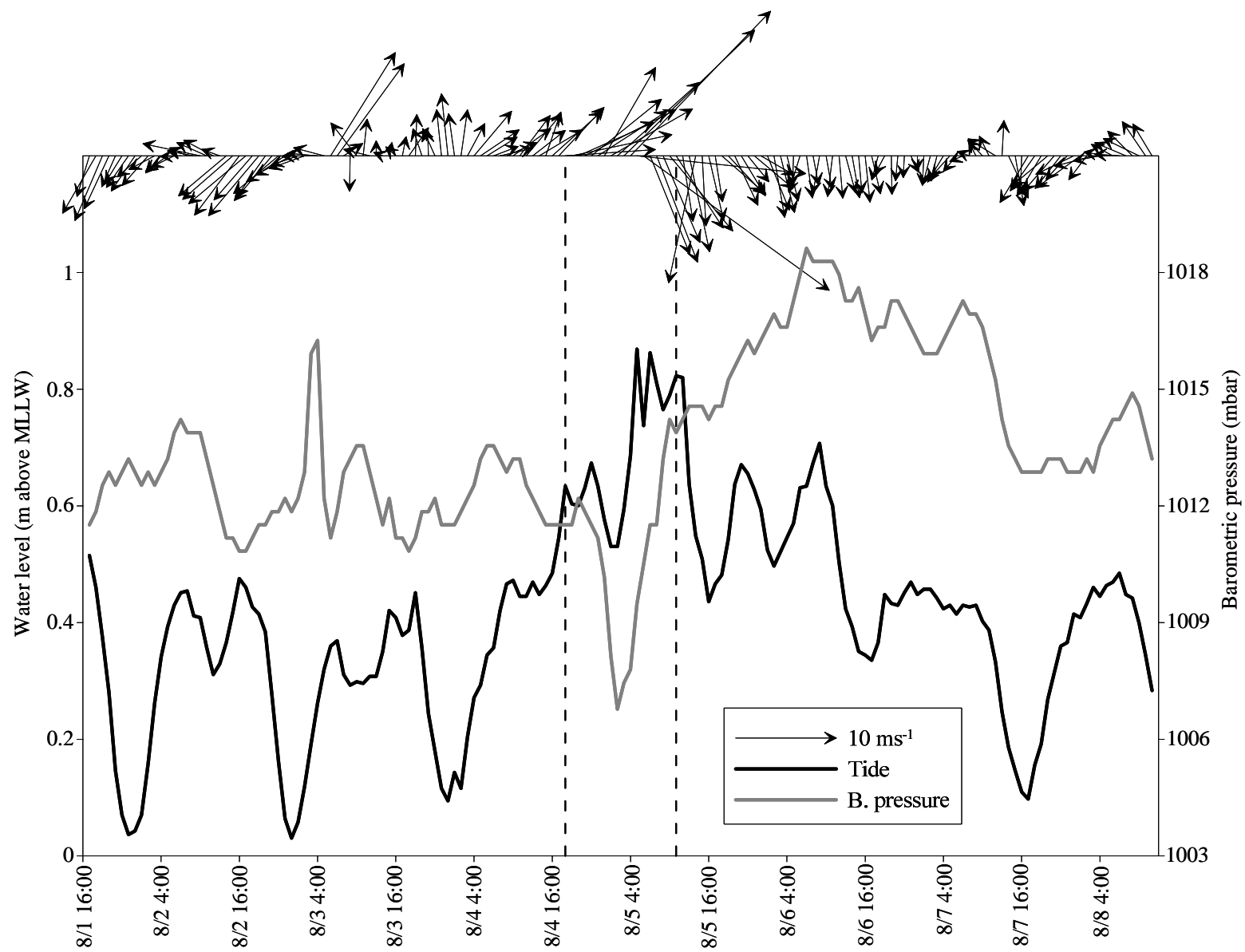


Figure 4.23. Official track of Tropical Storm Edouard from the National Hurricane Center. The black star depicts the study area, Calcasieu Lake. The infrared satellite image of the storm at landfall is shown in the upper right.

Figure 4.24. Meteorological and hydrological conditions during the passage of Tropical Storm Edouard. The time period shown is from three days before to three days after peak storm conditions. The dashed vertical lines encompass peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . Vector lengths are positively scaled to wind speed as indicated in the legend; arrows point towards the direction from which the wind was blowing. Hourly wind and tide data were obtained from the USGS station near Cameron (see Figure 2.12). Barometric pressure data were obtained from the Lake Charles airport (see Figure 2.12).



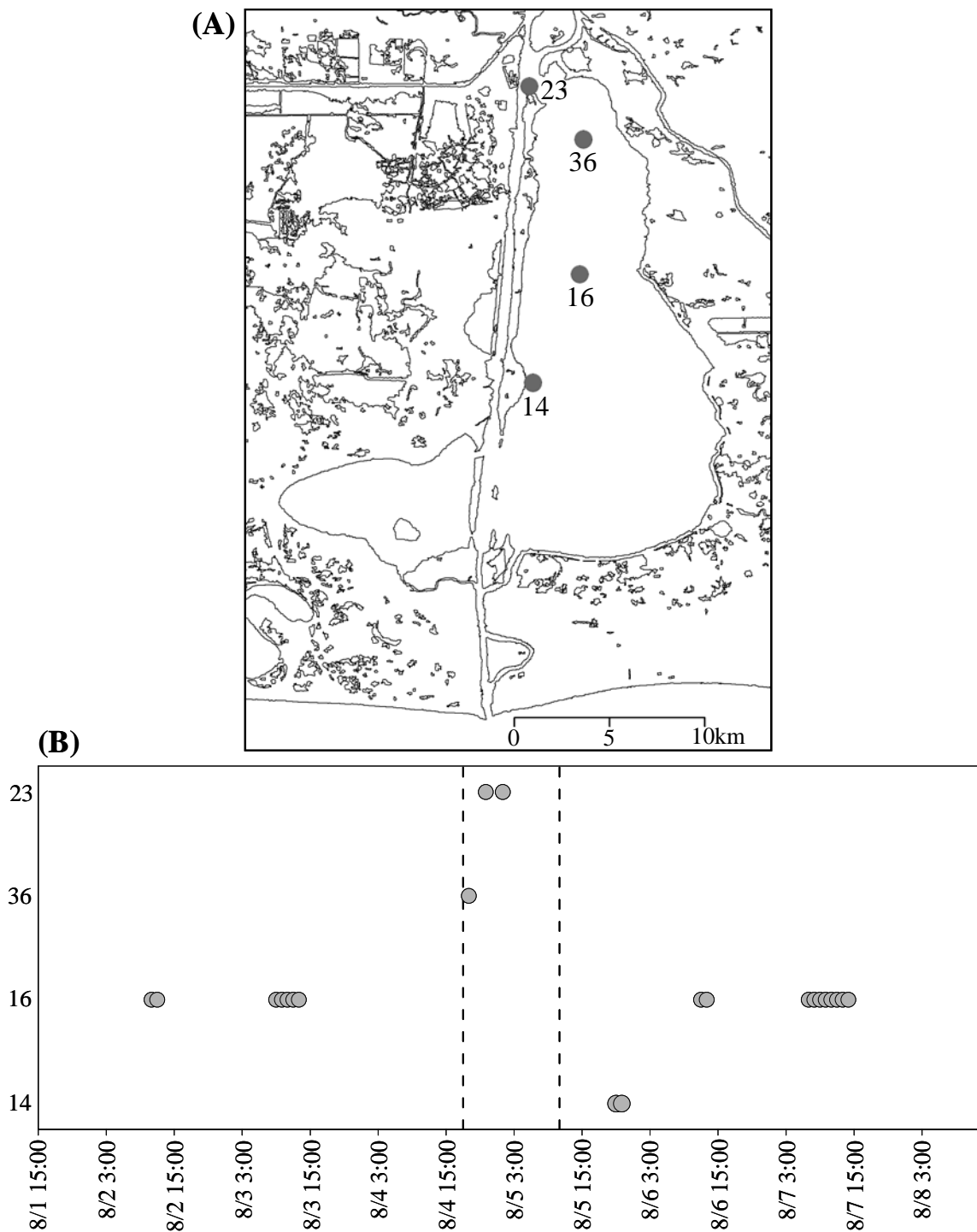


Figure 4.25. (A) Receiver stations (grey circles) where fish 184, a 490 mm female, was detected during a week-long period encompassing the three days before and after Tropical Storm Edouard made landfall (August 5, 2008). (B) Hourly detection chronology of fish 184 during this week-long span. The dashed vertical lines designate peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

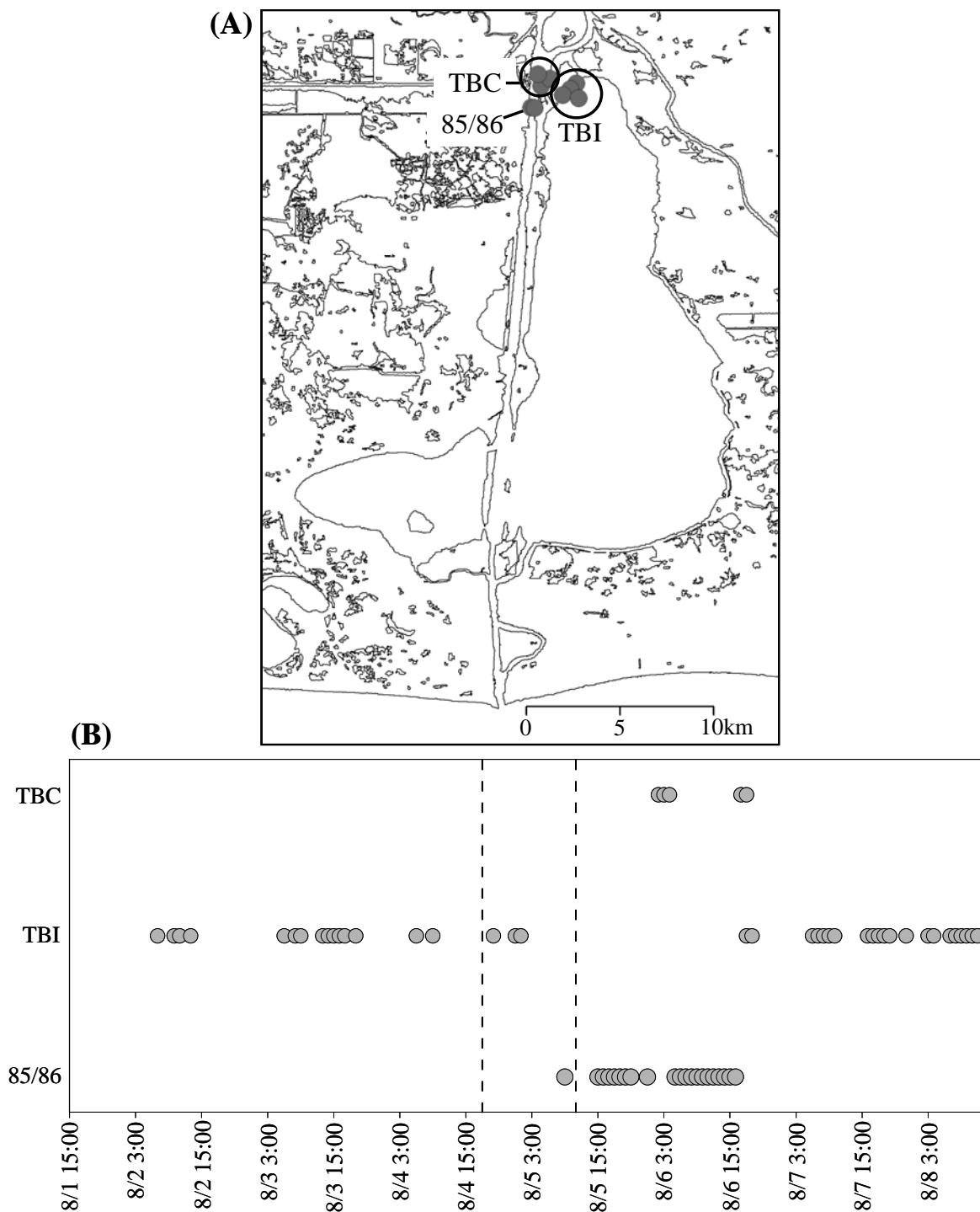


Figure 4.26. (A) Receiver stations (grey circles) where fish 198, a 620 mm female, was detected during a week-long period encompassing the three days before and after Tropical Storm Edouard made landfall (August 5, 2008). (B) Hourly detection chronology of fish 198 during this week-long span. The dashed vertical lines designate peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).



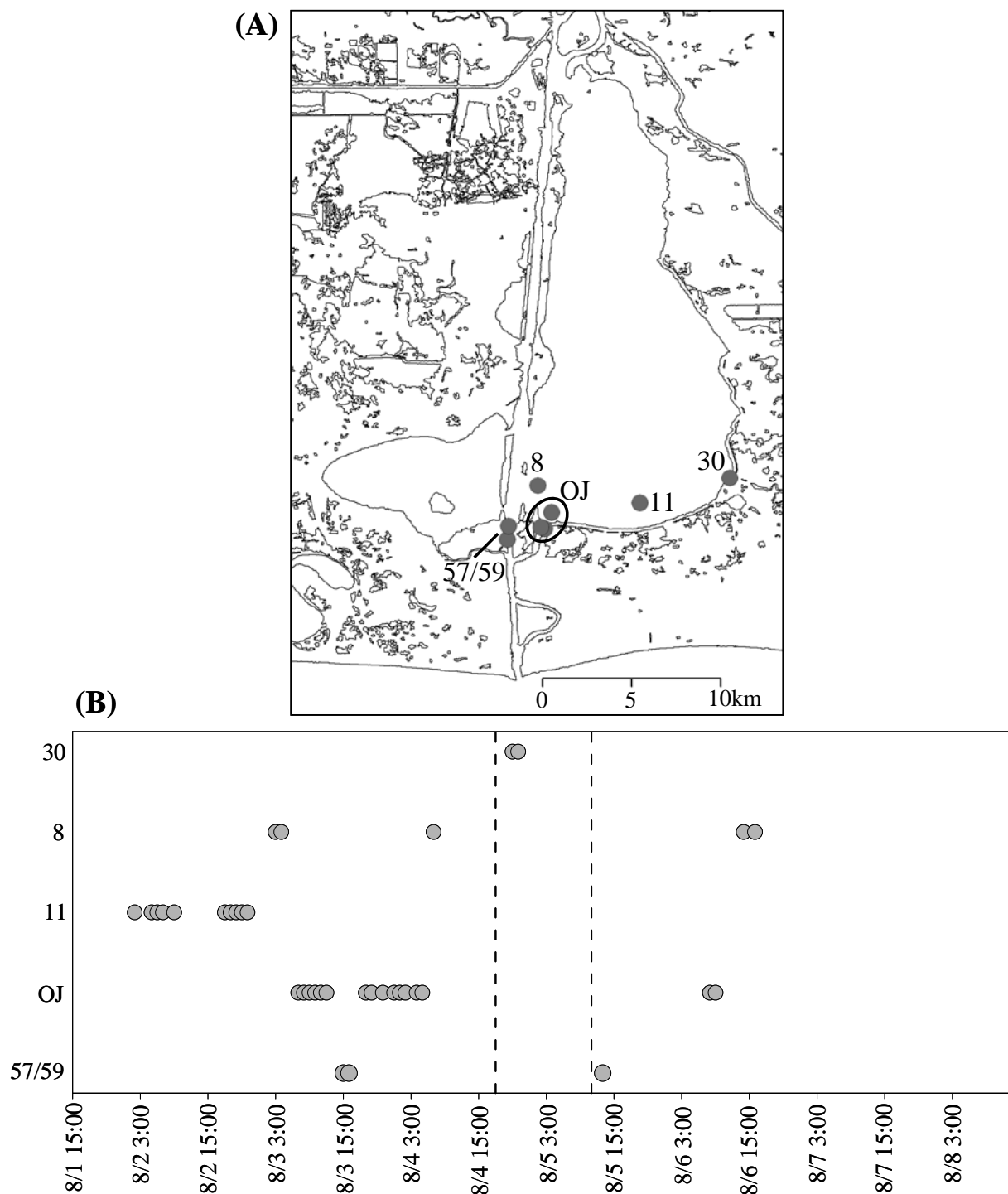


Figure 4.27. **(A)** Receiver stations (grey circles) where fish 172, a 482 mm female, was detected during a week-long period encompassing the three days before and after Tropical Storm Edouard made landfall (August 5, 2008). **(B)** Hourly detection chronology of fish 172 during this week-long span. The dashed vertical lines designate peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

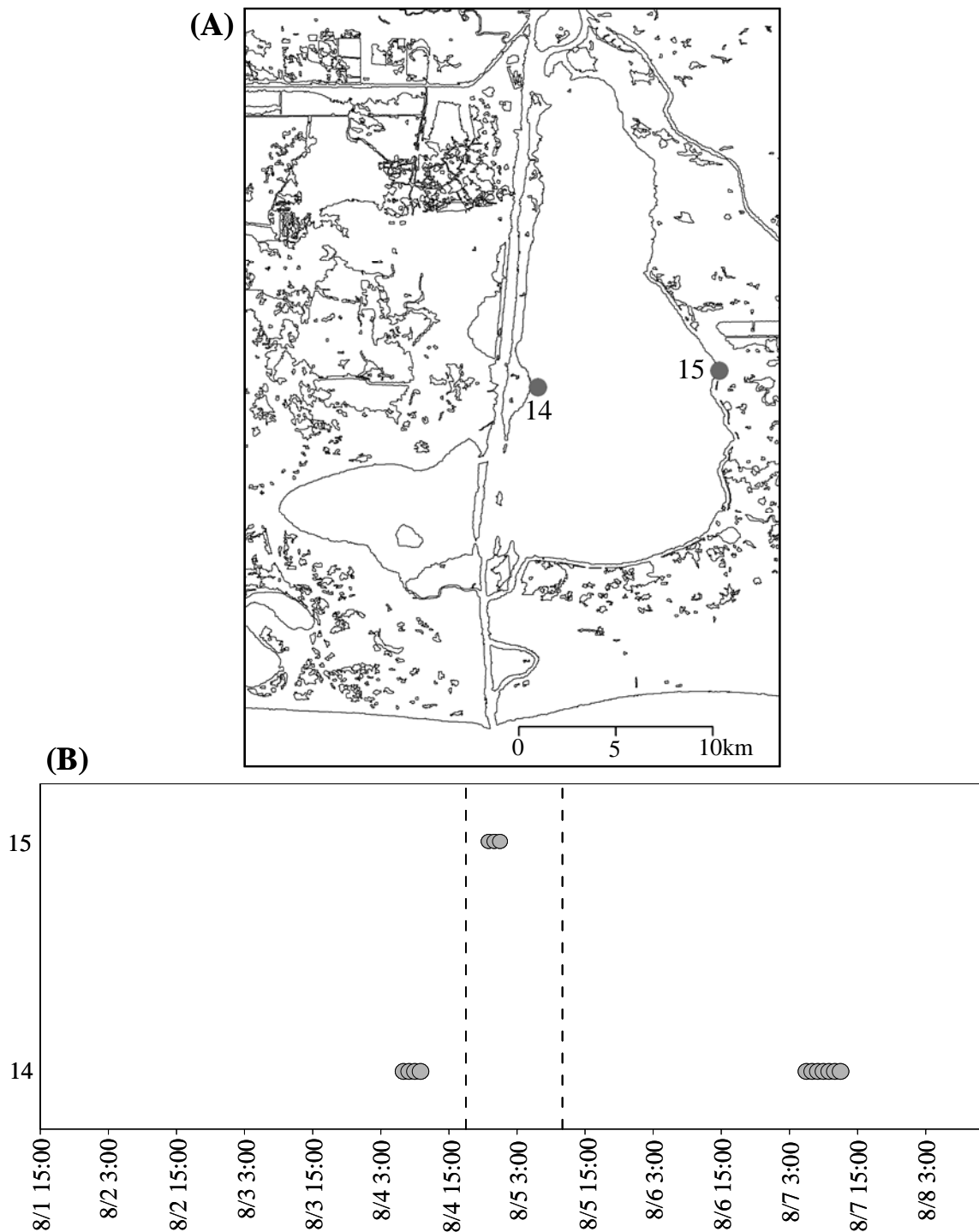


Figure 4.28. (A) Receiver stations (grey circles) where fish 6115, a 372 mm female, was detected during a week-long period encompassing the three days before and after Tropical Storm Edouard made landfall (August 5, 2008). (B) Hourly detection chronology of fish 6115 during this week-long span. The dashed vertical lines designate peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

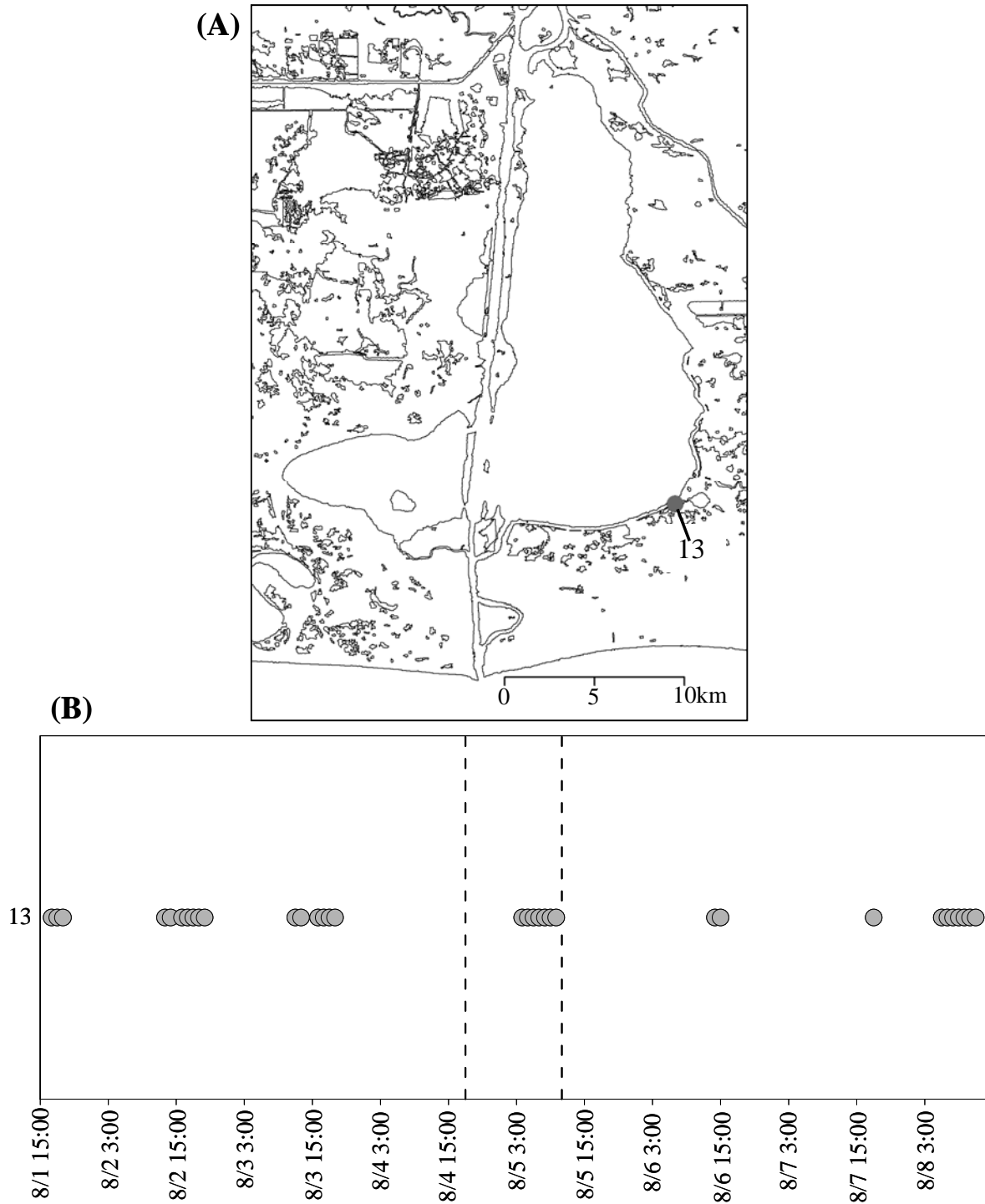


Figure 4.29. **(A)** Receiver stations (grey circles) where fish 156, a 455 mm female, was detected during a week-long period encompassing the three days before and after Tropical Storm Edouard made landfall (August 5, 2008). **(B)** Hourly detection chronology of fish 156 during this week-long span. The dashed vertical lines designate peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

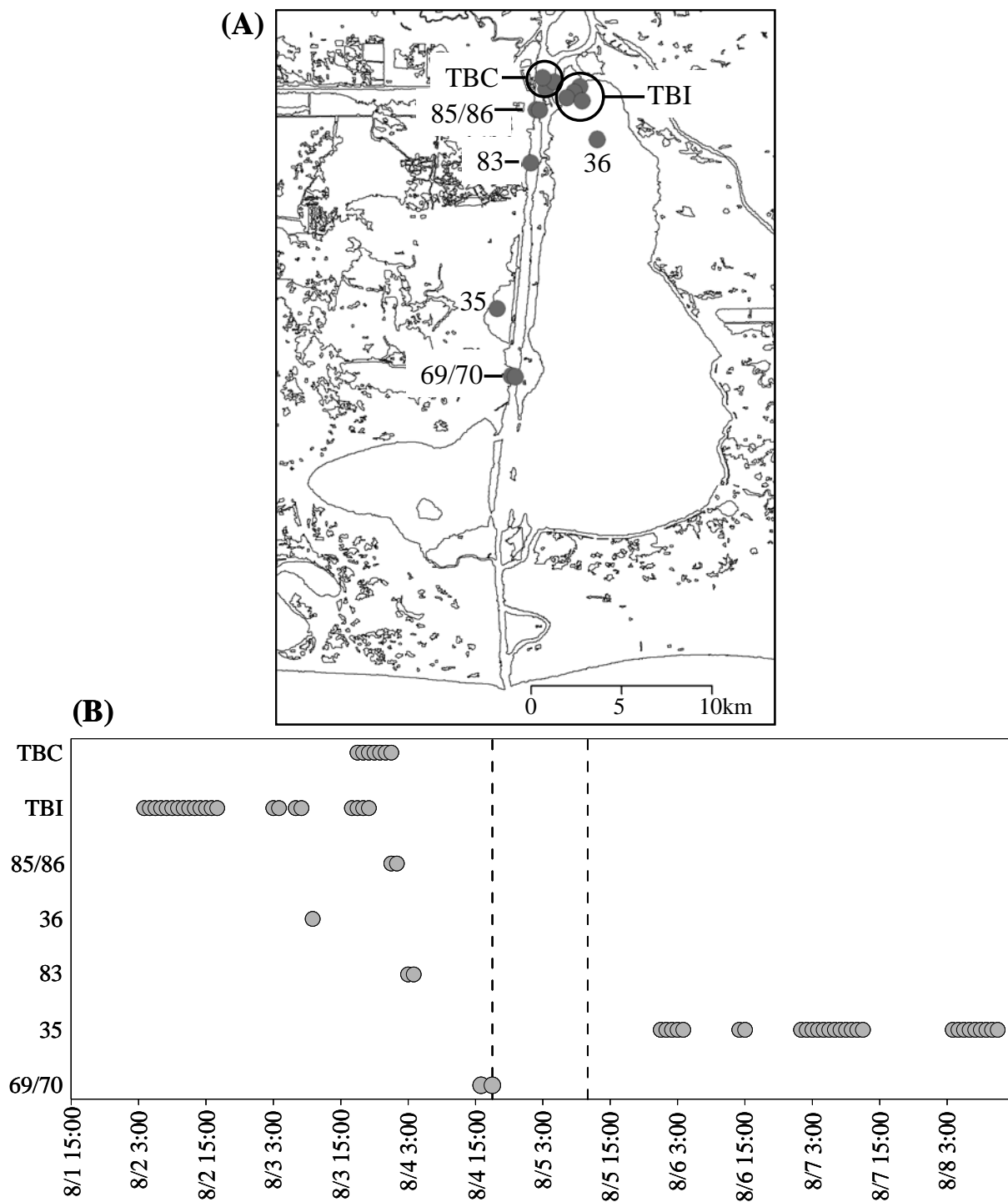


Figure 4.30. (A) Receiver stations (grey circles) where fish 168, a 532 mm female, was detected during a week-long period encompassing the three days before and after Tropical Storm Edouard made landfall (August 5, 2008). (B) Hourly detection chronology of fish 168 during this week-long span. The dashed vertical lines designate peak storm conditions, when wind speeds exceeded  $8 \text{ ms}^{-1}$ . The grey circles indicate hours during which this fish was detected at respective receiver stations (y-axis).

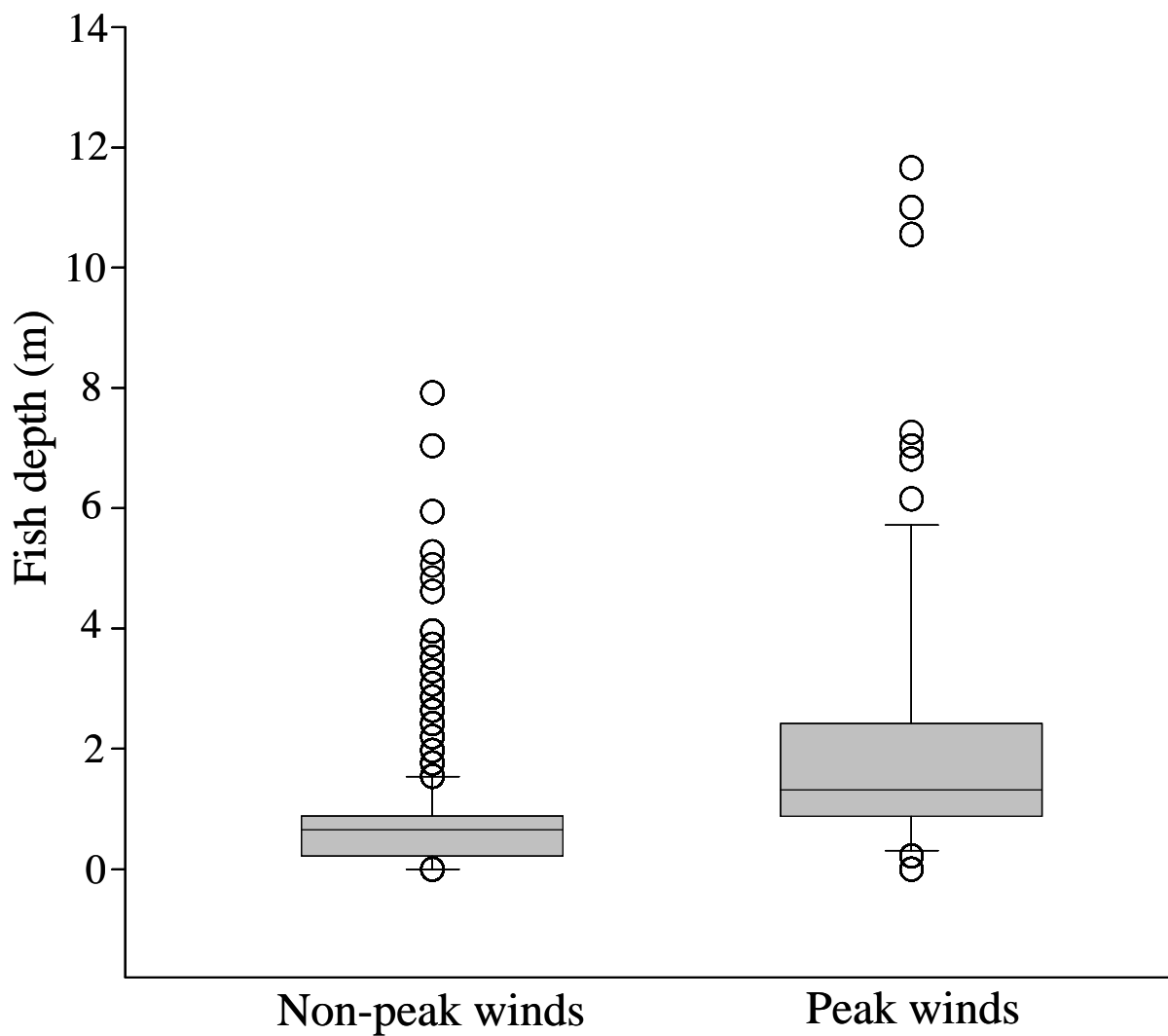


Figure 4.31. Fish depths during peak versus non-peak winds associated with the two cold fronts and Tropical Storm Edouard. Depth data were gleaned from the seven sensor-equipped fish that were detected before, during, and after frontal/storm passages. Detections recorded when wind speeds exceeded  $8 \text{ ms}^{-1}$  were classified as ‘peak’ detections; those recorded during the three days before and after peak wind conditions were classified as ‘non-peak’ detections. Depth detections were pooled across individuals and events for each wind class. A total of 1,162 fish depths were recorded during non-peak conditions and 163 during peak conditions.

## Discussion

Adult spotted seatrout showed clear responses to meteorological events. The sex-specific avoidance of low salinities associated with heavy rain events (freshets) was particularly interesting as this finding was completely unexpected. The movement responses of fish to severe weather (high-wind) events such as cold fronts and tropical storms more closely followed my prediction that fish would primarily use deeper, calmer regions of the estuary as refuge during peak storm conditions. Knowledge of the behavioral responses of this recreationally important species to weather events can aid interpretations of catch data in support of stock assessment. Also, a better understanding of the environmental preferences of this abundant species may enhance ecosystem models by providing insight on the time and space domains in which interactions occur with other species.

### Effects of Salinity on Fish Distribution

Freshet-induced low salinities appeared to have a direct effect on female spotted seatrout. During the two largest freshets, females vacated the upper bay after three to four days of low salinities ( $< 5$  psu) and did not re-appear until salinities increased ( $> 5$  psu) two to four weeks later. It is possible this response was due to factors other than salinity that also changed considerably during freshets (e.g., water temperature). Both freshets occurred during spring, when females likely utilize warmer waters to promote gonad (egg) development in preparation for the summer spawning season. Accordingly, if freshets caused a sharp drop in water temperature in the upper bay, but the lower bay remained warmer, the observed shift of females to the lower bay could be due to fish seeking out more suitable (warmer) temperatures. Yet, during neither freshet was there a decline in water temperature. In fact, temperature and salinity (measured at the USGS station in the upper bay, Figure 4.1) exhibited a significant negative

correlation during both freshets periods ( $r = -0.48$  in 2008,  $r = -0.31$  in 2009), indicating the warmest temperatures occurred during peak freshet (low salinity) conditions. More importantly, water temperatures in the upper and lower bay (USGS station 8, see Figure 2.1) were very similar during freshets (mean daily difference =  $0.1^{\circ}\text{C}$  in 2008,  $0.02^{\circ}\text{C}$  in 2009; paired t-tests:  $p > 0.6$  across years). Thus, the increased utilization of the lower bay by females during peak freshet conditions appeared to be unrelated to temperature. It is possible that reduced salinities during freshets led to a re-distribution of prey species to the lower bay, which in turn caused female spotted seatrout to leave the upper bay in search of more profitable foraging areas (i.e., salinity had an indirect vs. direct effect). Male spotted seatrout, which ranged in size from 300 to 435 mm TL, continued to utilize the upper bay during low salinity periods. Yet, females, including those of comparable size to the resident males, were absent from the upper bay during the same time periods. Assuming spotted seatrout of the same size can consume similar prey items (*sensu* Scharf et al. 2000), there is no reason to believe that reduced prey concentrations caused females to leave the upper bay because their similarly-sized male counterparts remained therein and presumably had a suitable forage base. Therefore, I conjecture that low salinities had a more direct (e.g., physiological) effect on female spotted seatrout which triggered them to move to the lower bay where salinities were higher.

The sex-specific avoidance of low salinities may be related to osmoregulatory costs. Osmoregulation is an energetically demanding process that can comprise up to 15% of maintenance costs (standard metabolism) in euryhaline teleosts (Kirschner 1993; Kidder et al. 2006a). Osmoregulatory costs are highest in extreme salinities due to the increased osmotic (ionic) gradient between the ambient environment and a fish's internal body fluids which are maintained at fairly constant solute concentrations (Sampaio and Bianchini 2002; Kidder et al.

2006b). Accordingly, during the major freshets observed in this study the upper bay probably constituted a stressful osmotic environment for adult spotted seatrout due to its low salinities ( $< 5$  psu). Nevertheless, only females avoided this region during freshets. This sex-specific behavior may be related to energy optimization. In oviparous fishes that do not exhibit parental care such as spotted seatrout, females maximize their fitness via fecundity, whereas males maximize fitness through mating opportunities (Magurran and Garcia 2000; Hutchings 2006). Thus, there is greater selective pressure for females to maximize growth and achieve a large body size that will accommodate more eggs and potentially increase reproductive success (Roff 1983). Indeed, female spotted seatrout are substantially larger-at-age and have much higher growth rates than males (Maceina et al. 1987; Murphy and Taylor 1994; Nieland et al. 2002). I hypothesize that in order to maximize the energy available for somatic growth and reproduction (egg production), female spotted seatrout generally avoid environmental conditions that are energetically expensive and pose additional maintenance costs. This would explain why females primarily utilized the lower bay (intermediate salinities) during freshets as maintenance costs associated with osmoregulation would be lower there due to the decreased osmotic gradient. Occupancy of this region would allow more acquired energy to be channeled into processes such as growth and reproduction. Males, on the other hand, may be more tolerant of extreme abiotic conditions and exhibit a more ‘exploratory’ life history than females. For instance, males may be more willing to traverse sub-optimal (i.e., energetically demanding) habitats to increase their access to potential mates or prey resources. My telemetry data support this notion. The lowest salinities occur in the northern extreme of the estuary (Figure 4.3). Of the fish detected in this region (six northern-most receivers; see Figure 2.2) whose sex could be determined, all were males. Moreover, system emigration rates were three-fold higher for males than females (see chapter 3).



Although under-studied, sex-specific preferences of abiotic variables have been documented for other estuarine and marine organisms. Swain (1997) and Swain and Morgan (2001) showed that female plaice (*Hippoglossoides platessoides*) utilized warmer ( $\sim 1^{\circ}\text{C}$ ) waters than males during the summer growing season in the Northwest Atlantic Ocean. The authors concluded this response was associated with fitness (growth) optimization. Specifically, they hypothesized females had higher foraging rates than males that allowed them to meet the increased metabolic demands of warmer habitats in which higher growth rates could be achieved. In another study, Jury et al. (1994a) determined via laboratory experiments that female lobsters (*Homarus americanus*) generally avoided and were more sensitive to low salinities (10-25) than males. In addition, oxygen consumption at low salinities was two-fold higher in females than males (Jury et al. 1994b). Only male lobsters are seasonally abundant in New England estuaries. The authors concluded this sex-specific distribution pattern is a result of the increased osmoregulatory efficiency of males.

Regardless of the underlying reasons for sex-specific environmental preferences of fishes, such relationships, if they are consistent and robust, can have great utility in fisheries assessment and management. The avoidance of low salinities by female spotted seatrout demonstrated in this study implies an important distributional constraint for this species, namely that adult females are rare in oligohaline waters (salinities 0.5-5 psu). This information could be used to adjust catch data to facilitate more accurate interpretations of temporal abundance trends of the spawning stock (i.e., mature females). As an example, to calculate mean or median catch-per-unit effort (CPUE), data could be excluded from stations with low salinities ( $< 5$  psu at the time of sampling). Without such an adjustment, mean CPUEs may be biased low because data (e.g., nil to minimal catches) would be included from stations where females are likely absent

and thus not available to the fishing gear. For instance, low annual CPUEs in ‘wet’ years could be erroneously interpreted as declines in female abundance when they are indeed related to altered fish distribution (accessibility). One uncertainty that may limit the broad applicability of such an approach is whether the low salinity ‘avoidance threshold’ (~5 psu) determined herein based on a single estuary is universal for this species throughout the Gulf of Mexico. This threshold may apply to coastal regions east of the Mississippi River through upper Texas (i.e., from the Mississippi River Delta to Galveston Bay) which are more directly influenced by freshwater flows from the Mississippi and Atchafalaya Rivers and thus have similar intermediate salinity regimes (Solis and Powell 1999). However, spotted seatrout inhabiting higher salinity environments such as the hypersaline coastal lagoons of South Texas and polyhaline estuaries of southwest Florida may exhibit different salinity preferences due to local adaptations. Fish in these regions may possess higher blood osmolalities; as a corollary, the onset of osmotic stress may occur at higher salinities (i.e., > 5 psu). As an example of adaptation to local salinity regimes, Kucera et al. (2002) found that female spotted seatrout collected from the hypersaline Laguna Madre were only capable of producing buoyant eggs in high salinities (30, 40 psu) as eggs produced in lower salinities (20 psu), atypical of this system, were negatively buoyant and thus would not be viable in the wild.

Knowledge of salinity preferences may also allow management agencies to better gauge the effects of freshwater diversions on aquatic communities. Freshwater diversions are now employed, particularly in Louisiana, as a major restoration tool to combat the dramatic loss of coastal wetlands and saltwater intrusion by diverting sediment-laden riverine waters to marsh habitats that have long been starved of sediments due to the leveeing of the Mississippi River after the Great Flood of 1927 (Chesney et al. 2000; Cowan et al. 2008; Day et al. 2007; Day et al.

2009). These diversions can substantially alter salinity regimes in the estuarine basins receiving diverted freshwater, specifically by lowering salinities and expanding the oligohaline zone (de Mutsert 2010). Such changes may result in shifts in the distribution of nektonic species, which in turn could lead to altered predator-prey interactions and modified community structure. Therefore, an integral component in understanding and predicting the nature and magnitude of such responses is knowledge of species-specific salinity preferences. Conventional wisdom is that adult spotted seatrout prefer higher salinities (meso- to polyhaline) and generally avoid oligohaline waters (Wohschlag and Wakeman 1978; Bourgeois et al. 1995). Tabb (1966) went so far to state this species was “intolerable” of salinities below 5 psu and this notion has generally persisted among both scientists and managers alike. Yet, my study, one of the first to use high resolution acoustic telemetry to investigate the movements and distribution of this species, suggests that salinity preference of adults is strongly sex-specific, in that only females avoid low salinities. This result, which differs from the traditional notion of low salinity avoidance irrespective of sex, has important implications for predicting responses of this recreationally important species to freshwater diversions. First, diversions should result in greater displacement of females than males. Consequently, anglers seeking larger trophy-size fish, most of which are females, would probably have to travel greater distances (i.e., towards the Gulf of Mexico) to find fish. Moreover, male spotted seatrout may still constitute an important predator or prey species in regions of the estuary in which salinities have been reduced ( $< 5$  psu) following diversions. This concept could be incorporated into and potentially enhance EcoPath/EcoSim predator-prey models that seek to quantify the effects of anthropogenic perturbations on aquatic communities as in de Mutsert (2010). For example, sex-specific salinity tolerances of spotted seatrout could be used in ecosystem models for the northern Gulf of

Mexico which currently assume a single tolerance function for this species (de Mutsert 2010). Understanding species-specific environmental preferences is clearly relevant to the current initiative of ecosystems-based fisheries management because this information can provide useful bounds on the set of abiotic conditions under which biotic (e.g., predator-prey) interactions among species are expected (Shepherd et al. 2002; Alcaraz et al. 2008).

#### Movement Responses to Severe Weather

Spotted seatrout primarily utilized deeper and presumably less turbulent habitats during storm events (cold fronts and TS Edouard). Sensor data from depth transmitters indicated that in addition to simply being present in channel regions during the height of storms, fish were actually utilizing the deeper water afforded by these habitats. Spotted seatrout occupied significantly greater depths ( $> 1$  m) and generally avoided surface waters ( $< 1$  m) during peak storm conditions. This behavior was likely due to the avoidance of highly turbulent flow. Turbulent energy associated with the wind-induced breaking of surface waves decreases with increasing depth in the water column (Schoellhamer 1995; Mann and Lazier 1996). Thus, by occupying greater depths fish can avoid turbulent surface waters where it may be difficult, and energetically expensive, to maintain proper body orientation. During storm events, turbulent flow may easily extend to the sea bed in the shallow habitats ( $< 2$  m) characteristic of the estuary proper. Therefore, channel habitats in this system likely function as important deep-water refuges during storm events. Still, a few individuals (2 of 13, 15%) were detected in shallow water habitats during peak storm conditions. This behavior was only observed during Tropical Storm Edouard, when water levels were about 1 m higher than during cold fronts. Furthermore, both fish were detected along the leeward (eastern) shoreline of the estuary. Turbulent flow in

this region may have been reduced due to higher water levels and limited wave action, thus facilitating fish use of the area.

Interestingly, the movement response of spotted seatrout to storm events was context-dependent. Most fish that were present in shallow water before the passage of storms exhibited a habitat shift by moving to and utilizing deeper water during peak storm conditions. Yet, individuals that were already present in deeper channel habitats prior to the storms did not exhibit a shift, but instead appeared to remain in the same deep-water location for the duration of the storm. This result implies that spotted seatrout do not display a concerted ‘flight’ response to extreme weather events. Such a response has been suggested for juvenile blacktip sharks based on the synchronicity and magnitude of their emigration from a shallow Florida estuary (Terra Ceia Bay) prior to the passage of a tropical storm (Heupel et al. 2003). The authors of this study argued that because barometric pressure was anomalously low and exhibiting the most change (of those variables measured) during the observed mass migration, it served as a cue for sharks to leave the bay before conditions deteriorated. This type of innate response does not seem to occur in spotted seatrout, given that fish showed different responses to the same storm events (i.e., some fish moved and some did not). Rather, my data suggest the response of adult spotted seatrout to severe weather events is more subtle and depends upon their location within a bay when a storm hits. Particularly, those individuals utilizing shallow, exposed environments prior to the storm probably seek out the nearest refuge when conditions begin to deteriorate (e.g., turbulence increases beyond some threshold). Meanwhile, those individuals occupying channel habitats can simply increase their depth distribution by moving deeper in the water column to avoid turbulent surface waters that occur during peak storm conditions. However, given that surveys of abundance are rarely conducted during peak storm conditions due to safety concerns,

the rapid return of fish to locations that resemble pre-storm conditions are unlikely to bias survey results. That said, these results may differ in the face of major storms that produce higher winds, more rain, and greater storm surges. These factors may extend the time it takes for estuarine conditions to return to pre-storm conditions.

This study highlighted the power of using remote acoustic telemetry to examine the movements and behavior of aquatic organisms. The responses documented herein could not easily be obtained with more conventional methods such as mark-recapture or point-sampling (e.g., weekly gear deployment) that simply lack the temporal resolution of telemetry studies. Continuous monitoring of the estuary with telemetry receivers allowed fish distribution (throughout the system) and use of particular regions (upper bay) to be linked to environmental variables (salinity) that were also constantly recorded. This approach unearthed the surprising result of sex-specific salinity preference. Furthermore, remote telemetry facilitated the evaluation of fish behavior during extreme weather conditions, when it is dangerous to sample using ‘manual’ methods that require the presence of researchers at the study site. Remote acoustic telemetry is an exciting tool that can reveal novel information on relationships between organisms and their environment that not only improves our understanding of the basic ecology and life history of aquatic species, but is also useful for resource management.

## **References**

- Agresti, A. 1996. An introduction to categorical data analysis. John and Wiley Sons, New York.
- Alcaraz, C., A. Bisazza, and E. García-Berthou. 2008. Salinity mediates the competitive interactions between invasive mosquitofish and an endangered fish. *Oecologia* 155:205-213.
- Baker, Jr. W.B., G.C. Matlock, L.W. McEachron, A.W. Green, and H.E. Hegen. 1986. Movement, growth and survival of spotted seatrout tagged in Bastrop Bayou, Texas. *Contributions in Marine Science* 22:91-101.

- Bigelow, K.A., C.H. Boggs, and X. He. 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. *Fisheries Oceanography* 8(3):178-198.
- Bourgeois, M.J., V. Guillory, and H. Blanchet. 1995. A biological and fisheries profile for Louisiana spotted seatrout, Cynoscion nebulosus. Louisiana Department of Wildlife and Fisheries, Fisheries Management Plan Series 3(1), Baton Rouge, Louisiana.
- Brill, R.W., and M.E. Lutcavage. 2001. Understanding environmental influences on movements and depth distributions of tunas and billfishes can significantly improve population assessments. *American Fisheries Society Symposium* 25:179-198.
- Chesney, E.J., D.M. Baltz, and R.G. Thomas. 2000. Louisiana estuarine and coastal fisheries and habitats: perspectives from a fish's eye view. *Ecological Applications* 10(2):350-366.
- Childs, A.R., P.D. Cowley, T.F. Naesje, A.J. Booth, W.M. Potts, E.B. Thorstad, and F. Okland. 2008. Do environmental factors influence the movements of estuarine fish? A case study using acoustic telemetry. *Estuarine, Coastal, and Shelf Science* 78:227-236.
- Cowan, Jr., J.H., C.B. Grimes, and R.F. Shaw. 2008. Life history, history, hysteresis, and habitat changes in Louisiana's coastal ecosystem. *Bulletin of Marine Science* 83(1):197-215.
- Day, Jr., J.W., D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, K. Orth, H. Mashriqui, D.J. Reed, L. Shabman, C.A. Simenstad, B.J. Streever, R.R. Tilley, C.C. Watson, J.T. Wells, and D.F. Whigham. 2007. Restoration of the Mississippi delta: lessons from hurricanes Katrina and Rita. *Science* 315:1679-1683.
- Day, Jr., J.W., J.E. Cable, J.H. Cowan, Jr., R. DeLaune, K. de Mutsert, B. Fry, H. Mashriqui, D. Justic, P. Kemp, R.R. Lane, J. Rick, S. Rick, L.P. Rozas, G. Snedden, E. Swenson, R.R. Twilley, and B. Wissel. 2009. The impacts of pulsed reintroduction of river water on a Mississippi delta coastal basin. *Journal of Coastal Research Special Issue* 54:225-243.
- de Mutsert, K. 2010. The effects of a freshwater diversion on nekton species biomass distributions, foodweb pathways, and community structure in a Louisiana estuary. Doctoral dissertation. Louisiana State University, Baton Rouge, Louisiana.
- Feng, Z., and C. Li. 2010. Cold-front induced flushing of the Louisiana bays. *Journal of Marine Systems* 82:252-264.
- Franklin, J.L. 2008. Tropical Storm Edouard. National Hurricane Center, Tropical Cyclone Report AL052008, Miami, Florida.
- Fréon, P., F. Gerlotto, and O.A. Misund. 1993. Consequences of fish behavior for stock assessment. *ICES Marine Science Symposium* 196:190-195.

- Hendon, J.R., J.R. Warren, J.S. Franks, and M.V. Buchanan. 2002. Movements of spotted seatrout (*Cynoscion nebulosus*) in Mississippi coastal waters based on tag-recapture. *Gulf of Mexico Science* 20(2):91-97.
- Heupel, M.R., Simpfendorfer, C.A., and R.E. Hueter. 2003. Running before the storm: blacktip sharks respond to falling barometric pressure associated with Tropical Storm Gabrielle. *Journal of Fish Biology* 63:1357-1363.
- Heupel, M.R., and C.A. Simpfendorfer. 2008. Movement and distribution of young bull sharks *Carcharinus leucas* in a variable estuarine environment. *Aquatic Biology* 1:277-289.
- Hobday, A.J., R. Kawabe, Y. Takao, K. Miyashita, and T. Itoh. 2009. Correction factors derived from acoustic tag data for a juvenile southern bluefin tuna abundance index in southern western Australia. Pages 405-422 in J.L. Nielsen, H. Arrizabalaga, N. Fragoso, A. Hobday, M. Lutcavage, and J. Sibert, editors. *Tagging and Tracking of Marine Animals with Electronic Devices, Reviews: Methods and Technologies in Fish Biology and Fisheries*. Springer, London.
- Hutchings, J.A. 2006. Survival consequences of sex-biased growth and the absence of a growth-mortality tradeoff. *Functional Ecology* 20:347-353.
- Jones, M.S., and K.B. Rogers. 1998. Palmetto bass movements and habitat use in a fluctuating Colorado irrigation reservoir. *North American Journal of Fisheries Management* 18:640-648.
- Jury, S.H., M.T. Kinnison, W.H. Howell, and W.H. Watson. 1994a. The behavior of lobsters in response to reduced salinity. *Journal of Experimental Marine Biology and Ecology* 180:23-37.
- Jury, S.H., M.T. Kinnison, W.H. Howell, and W.H. Watson. 1994b. The effects of reduced salinity on lobster (*Homarus americanus* Milne-Edwards) metabolism: implications for estuarine populations. *Journal of Experimental Marine Biology and Ecology* 176:167-185.
- Jury, S.H., W.H. Howell, and W.H. Watson. 1995. Lobster movements in response to a hurricane. *Marine Ecology Progress Series* 119:305-310.
- Kawabata, Y., J. Okuyama, K. Asami, K. Okuzawa, K. Yoseda, and N. Arai. 2010. Effects of a tropical cyclone on the distribution of hatchery-reared black-spot tuskfish *Choerodon schoenleinii* determined by acoustic telemetry. *Journal of Fish Biology* 77:627-642.
- Kidder, G.W., C.W. Petersen, and R.L. Preston. 2006a. Energetics of osmoregulation: II. water flux and osmoregulatory work in the euryhaline fish, *Fundulus heteroclitus*. *Journal of Experimental Zoology* 305A:318-327.



- Kidder, G.W., C.W. Petersen, and R.L. Preston. 2006b. Energetics of osmoregulation: I. oxygen consumption by *Fundulus heteroclitus*. *Journal of Experimental Zoology* 305A:309-317.
- Kirschner, L.B. 1993. The energetics of osmotic regulation in ureotelic and hypoosmotic fishes. *The Journal of Experimental Zoology* 267:19-26.
- Klimley, A.P., B.J. Le Boeuf, K.M. Cantara, J.E. Richert, S.F. Davis, and S. Van Sommeran. 2001. Radio-acoustic positioning as a tool for studying site-specific behavior of the white shark and other large marine species. *Marine Biology* 138:429-446.
- Knott, D.M., and R.M. Martore. 1991. The short-term effects of Hurricane Hugo on fishes and decapod crustaceans in the Ashley River and adjacent marsh creeks, South Carolina. *Journal of Coastal Research* SI8:335-356.
- Kucera, C.J., C.K. Faulk, and G.J. Holt. 2002. The effect of spawning salinity on eggs of spotted seatrout (*Cynoscion nebulosus*, Cuvier) from two bays with historically different salinity regimes. *Journal of Experimental Marine Biology and Ecology* 272:147-158.
- Langtimm, C.A., M.D. Krohn, J.P. Reid, B.M. Stith, and C.A. Beck. 2006. Possible effects of the 2004 and 2005 hurricanes on manatee survival rates and movement. *Estuaries and Coasts* 29(6A):1026-1032.
- Maceina, M.J., D.N. Hata, T.L. Linton, and A.M. Landry, Jr. 1987. Age and growth analysis of spotted seatrout from Galveston Bay, Texas. *Transactions of the American Fisheries Society* 116:54-59.
- Magurran, A.E., and C.M. Garcia. 2000. Sex differences in behavior as an indirect consequence of mating system. *Journal of Fish Biology* 57:839-857.
- Mallin, M.A., and C.A. Corbett. 2006. How hurricane attributes determine the extent of environmental effects: multiple hurricanes and different coastal systems. *Estuaries and Coasts* 29(6A):1046-1061.
- Mann, K.H., and J.R.N. Lazier. 1996. Dynamics of marine ecosystems. Biological-physical interactions in the oceans, 2<sup>nd</sup> edition. Blackwell Science, Malden, Massachusetts.
- Moeller, C.C., O.K. Huh, H.H. Roberts, L.E. Gumley, and W.P. Menzel. 1993. Response of Louisiana coastal environments to a cold front passage. *Journal of Coastal Research* 9(2):434-447.
- Murphy, M.D., and R.G. Taylor. 1994. Age, growth, and mortality of spotted seatrout in Florida waters. *Transactions of the American Fisheries Society* 123:482-497.

- Nieland, D.L., R.G. Thomas, and C.A. Wilson. 2002. Age, growth, and reproduction of spotted seatrout in Barataria Bay, Louisiana. *Transactions of the American Fisheries Society* 131:245-259.
- Roff, D.A. 1983. An allocation model of growth and reproduction in fish. *Canadian Journal of Fisheries and Aquatic Sciences* 40:1395-1404.
- Rogillio, H.E. 1980. Movement and migration of the spotted seatrout in southeast Louisiana. Louisiana Department of Wildlife and Fisheries, Federal Aid in Sport Fish Restoration, Project F-33, Final Report, Baton Rouge, Louisiana.
- Sackett, D.K., K.W. Able, and T.M. Grothues. 2007. Dynamics of summer flounder, *Paralichthys dentatus*, seasonal migrations based on ultrasonic telemetry. *Estuarine, Coastal, and Shelf Science* 74:119-130.
- Sakabe, R., and J.M. Lyle. 2010. The influence of tidal cycles and freshwater inflow on the distribution and movement of an estuarine resident fish *Acanthopagrus butcheri*. *Journal of Fish Biology* 77:643-660.
- Sampaio, L.A., and A. Bianchini. 2002. Salinity effects on osmoregulation and growth of the euryhaline flounder *Paralichthys orbignyanus*. *Journal of Experimental Marine Biology and Ecology* 269:187-196.
- Scharf, F.S., F. Juanes, and R.A. Rountree. 2000. Predator size-prey size relationships of marine fish predators: interspecific variation and effects of ontogeny and body size on trophic-niche breadth. *Marine Ecology Progress Series* 208:229-248.
- Schroeder, W.W., and W.J. Wiseman, Jr.. 1999. Geology and hydrodynamics of Gulf of Mexico estuaries. Pages 3-28 in T.S. Bianchi, J.R. Pennock, and R.R. Twilley, editors. *Biogeochemistry of Gulf of Mexico Estuaries*. John Wiley and Sons, New York.
- Schoellhamer, D.H. 1995. Sediment resuspension mechanisms in old Tampa Bay, Florida. *Estuarine, Coastal, and Shelf Science* 40:603-620.
- Shepherd, T., F. Page, and B. Macdonald. 2002. Length and sex-specific associations between spiny dogfish (*Squalus acanthias*) and hydrographic variables in the Bay of Fundy and Scotian Shelf. *Fisheries Oceanography* 11(2):78-89.
- Smith, S.J. 1990. Use of statistical models for the estimation of abundance from groundfish trawl survey data. *Canadian Journal of Fisheries and Aquatic Sciences* 47:894-903.
- Solis, R.S., and G.L. Powell. 1999. Hydrography, mixing characteristics, and residence times of Gulf of Mexico estuaries. Pages 29-61 in T.S. Bianchi, J.R. Pennock, and R.R. Twilley, editors. *Biogeochemistry of Gulf of Mexico Estuaries*. John Wiley and Sons, New York.

- Swain, D.P. 1997. Sex-specific temperature distribution of American plaice (*Hippoglossoides platessoides*) and its relation to age and abundance. Canadian Journal of Fisheries and Aquatic Sciences 54:1077-1087.
- Swain, D.P., and M.J. Morgan. 2001. Sex-specific temperature distribution in four populations of American plaice *Hippoglossoides platessoides*. Marine Ecology Progress Series 212:233-246.
- Tabb, D.C. 1966. The estuary as a habitat for spotted seatrout, *Cynoscion nebulosus*. American Fisheries Society, Special Publication 3, Bethesda, Maryland.
- Walsh, W.J. 1983. Stability of a coral reef fish community following a catastrophic storm. Coral Reefs 2(1):49-63.
- Watterson, J.C., W.F. Patterson, R.L. Shipp, and J.H. Cowan, Jr. 1998. Movement of red snapper, *Lutjanus campechanus*, in the north central Gulf of Mexico: potential effects of hurricanes. Gulf of Mexico Science 16(1):92-104.
- Wohlschlag, D.E., and J.M. Wakeman. 1978. Salinity stresses, metabolic responses and distribution of the coastal spotted seatrout, *Cynoscion nebulosus*. Contributions in Marine Science 21:171

## **CHAPTER 5: HABITAT USE OF ADULT SPOTTED SEATROUT IN CALCASIEU LAKE, LOUISIANA**

### **Introduction**

Fishes occur in and utilize multiple habitat types (Stoner 2003; Rountree and Able 2007). However, certain habitats may be used to a greater extent and preferred over others. Determining how fish associate with readily identifiable habitat types is relevant to the global initiative of enhancing fisheries management by adopting an ecosystem-based approach. This approach is intended to more explicitly incorporate knowledge of how organisms interact with their environment in resource management plans (Pikitch et al. 2004; Fluharty 2005; Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2007; Norse 2010). For example, habitat use information can aid in planning and designing no-take marine reserves, which constitute a potentially valuable spatial management tool (Hilborn et al. 2004; Claudet et al. 2006). Specifically, to afford maximum protection from fishing mortality, the optimal location for marine reserves would be those habitats or areas that species of interest use most extensively (Kerwath et al. 2009). In addition, knowledge of habitat use can guide decisions regarding temporal fishery closures. For instance, if fish predictably aggregate in a specific habitat during a certain time period (e.g., as in seasonal spawning aggregations), this would be the most logical time to close a fishery because fish would be especially vulnerable to exploitation (Zeller 1998; Starr et al. 2007; Semmens et al. 2010).

Habitat utilization of fishes in coastal environments has traditionally been assessed by comparing incidence and/or relative abundance among geophysical or biogenic habitat types (Heck et al. 1989; Peterson and Turner 1994; Rozas and Minello 1998; Harding and Mann 2001). However, this conventional approach has limitations. First, there is often no single gear that can effectively sample (i.e., with the same catch efficiency) all habitats types of interest, thus

rendering abundance comparisons among habitats difficult from a logistical perspective or potentially biased from a statistical viewpoint (Rozas and Minello 1997; Able 1999). Secondly, simply documenting higher abundances at fixed points in time and space via cross-sectional sampling provides little indication of how animals allocate their time among available habitats. This is particularly true for more mobile species or life stages. For example, adult fish captured by gill nets may be moving through, rather than utilizing a sampling site (habitat) for some purpose (e.g., feeding, refugia, or spawning); in this case, abundance or presence at a given point in time may be a poor indicator of habitat use.

A tool that more rigorously measures habitat use is remote acoustic telemetry. This technique affords researchers the capability to quantify and compare the amount of time telemetered fish spend in range of stationary acoustic receivers that can be strategically deployed in, and effectively monitor, a variety of habitat types. Such telemetry studies are increasing in number (Hindell 2007; Hindell et al. 2008; Caposella 2010; Conrath and Musick 2010; Reynolds et al. 2010) and can augment habitat use data obtained by conventional approaches.

Spotted seatrout (*Cynoscion nebulosus*) is a very important recreational species that is abundant in estuaries of the southeastern United States and northern Gulf of Mexico (GOM). Few studies have examined the habitat use of adult spotted seatrout (but see Simonsen 2008; MacRae and Cowan 2010), as most research has focused on the early life history stages (larvae, juveniles) of this species (Peebles and Tolley 1988; McMichael and Peters 1989; Chester and Thayer 1990; Baltz et al. 1998; Kupschus 2003; Whaley et al. 2007; Neahr et al. 2010). The explicit identification of habitat use requires information for all life history stages (Langton et al. 1996; Levin and Stunz 2005), but for spotted seatrout, such data are clearly lacking for the adult stage (Bortone 2003). To address this important knowledge gap, I employed remote acoustic

telemetry to quantify the habitat use of adult spotted seatrout in a Louisiana estuary (Calcasieu Lake). The major habitat types found in Louisiana's estuaries are subtidal oyster reefs, mud-bottoms, marshes, and navigation channels. In addition to examining fish use of these main habitat types, I also evaluated the utilization of artificial reefs. These structures are typically deployed to increase angler accessibility to fishery resources or mitigate the loss of natural habitat (Bortone et al. 1994; Rogers and Bergersen 1999; Baine 2001). In either case, the underlying assumption is that fishes of interest depend upon, or prefer, structured habitats. Yet, this assumption remains largely untested for many species and systems. Artificial reefs are being deployed at an increasing rate in estuaries of the northern GOM, particularly in Louisiana (n=28 sites to date), with the expectation that they will increase the production of sportfish such as spotted seatrout and red drum. Still, few studies have evaluated how and to what degree fish use artificial reefs relative to other available habitat types in this region (but see Simonsen 2008). Clearly, there is a need for such information to gain insight into the potential effects of artificial reefs on important fishery resources and aid managers in deciding whether these structures are indeed an appropriate and cost-effective habitat management option.

Herein, I use telemetry data to test the hypothesis that the habitat utilization of adult spotted seatrout is random. In addition, I also evaluate seasonal, sex, and size differences in estuarine habitat use.

## **Methods**

### **Study Area**

Calcasieu Lake is an estuarine system (~300 km<sup>2</sup>) located in the Chenier Plain of southwestern Louisiana (see Figure 2.1). The main body of the estuary, hereafter referred to as the "estuary proper" is shallow (< 2.5 m depth), with a predominantly mud bottom. Expansive

low-relief (< 0.5 m height) subtidal oyster reefs are present in several areas of the estuary and support a commercial oyster fishery. Marsh habitats fringe the system and are connected to the estuary proper via narrow tidal creeks (< 50 m width) of moderate depth (~4 m). A relatively deep (~15 m) and narrow (200-500 m) navigation (shipping) channel, hereafter referred to as the “channel”, spans the length of the system from the main tidal inlet at the Cameron jetties to the Port of Lake Charles, a distance of 60 km (see Figure 2.1).

Two low-relief artificial reefs are also present in the Calcasieu system. One reef is located in the central portion of the estuary, midway between (~3 km from) the eastern and western shorelines, and the other reef is located in the lower bay approximately 1.5 km from the southern shoreline (Figure 5.1). These reefs were deployed in January 2007 by Cheniere Energy, Inc. as remediation for the loss of natural oyster habitat associated with the dredging of a liquefied natural gas pipeline through the estuary. Sites where the reef material (limestone cobble) was dumped had a firm mud substrate to reduce the risk of the cobble sinking or becoming buried. At the time of deployment, the mid-bay and southern reefs covered 26,284 m<sup>2</sup> and 38,908 m<sup>2</sup> of the estuary bottom, respectively. The limestone cobble appeared to be an effective cultch material (i.e., settlement substrate for oyster larvae). During substrate characterization surveys in September 2009 (see below), live adult oysters (*C. virginica*, 70-80 mm length) were collected via dredging at artificial reef sites and many of these individuals were found attached to the original artificial reef material (Figure 5.2).

### Telemetry

Following methods described in chapters 1 and 3, I surgically implanted acoustic transmitters (VEMCO V9-2Hs and V13TP-1Hs) into 172 adult spotted seatrout (300-725 mm total length, TL) and released the fish during four tagging events (spring and fall of both 2007

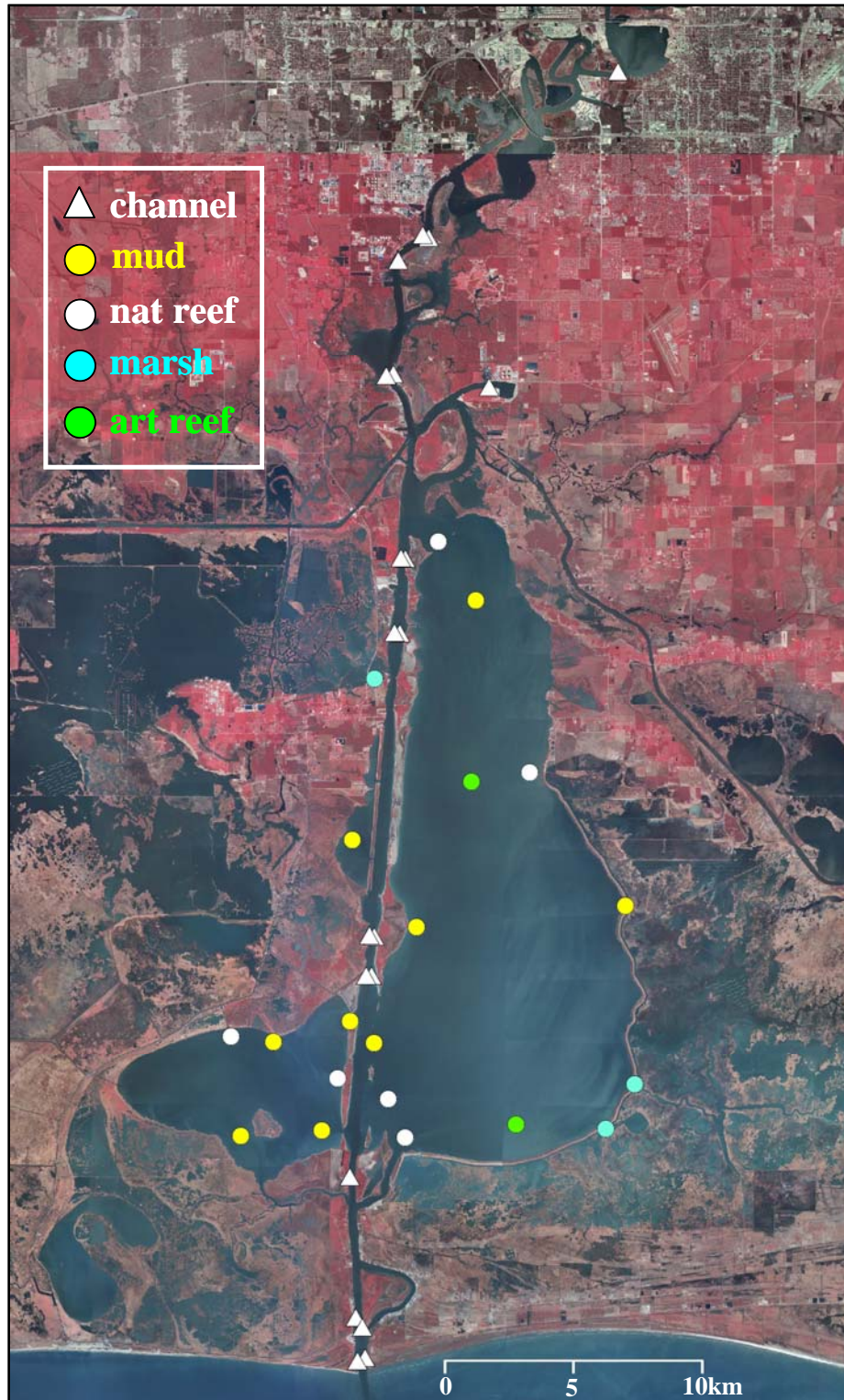


Figure 5.1. Receiver sites by habitat type. An acoustic telemetry receiver (VEMCO VR2/VR2W) was deployed at each symbol. Each receiver constituted a ‘site’ except at most channel locations, where two adjacent receivers were deployed to provide cross-channel coverage and thus comprised a single site.





Figure 5.2. (A) Artificial reef deployment, dumping of limestone cobble reef material. (B) Live adult oyster collected at an artificial reef 2.5 years post-reef deployment. Note the oyster is attached to limestone cobble. Photo credits: Michael Harbison.

and 2008). Transmitter battery lives were approximately one year. During the tagging process, fish were also measured (TL, nearest mm), weighed (nearest gram), sexed, and externally marked with a dart tag (HallPrint PDS series, 10 cm length).

To monitor the habitat use of telemetered fish, I deployed remote acoustic receivers (VEMCO VR2s and VR2Ws) in each of the five habitat types of interest: 1) channel, 2) marsh, 3) natural oyster reef, 4) artificial reef, and 5) mud-bottom. Details of receiver deployment and operation principles for the telemetry system are presented in chapter 2. Briefly, if a transmitter (fish) emitted a signal while in detection range of a receiver (~250 m), the receiver recorded and stored the transmitter ID number and date/time stamp of the detection. I serviced and downloaded data from receivers at approximately six week intervals during the course of this 2.5 year study (May 2007 to October 2009). All telemetry data were censored for spurious and duplicate detections (see chapter 4) before being entered into a database management system.

#### Habitat Characterization Surveys

The substrate type at planned receiver sites in the estuary proper was evaluated during the scouting phase of the study in February 2007, before receivers were deployed. However, more formal and extensive surveys were conducted in September 2009 to verify substrate types via cane poling and dredging. At each site, a survey was performed within a 250 m radius (average detection range, see chapter 2) of the buoyed receiver using transect lines spaced 30 m apart. Surveys were conducted aboard a six-meter vessel at a speed of four to six knots. Navigation was greatly aided by the use of a marine chartplotter (Humminbird 997ci, Garmin <sup>TM</sup>) capable of displaying a survey grid overlaid on user-inputted GPS points (receiver coordinates). The bottom was continuously poled (with a 3 m cane pole) for the duration of each survey (~1 hour),

and at sites where reefs were suspected, a one-minute tow of an oyster dredge was also performed to confirm the presence of oysters.

Receiver sites in the estuary proper were classified as ‘natural reef’ or ‘mud’ habitats based on their substrate properties. I classified sites with thick patches of live oyster beds, which were often interspersed with firm mud, as ‘natural reefs.’ Those sites with a predominantly mud bottom and occasional presence of scattered individual oyster shells (< 5-10% coverage) were classified as ‘mud’ habitats. I also conducted substrate characterization surveys at the two artificial reef sites. These reefs were much smaller and more discrete (i.e., less patchy) than natural reefs. For those receiver sites with available sidescan sonar data (n=8), substrate classifications from sidescan surveys matched my habitat designations, thus supporting my classification technique (Figure 5.3).

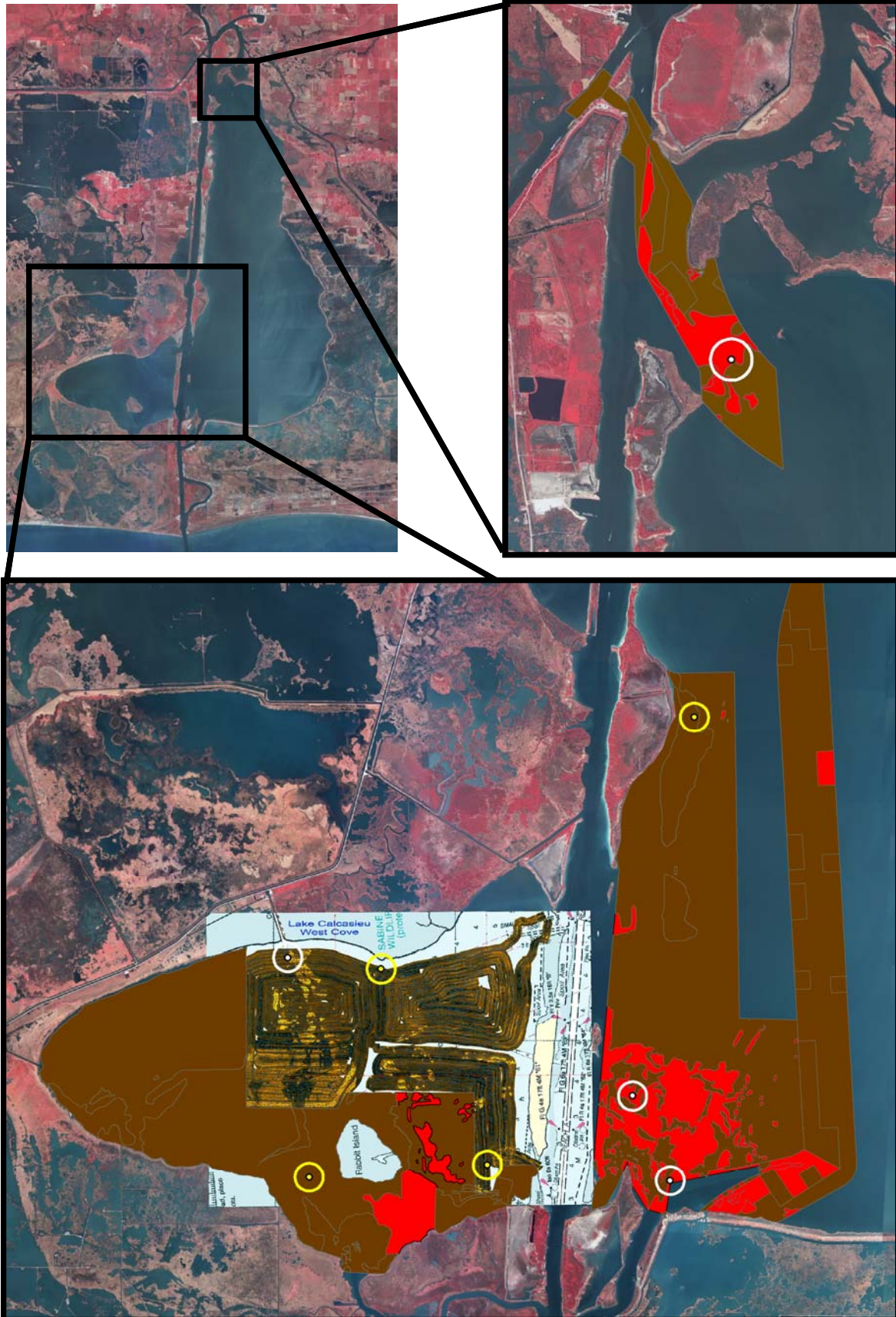
#### Data Analyses

For all habitat use analyses, I excluded detection data from the first week telemetered fish were at large. Some individuals that were released near receiver sites tended to remain there for a few days, but typically dispersed and were detected elsewhere in the array within one week post-release. Excluding data from the first week at large thereby ensured the utilization of release sites and their corresponding habitats was not overestimated due to potential tagging-induced behaviors.

For the purposes of this chapter, I used data from a subset of receivers (n=40) (Figure 5.1) from the entire array (n=60). In several areas of the estuary proper, multiple receivers were deployed in close proximity to one another (< 1 km) to discern movement directionality and increase spatial coverage for distribution analyses (chapters 3 and 4). However, from a habitat use perspective, the utilization of these areas (and their corresponding habitats) could be

Figure 5.3. Sidescan sonar data for Calcasieu Lake. Substrate types (red = natural oyster reef, brown = mud-bottom) were determined by ground-truthing sidescan reflectance data via poling, dredging, and SCUBA surveys. For the northern portion of West Cove, only raw reflectance data were available (i.e., no ground-truthing was conducted). For this region, lighter colors indicate hard substrates. Acoustic receiver sites with sidescan coverage (n=8) are shown on the map; circles represent the 250 m detection radii for receiver sites I classified as “natural reef” (white circles) and “mud” (yellow circles). Sidescan surveys were conducted from 2005-2009; data are courtesy of the Louisiana Department of Wildlife and Fisheries.





overestimated relative to locations where receivers were deployed singly and somewhat isolated. Therefore, for areas where multiple receivers were deployed within 1 km of each other (e.g., at the cluster of receivers in the upper bay), I selected and used data from the receiver that had the longest operation period. Channel receivers were the one exception to this criterion. Where channel widths exceeded 250 m, it was necessary to deploy two adjacent receivers to provide acoustic coverage of the entire width of the channel. Herein, I considered these adjacent receivers as a single receiver site that was only ‘operational’ if both receivers were active on a given day.

The primary metric I developed for habitat use analyses was the number of detections per habitat type per season for each sex/size group. I defined six sex/size groups as follows: 1) large females, 2) large males, 3) medium females, 4) medium males, 5) small females, and 6) small males. As in chapter 3, size classes were: small ( $< 400$  mm TL), medium (400-499 mm TL), and large ( $> 500$  mm TL). Seasons were classified as: winter = December-February, spring = March-May, summer = June-September 15, and fall = September 16-November. I used September 15 as the division between summer and fall because the first cold front typically passed over the study area in mid-September, after which water temperatures began to rapidly cool (Figure 5.4). Given this classification scheme, an example of the habitat use metric would be the total number of detections of large females at each of the five habitat types during winter.

In generating this habitat use metric, it was necessary to correct detection magnitudes for differences in habitat-specific receiver effort because the number of receiver sites was unequal among habitat types (Figure 5.1). Otherwise, detection values could be positively biased towards habitats with more receiver sites, even if habitat use was random. The number of operational receiver sites per habitat was not constant through time due to gear loss, human tampering,

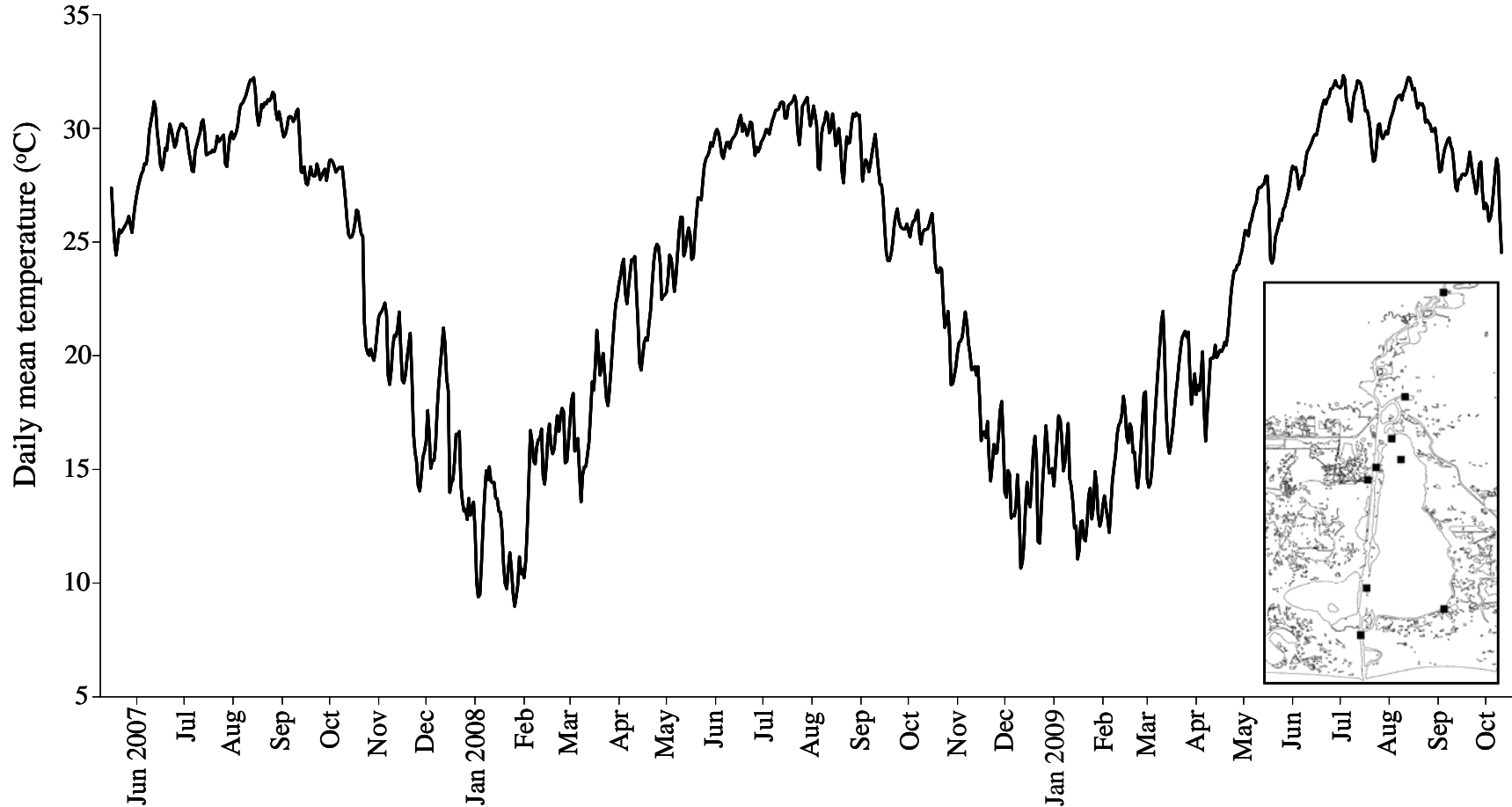


Figure 5.4. Daily mean surface (< 1.5 m depth) water temperatures in the Calcasieu Lake estuary during the study period (May 16, 2007 to October 11, 2009). Temperature data were obtained from the nine temperature logging stations deployed throughout the estuary, including HOBOS attached to acoustic receivers (n=5) and sondes mounted to pilings by LSU (n=1) and the United States Geological Survey (n=3). Black squares on the inset map depict the locations of temperature stations. There were some operation gaps for individual stations, and during these periods the overall mean was based on data from a reduced number of stations.

hardware failure, and the addition of new sites ( $n = 7$ ) during the second year of the study as more funding became available (Figure 5.5). Thus, it was necessary to use a daily time step to correct detection data. I used the following equation to calculate the daily number of corrected detections (CD) per habitat type for each sex/size group:

$$CD_{i,h,y} = \frac{\sum_{r=1}^n d_r}{n} i, h, y \quad (\text{Equation 5.1})$$

where CD = the daily number of corrected detections on day (y) for fish of a given sex/size group (i) and particular habitat type (h); d = the number of detections of fish of a given sex/size group recorded at a given receiver (r) deployed in a particular habitat type; n = the number of receivers that were operational in habitat h on day y. To obtain the habitat use metric (HUM), I then summed the CDs obtained in Equation 5.1 across years within each season and habitat type for respective sex/size groups using the following equation:

$$HUM_{i,h,z} = \sum_{y=1}^z CD_y i, h \quad (\text{Equation 5.2})$$

where all letters represent the same variables as above except z, which corresponds to a particular season and y, which constitutes individual days within defined seasons. As an example calculation of the HUM: if during the winters of 2007 and 2008 (181 days) only four of five natural reef receivers were operational per day and there were 100 detections of large females (across individuals) recorded per day across the natural reef sites, the HUM for large females (i) at natural reefs (h) in winter (z) would be 4,525 (or  $HUM = ((100/4) \times 181) = 4,525$ ). It should be noted here that it was necessary to pool data across years (within seasons) due to the high interannual variability in detections for some sex/size groups, which also precluded an examination of year effects (at least for the sex/size groups used herein). Interannual detection



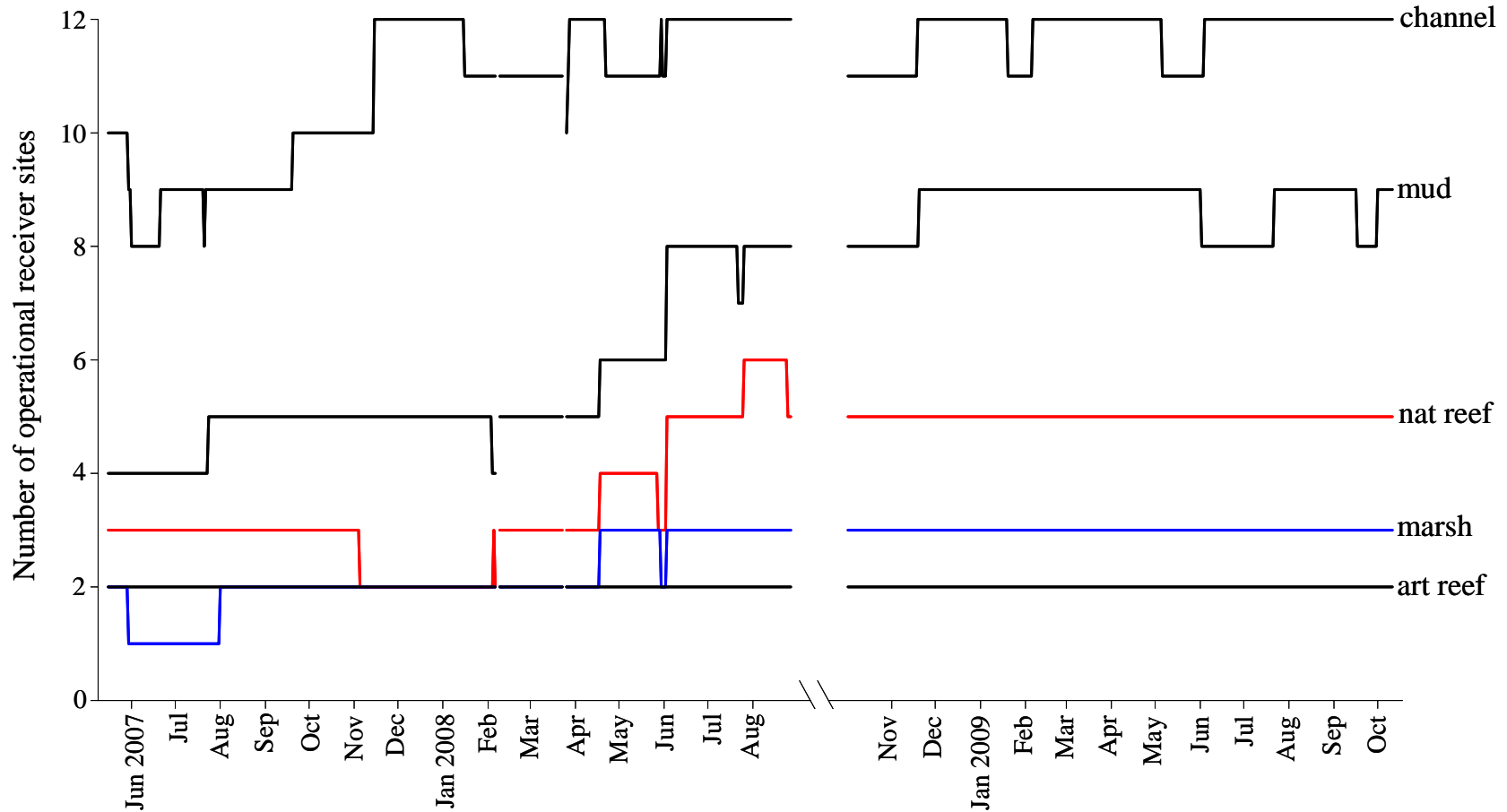


Figure 5.5. Number of operational receiver sites per habitat per day during the study period (May 16, 2007 to October 11, 2009). The one month operation gap from August 28 to October 1, 2008 was due to Hurricanes Gustav and Ike. All receivers were temporarily removed from the estuary during this period to prevent gear loss. The short-term operation gaps from February 7-8, 2008 and March 24-25, 2008 were associated with receiver battery changes, during which time it was necessary to bring receivers into the laboratory for servicing.

variability was mainly due to differences in capture rates of particular sex/size groups across tagging events. For example, no small females were caught during the first tagging event; consequently, detection data from this group were lacking for summer 2007.

Using the HUM data, I performed chi-square tests of independence to determine if the habitat use of adult spotted seatrout was random. I conducted these tests separately for each sex/size group x season combination (e.g., for large females in winter). Under a scenario of random habitat use, the number of detections should theoretically be equal among habitat types. Accordingly, for chi-square analyses, the ‘expected’ number of detections per habitat was obtained by dividing the total number of detections recorded across all habitats (for each sex/size x season combination) by five, the number of habitat types (i.e., the individual HUMs for each sex/size x season combination, as obtained above, were summed and divided by 5). The ‘observed’ number of detections per habitat (i.e., the individual HUMs) were compared to these ‘expected’ values via chi-square tests of independence. I used a Bonferonni-adjusted alpha value of 0.002 to assess the statistical significance of individual chi-square tests ( $n=21$ ).

I also examined residuals from chi-square analyses to aid in the identification of habitat use trends. Residuals provide additional insight as to where (i.e., for which habitats) and to what degree observed values diverge from expected values for chi-square tests deemed statistically significant (Agresti 1996). To facilitate comparisons of residuals among seasons and sex/size groups, I adjusted raw residuals by dividing them by the total number of detections for each sex/size x season combination. Given there were five habitat types, adjusted residuals ranged from -0.2 to +0.8. If habitat use was random, adjusted residuals would be approximately zero for each habitat. Meanwhile, if habitat use was not random, those (preferred) habitats utilized to the

greatest extent would possess the highest (positive) residuals. For example, if 90% of all detections were recorded in a particular habitat type, the residuals for that habitat would be 0.7.

To facilitate qualitative comparisons of habitat use among sex/size groups and seasons, I also expressed HUMs in terms of relative percentages, referred hereafter as habitat utilization indices (HUIs). I calculated HUIs using the following equation:

$$HUI_{h,i,z} = \frac{HUM_{h,i,z}}{\sum_{h=1}^5 HUM_{h,i,z}} \times 100 \quad (\text{Equation 5.3})$$

where HUM = individual (habitat-specific) HUMs obtained from Equation 5.2 (see above), i = respective sex/size groups of fish, z = season, and h = a given habitat type, of 5 total (natural oyster reef, artificial reef, mud-bottom, channel, and marsh). As an example calculation: if there were 5,000 total detections of large females (across habitats) in winter and 4,000 of those occurred on natural reefs, the HUI for natural reefs would be 80% for large females in winter, or  $((4000/5000) \times 100) = 80\%$ . Habitat utilization indices summed to 100% within each sex/size group x season combination; therefore, in this example, the HUIs for the other habitat types would sum to 20%. It should be noted the HUI developed herein differed from that presented in Pihl et al. (2002). Their HUI assessed relative habitat importance based on the number of species (and life stages) that occurred in defined habitat types and how those habitats were utilized (i.e., habitat function was assumed). Meanwhile, the HUI that I developed was based only on a single species and life stage, did not assume habitat function (see below), but more rigorously quantified habitat use as habitat-specific detection magnitudes were used instead of fish occurrence (as in Pihl et al. 2002), which is indeed a very coarse metric of habitat use (Able 1999).

## Results

Habitat use of adult spotted seatrout was not random. All chi square tests of independence were highly significant ( $p < 0.001$ ) indicating that each sex/size group utilized habitats disproportionately within seasons. Overall, fish used channel and marsh habitats far less than the estuary proper (natural/artificial reefs and mud-bottoms). Habitat use indices were indeed very low for both channel and marsh habitats. Channel HUIs did not exceed 2% for females and were similarly low for males, less than 3% during all seasons except fall, when HUIs were only slightly higher and ranged from 11 to 13% (Figure 5.6). Marsh HUIs were less than 3% for males (all size classes), small females, and large females; moderately higher (4-30%) for medium females (Figure 5.6). The consistently negative residuals for channel and marsh habitats from chi-square analyses provide further evidence that these habitats were used less frequently (Figure 5.7). Residuals for channel habitats were negative in all tests and residuals for marsh habitats were negative in all but one test (medium females during summer) (Figure 5.7).

Interestingly, the affinity for structured (reef) habitats appeared to be size-specific. Spotted seatrout larger than 400 mm TL had an increased affinity for reef habitats. The residuals for medium and large fish of both sexes were always highest (across seasons) for either natural or artificial reefs (0.2 to 0.8), whereas residuals for mud habitats hovered about 0 and ranged from -0.2 to 0.2 (Figure 5.8). On the contrary, small fish (< 400 mm TL) did not show a high affinity for reefs. Small females primarily used natural reefs in fall and winter (HUIs 84-88%), but in spring and summer utilized mud habitats to a similar extent as reefs (HUIs ~40%) (Figure 5.6). Small males showed the opposite pattern as they mainly used reefs in spring and summer

Figure 5.6. Habitat utilization indices (HUIs) for (A) large females, (B) large males, (C) medium females, (D) medium males, (E) small females, and (F) small males. HUIs were calculated as the relative percent of detections recorded at each habitat type during a given season for respective sex/size groups of fish. Habitat types are represented by the different bar colors and patterns shown in the legend; “nat reef” = natural oyster reef and “art reef” = artificial reef. Seasonal definitions are: winter = December-February, spring = March-May, summer = June-Sept 15, fall = Sept 15-November. Size classes are: small (< 400 mm TL), medium (400-499 mm TL), large (> 500 mm TL). Only one large male was released during the study and this fish was only detected during the summer (2,211 detections).

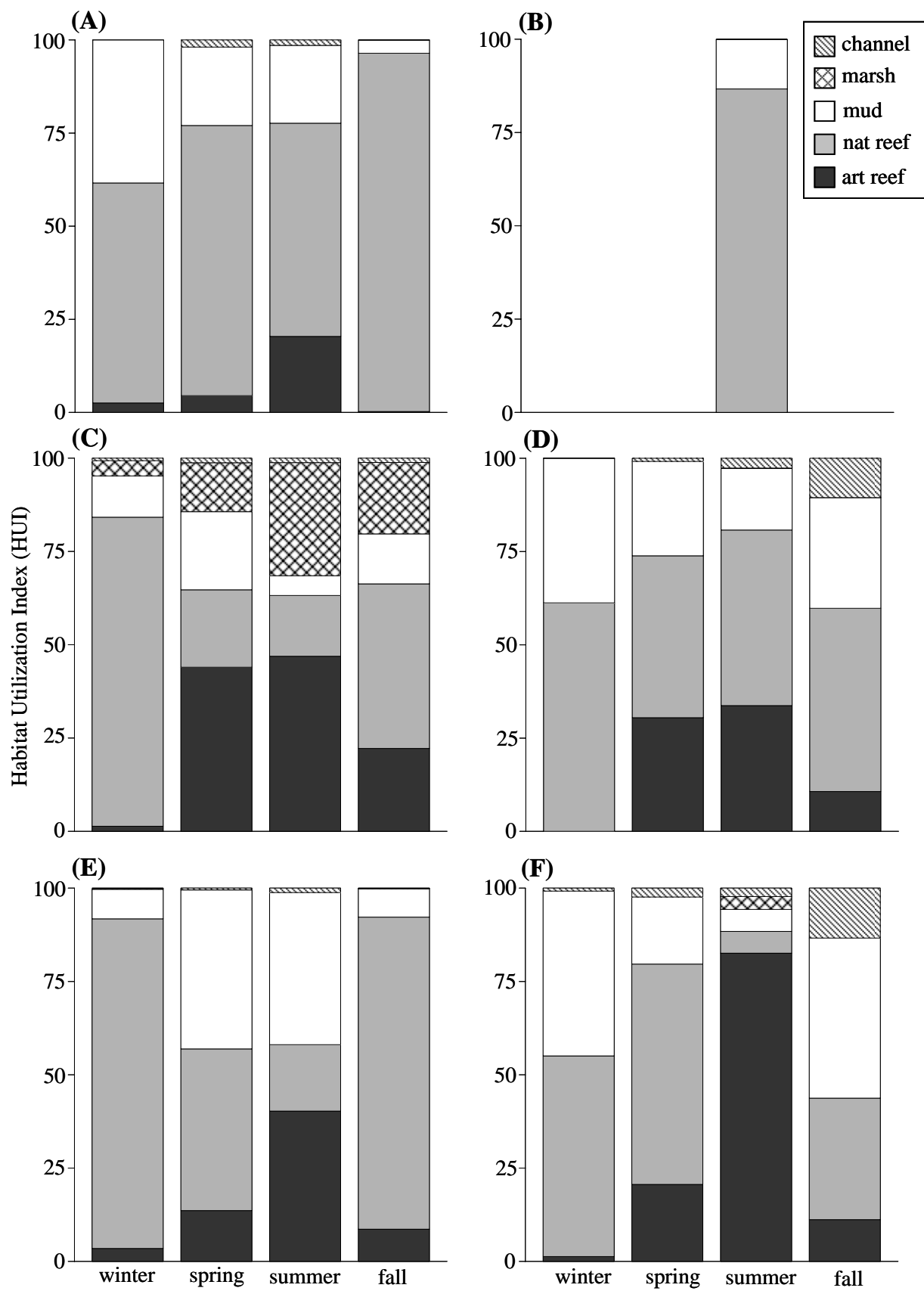


Figure 5.7. Adjusted chi-square residuals for channel (triangles) and marsh habitats (dots) for each sex/size group of fish: **(A)** large females, **(B)** large males, **(C)** medium females, **(D)** medium males, **(E)** small females, and **(F)** small males. Adjusted residuals range from -0.2 to 0.8. Under a scenario of random habitat use, residuals would be approximately zero (dashed reference line) across all habitat types within each sex/size x season combination. Meanwhile, those habitats utilized to lesser and greater extents possess lower (negative) and higher (positive) residuals, respectively. Seasonal definitions are: winter = December-February, spring = March-May, summer = June-Sept 15, fall = Sept 15-November. Size classes are: small (< 400 mm TL), medium (400-499 mm TL), large (> 500 mm TL).

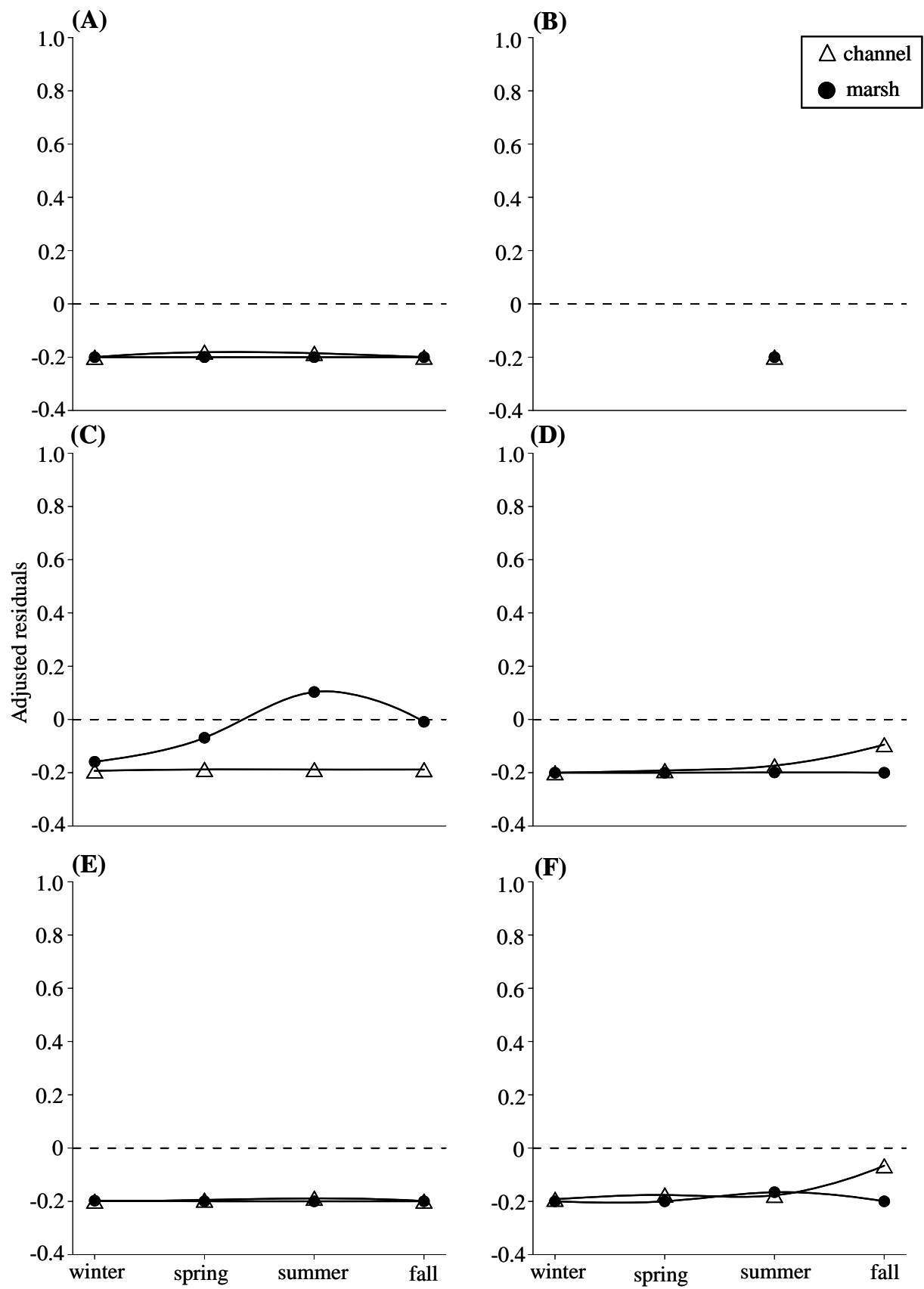
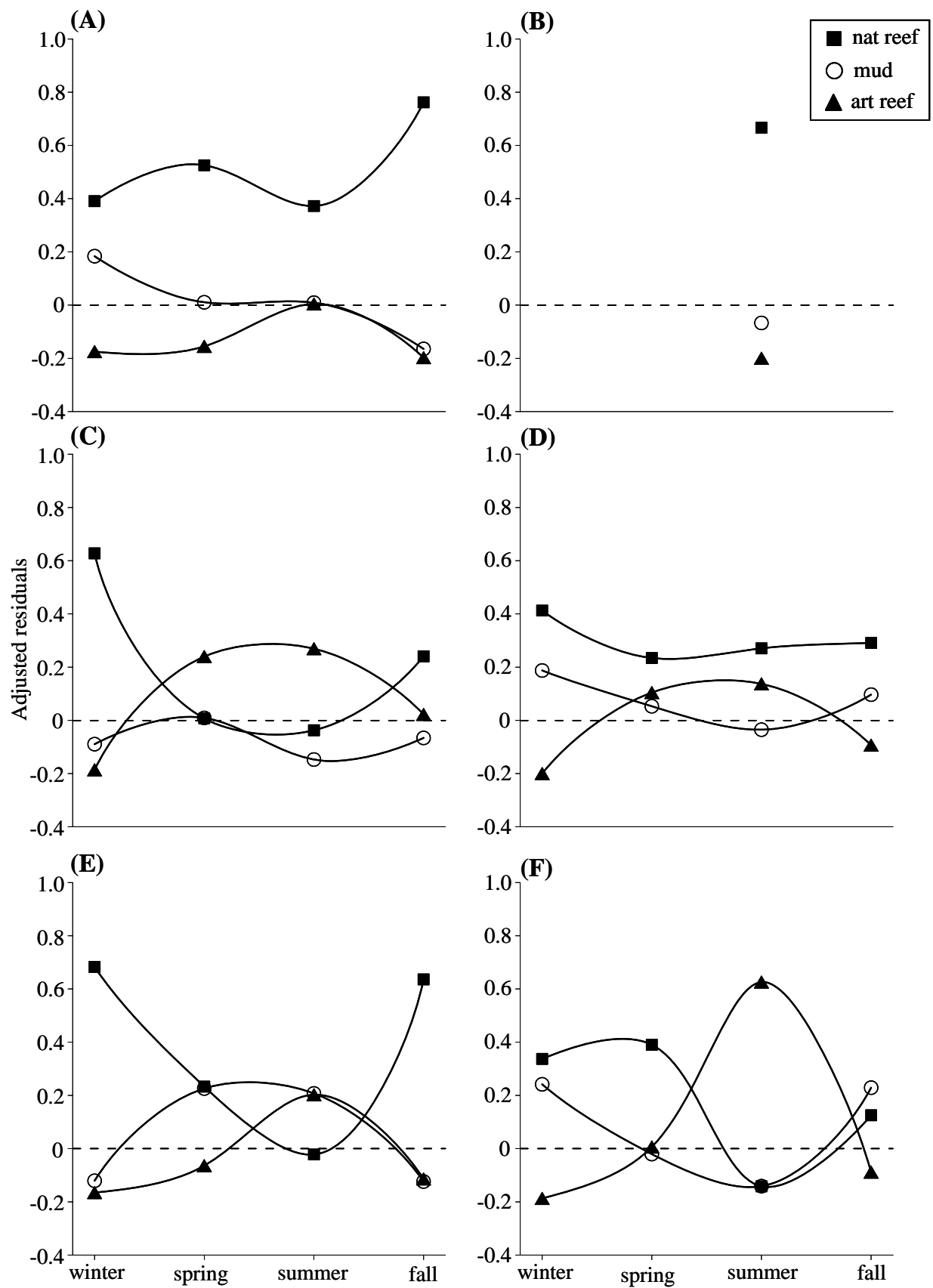




Figure 5.8. Adjusted chi-square residuals for natural reef (squares), artificial reef (triangles), and mud-bottom habitats (dots) for each sex/size group of fish: **(A)** large females, **(B)** large males, **(C)** medium females, **(D)** medium males, **(E)** small females, and **(F)** small males. Adjusted residuals range from -0.2 to 0.8. Under a scenario of random habitat use, residuals would be approximately zero (dashed reference line) across all habitat types within each combination. Meanwhile, those habitats utilized to lesser and greater extents possess lower (negative) and higher (positive) residuals, respectively. Seasonal definitions were as follows: winter = December-February, spring = March-May, summer = June-Sept 15, fall = Sept 15-November. Size classes were defined as follows: small (< 400 mm TL), medium (400-499 mm TL), large (> 500 mm TL).



(HUIs 60-80%), but utilized mud habitats to a similar extent as reefs in fall and winter (HUIs ~45%) (Figure 5.6).

The utilization of artificial reef habitats was highly seasonal. Across all sex/size groups, HUIs for artificial reefs were higher in spring and summer (5-83%) than fall and winter (0-22%) (Figure 5.6). Surprisingly, for some sex/size groups, HUIs were higher for artificial reefs than any other habitat type, namely for medium females in spring and summer (HUIs 44-47%) and small males in summer (HUI=83%) (Figure 5.6).

## **Discussion**

Adult spotted seatrout were detected in all habitat types I examined. This is not surprising given the high mobility of this life stage. Indeed, telemetry data revealed that individuals were highly transient and moved widely throughout the estuary, often at time scales of days to weeks. Still, habitat use was not random as fish tended to spend more time at certain habitats as evidenced by a disproportionately higher number of detections at corresponding (habitat-specific) acoustic receivers. Some habitat types were less frequently used across all sexes, sizes, and seasons; whereas others were differentially utilized with respect to fish size and season. The habitat preferences of adult spotted seatrout revealed by this acoustic telemetry study provide insight into how habitats may be included in spatial management plans; moreover, afford managers important information on habitat-specific vulnerability to fishing mortality for this extremely popular sportfish.

### **Habitat Use Trends**

Fish use of channel habitats was extremely low regardless of sex, size, or season. Several factors may explain the low utilization of this habitat. The dredged ship channel has captured the majority of the tidal flow in the Calcasieu system; as a corollary, current speeds and salinity

variation are much higher in the channel than the surrounding shallow waters of the estuary proper. For instance, during the course of this study, daily salinity ranges were two- to three-fold higher in the channel (mean=7.3, maximum=20.6) than the estuary proper (mean=1.9, maximum=8.1) based on data from 499 days during which salinity stations were operational in both areas (stations 6 and 8; see Figure 2.12). Although there are no comparative data on current speeds in this system to my knowledge, studies in other Louisiana estuaries have demonstrated that current speeds are substantially higher (often three-fold) in dredged navigation channels than the estuary proper (Saucier and Baltz 1993; Inoue and Wiseman 2000). It is possible that spotted seatrout do not extensively utilize the channel because it is energetically expensive to remain in this habitat for extended periods of time (hours, days) due to the combination of high flow and extreme salinity variation. Additionally, predation risk may be higher in channel habitats. Bottlenose dolphins (*Tursiops truncatus*) are a potentially important predator of adult spotted seatrout. Numerous studies have shown that adult *Cynoscion sp.* were indeed a major prey item of bottlenose dolphins collected in coastal waters along the southeastern United States (Mead and Potter 1990; Barros 1993; Gannon and Waples 2004). During receiver downloading trips, bottlenose dolphins were most frequently observed in the channel; other studies have demonstrated that within estuaries, this species prefers deeper channel habitats (Fertl 1994; Harzen 1998; Allen et al. 2001). Given that dolphins and other large predators (e.g., sharks) are likely more abundant in the channel, the low use of this habitat by adult spotted seatrout could be due in part to predator avoidance.

Surprisingly, fish utilization of marsh habitats was also very low. Access to two of the three marsh sites (those on the eastern side of the estuary) was semi-restricted by water control structures (lift-gate weirs) through which fish must have passed to reach receiver sites (Figure

5.9). These physical structures undoubtedly impeded fish movement and were probably the main reason I observed such low use of marsh habitats. Interestingly, 34 fish were detected at receivers placed just outside of the weirs (in the estuary proper), but only 8 of those individuals (5% of all tagged fish) were detected in the marsh and passed through the weirs. Accordingly, my results are probably not representative, and likely underestimate, the degree to which adult spotted seatrout utilize marsh habitats in other Louisiana estuaries, particularly those in the deltaic plain where broken marshes are more commonly interspersed throughout the estuary and access to marsh habitats is not nearly as restricted as in Calcasieu Lake. As a case in point, during my pilot telemetry studies in Barataria Bay in 2006, spotted seatrout (276-376 mm TL) were frequently detected in marsh habitats.

Larger spotted seatrout ( $\geq 400$  mm TL) exhibited a stronger preference for structured (reef) habitats than smaller fish. This trend could be related to size differences in prey preference. However, diet data for adult spotted seatrout collected from Calcasieu Lake indicate that prey composition is very similar across size classes and dominated by gulf menhaden and penaeid shrimp (Figure 5.10). These abundant prey taxa are schooling, pelagic and demersal species, respectively, that do not necessarily associate with a given habitat type and are ubiquitously distributed throughout Louisiana's estuaries. Other researchers have noted statistically similar abundances of these taxa between subtidal reef and mud-bottom habitats in estuaries of Louisiana (Plunket and La Peyre 2005; Simonsen 2008) and Texas (Reese-Robillard et al. 2010; Stunz et al. 2010). Given that adult spotted seatrout of all sizes seem to forage opportunistically rather than specializing on prey that only occur or are more abundant in particular habitats, it seems unlikely that prey availability is driving the size-specific affinity of



Figure 5.9. Life-gate weirs located at two of the three monitored marsh sites, both of which were on the eastern shore of the estuary. To reach the interior marsh where acoustic receivers were deployed, fish had to pass through these water control structures, which contained either **(A)** a single 2.5 m wide opening (or bay) that traversed the entire water column or **(B)** four bays (each 2.5 m in width). Photo credits: Michael Harbison.

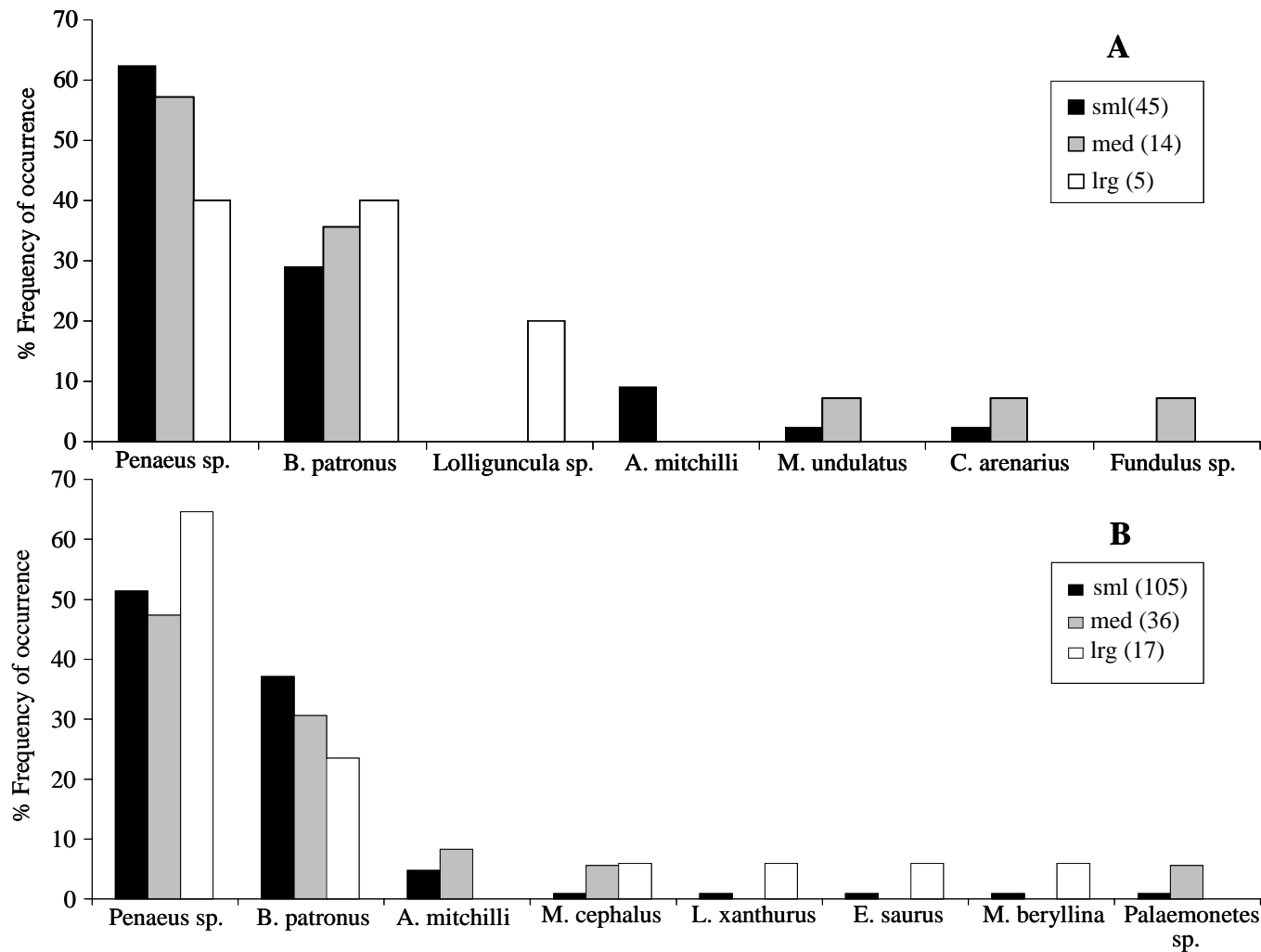


Figure 5.10. Diet composition of (A) male and (B) female adult spotted seatrout collected in Calcasieu Lake from 1986-1996. Frequency of occurrence was calculated as the percentage of non-empty stomachs in which respective prey taxa occurred. Size classes were: small (300-399 mm TL), medium (400-499 mm TL), large (> 500 mm TL). Sample sizes (the number of non-empty stomachs with identifiable prey) are listed parenthetically in the legend. Data are courtesy of the Louisiana Department of Wildlife and Fisheries.

spotted seatrout for oyster reefs. A more plausible explanation for this pattern may be age- or size-specific differences in behavioral tendencies or social interactions of spotted seatrout. Older spotted seatrout (~age 5+) are thought to school less and lead a more solitary existence (Tabb 1966). Accordingly, older (larger) individuals may generally travel alone and thus have a greater tendency to associate with topographical or structural features (i.e., thigmotaxis, *sensu* Bohnsack 1989; Brickhill et al. 2005) than their younger (smaller) counterparts which are probably more gregarious and as such, may be equally, if not more likely, to associate with their conspecifics than the surrounding physical environment (*sensu* DeMartini and Anderson 2007). As larger, and presumably older, spotted seatrout are moving throughout the bay, they may simply be attracted to reefs and use them as stopping or resting points along their migratory routes. The thigmotactic tendencies and general attraction of fishes to structure are well-known and have been documented in a variety of ecosystems, from freshwater lakes (Rogers and Bergersen 1999) to the tropical ocean (Ohta and Kakuma 2005).

#### Data Utility and Future Research

To determine why, not how often, the primary habitats of spotted seatrout identified in this study were used differentially will require additional, more difficult to obtain information on habitat function (i.e., how the use of a given habitat contributes to growth, survival, and reproduction). It is tempting to designate natural oyster reefs most important to large spotted seatrout (> 400 mm TL) because they spent the most time in this habitat. However, to be considered vital for supporting fish production, it must be shown that the utilization of oyster reefs somehow increases growth or survival relative to other habitat types (e.g., by providing a refuge from predation) (Rountree and Able 2007). Clearly, such information cannot be obtained from basic telemetry data alone, which provide no indication of *what* fish are doing when they



are detected. For example, spotted seatrout may undergo foraging excursions throughout the bay in search of prey schools and be detected only briefly at receiver sites (across habitats) while foraging, then move to oyster reefs to rest and digest their food (accumulating a large number of detections at the reef site/habitat). In this situation, habitat-specific detection magnitudes would not be indicative of relative habitat value or function per se (i.e., the most utilized habitat was not the principal foraging habitat). The evaluation of habitat function is a formidable task (Able 1999), but is becoming more feasible with the advent of novel tools to study the behavior of aquatic organisms. One such tool is acoustic imaging via dual-frequency identification sonar (DIDSON). This technology provides real-time *in situ* video feeds of the underwater environment, is non-intrusive, and allows direct observations of fish behavior and fish-habitat interactions irrespective of turbidity and light levels (Boswell et al. 2007; Boswell et al. 2008). Although species identification is still challenging in many cases, with continued technological advances, it should be possible with this tool to directly observe and compare fish behavior in different habitats to determine if habitat-specific behaviors exist that would confer a growth or survival advantage to fishes of interest (e.g., higher feeding incidence or success in habitat X).

Even without complementary information on habitat function, one of my principal results is still of immediate value to fisheries managers. I found that artificial reefs were heavily utilized during the spring and summer, which is the peak fishing season for spotted seatrout in coastal Louisiana (M. Harbison, Louisiana Department of Wildlife and Fisheries, personal communication). For some sex/size groups, HUIs were higher for artificial reefs in the spring and summer than any other habitat type. In addition, it was not uncommon for multiple telemetered fish (2-5 individuals) to be detected during the same hour at the artificial reef sites, indicating that fish were aggregating at these structures. Not surprisingly, fishermen have begun

targeting these reefs, whose coordinates are publicly available. During data downloading trips in the spring and summer, recreational boats were almost always present at the artificial reef sites. Furthermore, a headboat from a local guide service frequently fishes one of the artificial reefs and these trips appear to be very successful. For example, this headboat fished the southern reef for 61 consecutive days from May 1, 2008 to June 30, 2008 and caught a limit of fish every night (n=105 fish per night for a party of 7 persons) (J. Broussard, Hackberry Rod and Gun, personal communication). Although the artificial reefs I studied were deployed as mitigation for the destruction of natural oyster reefs, many similar reefs are being deployed in Louisiana's estuaries. These projects are typically funded by private conservation organizations under the presumption that artificial reefs will benefit important fishery resources. However, my data suggest these reefs could have a negative impact on sportfish, at least spotted seatrout, by aggregating fish and thus increasing their vulnerability to exploitation via increased catch efficiency. Clearly, state management agencies throughout the GOM should consider this possibility when deciding to grant permission for the deployment of additional artificial reefs in inshore estuarine waters.

In this study, I used remote acoustic telemetry to quantify the habitat use of the nation's most popular coastal sportfish. This approach was largely successful in that it generated a wealth of data (227,480 unique detections for the analyses herein) which facilitated the identification of the primary habitats of adult spotted seatrout. Still, a more mechanistic understanding of habitat utilization will require additional data on habitat function, which is lacking for most species, but should become easier to obtain with continued technological advances in the field of aquatic sciences. In particular, several new telemetry tags are being developed that could be used to gain a better understanding of habitat use and function. One such tag is capable of monitoring jaw

movements to infer feeding incidence, which could be useful for evaluating habitat-specific feeding behaviors (Metcalf et al. 2009). Another tag is being developed that functions both as a transmitter and receiver, referred to as a “business card tag” (Holland et al. 2009). These tags can provide data on schooling dynamics and predator-prey interactions; could be used to test Tabb’s (1966) hypothesis of age-specific schooling of spotted seatrout as the evidence for this hypothesis is anecdotal at best. Finally, as electronic tags continue to become miniaturized, remote acoustic telemetry could be used to investigate the habitat use of juvenile fishes, as this method has largely been restricted to adults due to tag size constraints. VEMCO has developed a new V6 transmitter (6 mm diameter) that many juvenile fishes can easily accommodate. All of these approaches represent novel ways in which we can interrogate stubbornly opaque aquatic systems to better understand how organisms interact with their environment to support sound resource management.

## References

- Able, K.W. 1999. Measures of juvenile fish habitat quality: examples from a National Estuarine Research Reserve. Pages 134-147 *in* L.R Benaka, editor. Fish habitat: essential fish habitat and rehabilitation. American Fisheries Society, Symposium 22, Bethesda, Maryland.
- Agresti, A. 1996. An introduction to categorical data analysis. John and Wiley Sons, New York.
- Allen, M.C., A.J. Read, J. Gaudet, and L.S. Sayigh. 2001. Fine-scale habitat selection of foraging bottlenose dolphins *Tursiops truncatus* near Clearwater, Florida. Marine Ecology Progress Series 222:253-264.
- Baine, M. 2001. Artificial reefs: a review of their design, application, management and performance. Ocean and Coastal Management 44:241-259.
- Baltz, D.M., J.W. Fleeger, C.F. Rakocinski, and J.N. McCall. 1998. Food, density, and microhabitat: factors affecting growth and recruitment potential of juvenile saltmarsh fishes. Environmental Biology of Fishes 53:89-103.
- Barros, N.B. 1993. Feeding ecology and foraging strategies of bottlenose dolphins on the central east coast of Florida. Doctoral dissertation. University of Miami, Coral Gables, Florida.

- Bohnsack, J.A. 1989. Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bulletin of Marine Science* 44(2):631-645.
- Bortone, S.A. 2003. Spotted seatrout as a potential indicator of estuarine conditions. Pages 297-300 *in* S.A. Bortone, editor. *Biology of the spotted seatrout*. CRC Press, Boca Raton, Florida.
- Bortone, S.A., T. Martin, and C.M. Bundrick. 1994. Factors affecting fish assemblage development on a modular artificial reef in a northern Gulf of Mexico estuary. *Bulletin of Marine Science* 55(2-3):319-332.
- Boswell, K.M., M.W. Miller, and C.A. Wilson. 2007. A lightweight transducer platform for use in stationary shallow water horizontal-aspect acoustic surveys. *Fisheries Research* 85:291-294.
- Boswell, K.M., M.P. Wilson, and J.H. Cowan, Jr.. 2008. A semiautomated approach to estimating fish size, abundance, and behavior from dual-frequency identification sonar (DIDSON) data. *North American Journal of Fisheries Management* 28(3):799-807.
- Brickhill, M.J., S.Y. Lee, and R.M. Connolly. 2005. Fishes associated with artificial reefs: attributing changes to attraction or production using novel approaches. *Journal of Fish Biology* 67(Supplement B):53-71.
- Capossela, K.M. 2010. Migration dynamics, within-estuary behaviors and cardiorespiratory responses of summer flounder to selected estuarine conditions. Master's thesis. The College of William and Mary, Williamsburg, Virginia.
- Chester, A.J., and G.W. Thayer. 1990. Distribution of spotted seatrout (*Cynoscion nebulosus*) and gray snapper (*Lutjanus griseus*) juveniles in seagrass habitats of western Florida Bay. *Bulletin of Marine Science* 46(2):345-357.
- Claudet, J., S. Roussel, D. Pelletier, and H. Rey-Valette. 2006. Spatial management of near shore coastal areas: the use of marine protected areas (MPAS) in a fisheries management context. *Vie et Milieu – Life and Environment* 56(4):301-305.
- Conrath, C.L., and J.A. Musick. 2010. Residency, space use and movement patterns of juvenile sandbar sharks (*Carcharhinus plumbeus*) within a Virginia summer nursery area. *Marine and Freshwater Research* 61:223-235.
- DeMartini, E.E., and T.W. Anderson. 2007. Habitat associations and aggregations of recruit fishes on Hawaiian coral reefs. *Bulletin of Marine Science* 81(1):139-152.
- Fertl, D. 1994. Occurrence patterns and behavior of bottlenose dolphins (*Tursops truncatus*) in the Galveston Ship Channel. *The Texas Journal of Science* 46(4):299-317.

- Fluharty, D. 2005. Evolving ecosystem approaches to management of fisheries in the USA. *Marine Ecology Progress Series* 300:241-296.
- Gannon, D.P., and D.M. Waples. 2004. Diets of coastal bottlenose dolphins from the U.S. mid-Atlantic coast differ by habitat. *Marine Mammal Science* 20(3):527-545.
- Harding, J.M., and R. Mann. 2001. Oyster reefs as fish habitat: opportunistic use of restored reefs by transient fishes. *Journal of Shellfish Research* 20(3):951-959.
- Harzen, S. 1998. Habitat use by the bottlenose dolphin (*Tursops truncatus*) in the Sado estuary, Portugal. *Aquatic Mammals* 24(3):117-128.
- Heck, Jr., K.L., K.W. Able, M.P. Fahay, and C.T. Roman. 1989. Fishes and decapod crustaceans of Cape Cod eelgrass meadows: species composition, seasonal abundance patterns and comparison with unvegetated substrates. *Estuaries* 12(2):59-65.
- Hilborn, R., K. Stokes, J-J. Maguire, T. Smith, L.W. Botsford, M. Mangel, J. Orensanz, A. Parma, J. Rice, J. Bell, K. Cochrane, S. Garcia, S.J. Hall, G.P. Kirkwood, K. Sainsbury, G. Stefansson, and C. Walters. 2004. When can marine reserves improve fisheries management? *Ocean and Coastal Management* 47:197-205.
- Hindell, J.S. 2007. Determining patterns of use by black bream *Acanthopagrus butcheri* (Munro, 1949) or re-established habitat in a south-eastern Australian estuary. *Journal of Fish Biology* 71:1331-1346.
- Hindell, J.S., Jenkins, G.P., and Womersley, B. 2008. Habitat utilisation and movement of black bream *Acanthopagrus butcheri* (Sparidae) in an Australian estuary. *Marine Ecology Progress Series* 366:219-229.
- Holland, K.N., C.G. Meyer, and L.C. Dagorn. 2009. Inter-animal telemetry: results from first deployment of acoustic 'business card' tags. *Endangered Species Research* 10:287-293.
- Inoue, M., and W.J. Wiseman, Jr. 2000. Transport, mixing, and stirring processes in a Louisiana estuary: a model study. *Estuarine, Coastal, and Shelf Science* 50:449-466.
- Kerwath, S.E., E.B. Thorstad, T.F. Naesje, P.D. Cowley, F. Okland, C. Wilke, and C.G. Attwood. 2009. Crossing invisible boundaries: the effectiveness of the Langebaan Lagoon marine protected area as a harvest refuge for a migratory fish species in South Africa. *Conservation Biology* 23(3):653-661.
- Kupschus, S. 2003. Development and evaluation of statistical habitat suitability models: an example based on juvenile spotted seatrout *Cynoscion nebulosus*. *Marine Ecology Progress Series* 265:197-212.

- Langton, R.W., R.S. Steneck, V. Gotceitas, F. Juanes, and P. Lawton. 1996. The interface between fisheries research and habitat management. *North American Journal of Fisheries Management* 16(1):1-7.
- Levin, P.S., and G.W. Stunz. 2005. Habitat triage for exploited fishes: can we identify essential “essential fish habitat”? *Estuarine, Coastal and Shelf Science* 64:70-78.
- MacRae, P.S.D., and J.H. Cowan, Jr. 2010. Habitat preferences of spotted seatrout, *Cynoscion nebulosus*, in coastal Louisiana: a step towards informing spatial management in estuarine ecosystems. *The Open Fish Science Journal* 3:154-163.
- Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2007. Public Law 109-479, United States Department of Commerce, January 12, 2007.
- McMichael, Jr., R.H., and K.M. Peters. 1989. Early life history of spotted seatrout, *Cynoscion nebulosus* (Pisces: Sciaenidae), in Tampa Bay, Florida. *Estuaries* 12(2):98-110.
- Mead, J.G., and C.W. Potter. 1990. Natural history of bottlenose dolphins along the central Atlantic coast of the United States. Pages 165-198 in S. Leatherwood and R.R. Reeves, editors. *The bottlenose dolphin*. Academic Press, San Diego.
- Metcalf, J.D., M.C. Fulcher, S.R. Clarke, M.J. Challiss, and S. Hetherington. 2009. An archival tag for monitoring key behaviors (feeding and spawning) in fish. Pages 243-254 in *Tagging and tracking of marine animals with electronic devices, reviews: methods and technologies in fish biology and fisheries* 9. J.L. Nielsen, H. Arrizabalaga, N. Fragoso, A. Hobday, M. Lutcavage, and J. Sibert, editors. Springer, New York.
- Neahr, T.A., G.W. Stunz, and T.J. Minello. 2010. Habitat use patterns of newly settled spotted seatrout in estuaries of the north-western Gulf of Mexico. *Fisheries Management and Ecology* 17:404-413.
- Norse, E. 2010. Ecosystem-based spatial planning and management of marine fisheries: why and how? *Bulletin of Marine Science* 86(2):179-195.
- Ohta, I., and S. Kakuma. 2005. Periodic behavior and residence time of yellowfin and bigeye tuna associated with fish aggregating devices around Okinawa Islands, as identified with automated listening stations. *Marine Biology* 146:581-594.
- Peebles, E.B., and S.G. Tolley. 1988. Distribution, growth and mortality of larval spotted seatrout, *Cynoscion nebulosus*: a comparison between two adjacent estuarine areas of southwest Florida. *Bulletin of Marine Science* 42(3):397-410.
- Peterson, G.W., and R.E. Turner. 1994. The value of salt marsh edge vs interior as a habitat for fish and decapod crustaceans in a Louisiana tidal marsh. *Estuaries* 17(1B):235-262.

- Pihl, L., A. Cattirjse, I. Codling, S. Mathieson, D.S. McLusky, and C. Roberts. 2002. Habitat use by fishes in estuaries and other brackish areas. Pages 10-53 *in* M. Elliott and K.L. Hemingway, editors. Fishes in estuaries. Blackwell Science, Oxford.
- Pikitch, E.K., C. Santora, E.A. Babcock, A. Bakun, R. Bonfil, D.O. Conover, P. Dayton, P. Doukakis, D. Fluharty, B. Heneman, E.D. Houde, J. Link, P.A. Livingston, M. Mangel, M.K. McAllister, J. Pope, and K.J. Sainsbury. 2004. Ecosystem-based fishery management. *Science* 305:346-347.
- Plunket, J., and M.K. La Peyre. 2005. Oyster beds as fish and macroinvertebrate habitat in Barataria Bay, Louisiana. *Bulletin of Marine Science* 77(1):155-164.
- Reynolds, B.F., S.P. Powers, and M.A. Bishop. 2010. Application of acoustic telemetry to assess residency and movements of rockfish and lingcod at created and natural habitats in Prince William Sound. *PLoS One* 5(8):e12130.
- Reese-Robillard, M.M., G.W. Stunz, and J. Simons. 2010. Relative value of deep subtidal oyster reefs to other estuarine habitat types using a novel sampling method. *Journal of Shellfish Research* 29(2):291-302.
- Rogers, K.B., and E.P. Bergersen. 1999. Utility of synthetic structures for concentrating adult northern pike and largemouth bass. *North American Journal of Fisheries Management* 19:1054-1065.
- Rountree, R.A., and K.W. Able. 2007. Spatial and temporal habitat use patterns for salt marsh nekton: implications for ecological functions. *Aquatic Ecology* 41:25-45.
- Rozas, L.P., and T.J. Minello. 1997. Estimating densities of small fishes and decapod crustaceans in shallow estuarine habitats: a review of sampling design with focus on gear selection. *Estuaries* 20(1):199-213.
- Rozas, L.P., and T.J. Minello. 1998. Nekton use of salt marsh, seagrass, and nonvegetated habitats in a south Texas (USA) estuary. *Bulletin of Marine Science* 63(3):481-501.
- Saucier, M.H., and D.M. Baltz. 1993. Spawning site selection by spotted seatrout, *Cynoscion nebulosus*, and black drum, *Pogonias cromis*, in Louisiana. *Environmental Biology of Fishes* 36:257-272.
- Semmens, J.M., C.D. Buxton, E. Forbes, and M.J. Phelan. 2010. Spatial and temporal use of spawning aggregation sites by the tropical sciaenid *Protonibea diacanthus*. *Marine Ecology Progress Series* 403:193-203.
- Simonsen, K.A. 2008. The effect of an inshore artificial reef on the community structure and feeding ecology of estuarine fishes in Barataria Bay, Louisiana. Master's thesis. Louisiana State University, Baton Rouge, Louisiana.

- Starr, R.M., E. Sala, E. Ballesteros, and M. Zabala. 2007. Spatial dynamics of the Nassau grouper *Epinephelus striatus* in a Caribbean atoll. *Marine Ecology Progress Series* 343:239-249.
- Stoner, A.W. 2003. What constitutes essential nursery habitat for a marine species? A case study of habitat form and function for queen conch. *Marine Ecology Progress Series* 257:275-289.
- Stunz, G.W., T.J. Minello, and L.P. Rozas. 2010. Relative value of oyster reef as habitat for estuarine nekton in Galveston Bay, Texas. *Marine Ecology Progress Series* 406:147-159.
- Tabb, D.C. 1966. The estuary as a habitat for spotted seatrout, *Cynoscion nebulosus*. American Fisheries Society, Special Publication 3, Bethesda, Maryland.
- Whaley, S.D., J.J. Burd, Jr., and B.A. Robertson. 2007. Using estuarine landscape structure to model distribution patterns in nekton communities and in juveniles of fishery species. *Marine Ecology Progress Series* 330:83-99.
- Zeller, D.C. 1998. Spawning aggregations: patterns of movement of the coral trout *Plectropomus leopardus* (Serranidae) as determined by ultrasonic telemetry. *Marine Ecology Progress Series* 162:253-263.



## **GENERAL SUMMARY AND CONCLUSIONS**

This dissertation examined the spatial ecology of adult spotted seatrout in Louisiana coastal waters. I primarily employed remote acoustic telemetry, and to a lesser degree, conventional tagging to investigate the movements, distribution, and habitat use of this important recreational species. This body of work revealed novel information on the ecology of spotted seatrout that will aid and potentially enhance its assessment and management. In addition, results from my methods validation work (chapters 1 and 2) have important implications for future telemetry studies.

Understanding the performance of telemetry equipment is crucial for designing receiver arrays and interpreting collected data, but is often overlooked in contemporary studies. My study was unique as it represented one of the most thorough examinations to date of the performance of remote acoustic telemetry equipment. The long-term range test showed that receiver performance was highly dynamic and principally controlled by meteorological conditions (i.e., wind velocity and associated turbidity). The high degree of temporal variability in receiver performance and detection ranges I observed was not surprising given the dynamic biophysical conditions typical of estuarine and coastal ecosystems. Still, this finding has important implications for telemetry research, particularly those studies using acoustic gate designs to investigate fish migration. Namely, gate receivers need to be spaced as conservatively as possible to facilitate the detection of migrants during poor acoustic conditions. Another challenge in telemetry research is that receiver performance can be affected by the same environmental variables to which fish movements and habitat use are often related. For example, my study demonstrated that receiver performance was strongly related (negatively) to turbidity. Without this information, greater detection magnitudes in low (versus high) turbidity areas could

be interpreted as a preference for low turbidity, when indeed the detection pattern is due to poor receiver performance (reduced detectability) in high turbidity areas (i.e., fish behavior and receiver performance are confounded). This example illustrates how an understanding of the environmental controls on receiver performance can help determine the questions that can be validly addressed with telemetry methods and also facilitate data analysis. In general, I recommend that telemetry researchers more explicitly examine and consider, as a routine part of their studies, both the temporal and spatial variation in receiver performance. While of obvious utility on a study-specific basis, through this heightened effort, it is possible that several commonalities may emerge that will aid the design and analyses of remote telemetry studies and enhance the applications of this technique.

As one of the first biotelemetry studies on spotted seatrout, it was necessary to evaluate the effects of the potentially stressful and invasive surgical procedure used to implant acoustic transmitters. Survival of implanted fish was nearly 100% in my laboratory experiment. In addition, the majority of telemetered fish in the Calcasieu Lake study (85%) were detected more than a week after release and moving throughout the estuary, indicating they survived the surgery process. My laboratory experiment also demonstrated the retention of acoustic transmitters was excellent (100%) and fish began feeding shortly after tagging (< 24 hours). Although spotted seatrout are generally considered a fragile species, my results indicate they were not adversely affected by the surgical implantation of acoustic transmitters. The implications of this finding are two-fold. First, my telemetry results were not compromised by tagging effects or transmitter loss. Second, because of high fish survival and transmitter retention rates, telemetry appears to be a feasible approach and could be used in future studies on the movement and behavior of this species.

Despite their mobility and capacity for dispersal, I found that adult spotted seatrout exhibited a high degree of estuarine fidelity and rarely undertook large-scale movements (i.e., > 100 km). Only 18% of telemetered fish emigrated from the Calcasieu Lake estuary; interestingly, emigration rates were approximately three-fold lower for females (11%) than males (29%). The ultimate fate of emigrants was unknown. Thus, it cannot simply be assumed that all emigrants undertook large-scale migrations upon leaving the estuary. For instance, it is possible that some emigrants remained in close proximity to Calcasieu Lake (e.g., in nearshore waters of the Gulf of Mexico) or returned to the estuary after their transmitter batteries expired. Conventional tagging data indicated that large-scale movements of spotted seatrout were indeed rare as only 1% of tag returns occurred beyond 50 km of release sites and most fish (94%) were recaptured in the same estuarine basin in which they were tagged. Collectively, these results suggest that considerable spatial (stock) structure occurs *within* coastal Louisiana. It appears likely that each major estuary or at least each complex of adjacent estuaries (e.g., Barataria and Terrebonne Bays) contains a separate stock of fish that do not extensively interact with and are thus demographically independent from others across the vast Louisiana coastline.

At smaller spatial scales (i.e., within the estuary), I found that abiotic factors exerted a strong effect on fish distribution and spotted seatrout exhibited clear habitat preferences. During freshet events, females avoided low-salinity waters (< 5 psu) of the upper bay and primarily utilized the lower bay, where salinities were higher. Meanwhile, males were unaffected by low salinity conditions and continued to utilize the upper bay, despite salinities as low as 1 to 2 psu. Thus, it appears that only female spotted seatrout avoid low salinities, which may be related to differences in energy optimization strategies between sexes as discussed in chapter 4. Within Calcasieu Lake, spotted seatrout utilized oyster reef and mud-bottom habitats of the estuary

proper to a much greater extent than marsh and channel regions. However, channel habitats appeared to provide an important deep-water refuge during severe weather events (e.g., cold fronts and tropical storms) and the use of marshes may have been underestimated due to restricted habitat accessibility (presence of weirs). Seasonal and size trends in habitat use were also evident, whereby larger fish (> 400 mm TL) displayed a high affinity for structured (reef) habitats and across size classes, artificial reefs were most heavily utilized during spring and summer (April-August).

The novel ecological information revealed in this dissertation (chapters 3-5) will aid the assessment and management of spotted seatrout in coastal Louisiana. Currently in Louisiana, spotted seatrout are assessed as a single state-wide stock. However, my results suggest that stock boundaries occur at a much finer spatial scale, with each region, or possibly each estuary, possessing a separate stock of fish with largely independent dynamics. Therefore, as I argue in chapter 3, the most prudent assessment strategy may be to conduct stock assessments at a hierarchy of spatial scales, from individual estuarine basins to regional and state-wide levels. Otherwise, if assessment metrics are simply pooled across the entire state (the status quo), divergent stock trajectories may go unrecognized. For example, declining spawning biomass of stocks inhabiting regions with greater habitat loss and fishing pressure could be offset by increasing biomass trends for stocks found in estuaries with higher biological productivity and a more optimal forage base. If localized stock depletions are revealed through this alternative assessment method, spatially-explicit fishing regulations and habitat restoration plans (e.g., at the scale of an individual estuary) should be effective methods to promote stock rebuilding.

As we move towards the future of fisheries management and attempt to implement a more holistic, ecosystem-based approach, knowledge of how fishes interact with their

environment and other organisms is becoming of paramount importance. Two of my principal findings are directly relevant to and support this ecosystem-based initiative. First, I found that male spotted seatrout remained in low salinity waters ( $< 5$  psu), which differs from conventional wisdom that all adults, regardless of their sex, generally avoid low salinities. This finding has an important implication for ecosystem models (e.g., EcoSim/EcoSpace) that incorporate predator-prey dynamics to gauge the effects of alternative management scenarios (e.g., different fishing regulations or hydrologic operations) on aquatic communities. Namely, for models involving estuaries along the northern Gulf, spotted seatrout will need to be included as an important and abundant predator/prey species in oligohaline regions (0.5-5 psu). Secondly, I demonstrated that adult (legal-sized) spotted seatrout aggregated at and used artificial reefs most extensively during the peak fishing season for this species in coastal Louisiana (spring-summer). This finding highlights the important need for managers to carefully consider both the negative (e.g., increased vulnerability to fishing mortality) and positive aspects of artificial reefs (e.g., benefits to other species, ecotourism) when deciding to grant permission for the deployment of additional artificial structures in estuarine waters.

While this dissertation advanced our knowledge of the ecology and life history of spotted seatrout, our understanding of these topics is far from complete, as my results beg several intriguing research questions that could be addressed in future work. For example, what is the underlying mechanism that promotes such high estuarine fidelity of this mobile species? Is this fidelity maintained by an affinity for certain sites or regions within estuaries? Or perhaps spotted seatrout are capable of detecting and utilizing geo-magnetic fields, chemical cues, and/or visual landmarks for navigation purposes, any of which could prevent the random wandering of fish? It is possible that many estuarine and coastal fishes possess strong homing and navigation abilities,

similar to those of highly migratory fishes (e.g., tuna and salmon) that exhibit a high degree of philopatry despite undergoing extensive movements. Another interesting question is: *why* do spotted seatrout, particularly larger fish, exhibit a high affinity for oyster reef habitats? An increased understanding of the role and function of different habitat types, perhaps obtained through direct behavioral observations, should enhance habitat management and conservation plans. The answers to these questions, in addition to those addressed in this dissertation, will advance our fundamental understanding of species biology and ecology and also support the wise management of our valuable fishery resources.

## VITA

Jody L. Callihan was born in Osterburg, Pennsylvania on May 12, 1980. He graduated from Chestnut Ridge High School in 1998. In his first big move away from rural Pennsylvania, Jody matriculated at the University of Miami in 1998. During his time at Miami, Jody completed the Saltwater Semester Program at the Rosenstiel School of Marine and Atmospheric Science, where he investigated the foraging ecology of juvenile mojarra. He received his B.S. in 2002, with a double major in marine science and biology and a minor in chemistry. Shortly thereafter, Jody started his graduate work at the University of Maryland's Chesapeake Biological Laboratory under the tutelage of Dr. David H. Secor. While at CBL, Jody gained valuable research experience and technical skills, particularly otolith microstructural analysis, which he applied to study the recruitment dynamics of juvenile bluefish. He earned his M.S. in Marine, Estuarine, and Environmental Science in the fall of 2005, and during that same semester began his doctoral work at Louisiana State University as a Board of Regents Fellow under the direction of Dr. James H. Cowan, Jr. in the Department of Oceanography and Coastal Sciences. While at LSU, Jody was exposed to and learned a variety of new tools useful for investigating the ecology and behavior of coastal fishes. His dissertation work focused on the spatial ecology of adult spotted seatrout. Jody will receive his Ph.D. in December 2011, and will continue to pursue his passion of conducting applied marine fisheries ecology research through a post-doctoral fellowship with Dr. Jeffrey A. Buckel at North Carolina State University.