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Spatiotemporal Modeling of Shorebird Habitat Availability at Rankin Wildlife Management Area, Tennessee

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To the Graduate Council:

I am submitting herewith a thesis written by Matthew D. Smith entitled "Spatiotemporal Modeling of Shorebird Habitat Availability at Rankin Wildlife Management Area, Tennessee." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Ken Orvis, Major Professor

We have read this thesis and recommend its acceptance:

Roger Tankersley, Matt Gray

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Dean of Graduate Studies

Spatiotemporal Modeling of Shorebird Habitat Availability at Rankin Wildlife Management Area, Tennessee

A Thesis
Presented for the
Master of Sciences
Degree
The University of Tennessee, Knoxville

Matthew D. Smith
May 2006

DEDICATION

This thesis is dedicated to my son Wyatt who is the
most fascinating person that I know.

Acknowledgements

I would like to thank the members of my committee for their guidance, support, and critical insight on this project. I would especially like to thank Dr. Orvis for helping me to improve my writing and communicate more effectively.

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Abstract

This study examines spatiotemporal patterns of shorebird stopover habitat availability at Rankin Wildlife Management Area (Rankin Bottoms) on the Douglas Reservoir, Tennessee, USA. Rankin Bottoms is a key stopover site for fall migrating shorebirds traveling through the Tennessee River Valley (TRV). In the TRV, the majority of shorebird habitats consist of mudflats created along reservoirs in the fall as the Tennessee Valley Authority (TVA) lowers reservoir levels to prepare for winter and spring rains. Occasional changes to the annual reservoir management cycle enacted by TVA have affected the timing of mudflat exposure and thus the timing of availability of stopover habitats for migrating shorebirds in the TRV.

I used high-resolution LiDAR elevation data of the lake bottom along with recorded reservoir stage values from 1972 to the present in a Geographic Information System (GIS) to model mudflat exposure at Rankin Bottoms. I defined model parameters that allow me to report values for shorebird habitat availability as it changes through the migration period, and modeled these values for three reservoir management scenarios including the current management scenario. I used average reservoir stage data for the 1972–1990 and 1991–2003 reservoir management scenarios and predictive reservoir stage data for the current ROS management regime as input into this model. My results suggest that changes made in 1991, and more so in 2004, delay the creation of habitat at Rankin Bottoms to the beginning of August, but extend habitat availability further into the winter. Under the most recent management scenario implemented by TVA in 2004, the 15 species of shorebirds known to potentially arrive in the TRV in July will find their habitat at Rankin Bottoms inundated upon their arrival. Based on these models, shorebird-optimal reservoir management guidelines have been prepared for TVA to consider as part of their adaptive management plan.

The findings of this study are presented in the *Rankin Wildlife Management Area Shorebird Habitat Viewer*, a visualization tool, which offers 3-Dimensional animations of habitat availability at Rankin Bottoms. Using this tool, interested parties can compare and contrast the amount of available habitat for any day of the migration period under the historic and current management regimes.

The models generated for this study can help TVA's reservoir managers to assess the habitat impacts of proposed reservoir management activities now and in the future. The methods developed in this study are not specific to the phenomenon of shorebird migration or to the TVA river system. They may be used by reservoir and wildlife managers elsewhere to assess the habitat consequences of different management strategies and ultimately determine the optimal management strategy for species of concern.

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Chapter 1: Introduction

1.1 Purpose

Shorebirds (Aves: *Charadrii*) migrate through North America from breeding grounds in the arctic and sub-arctic to wintering grounds in Central and South America, and a few areas in the southern United States (Myers 1983; Skagen and Knopf 1993). In the Western Hemisphere these species use one or some combination of migration routes along the coasts or interior of North America (Myers et al. 1987) (Fig. 1). While en route to breeding and wintering grounds, these species use stopover habitats to rest and refuel so that they may complete their long journeys (Ashkenazie and Safriel 1979; Helmers 1992; Myers et al. 1987; Skagen and Knopf 1993). During fall migration some shorebirds have adapted to use mudflat habitats on reservoirs in the Tennessee River Valley (TRV) (Brown et al. 2001; Robinson 1990; U.S. Fish and Wildlife Service 2004). The reservoirs are managed by the Tennessee Valley Authority (TVA), the largest public power company in the U.S. Reservoir management changes made in the last two decades may threaten these habitats, but until now the interplay between stopover availability and reservoir management in the TRV has not been formally studied (Davis 2004; Tennessee Ornithological Society 2004b).

TVA has managed the nine main-stem reservoirs and 40 tributary reservoirs in the TRV since their inception (Fig. 2). TVA periodically reviews reservoir management procedures to assess the value of the current management policy and make adjustments to optimize the benefits of the reservoir system to TVA and citizens of the TRV. Each year TVA manages the reservoir stage, or height to which a reservoir is filled with water, for

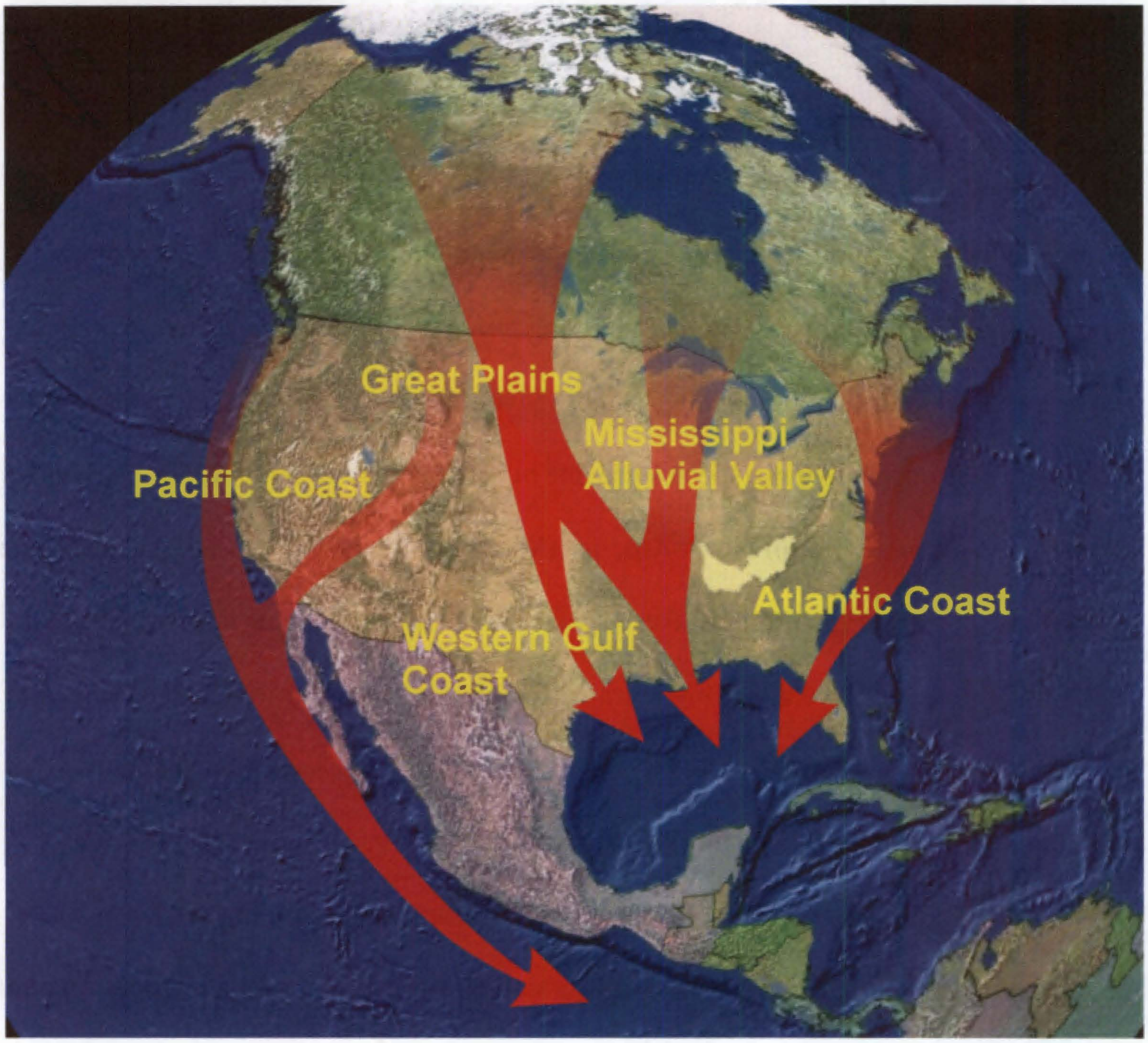


Figure 1: The four primary North American fall migration corridors for southward migrating shorebirds. The Tennessee River Valley, in yellow, is sandwiched between the Atlantic and Mississippi migration routes and receives migrants from both.

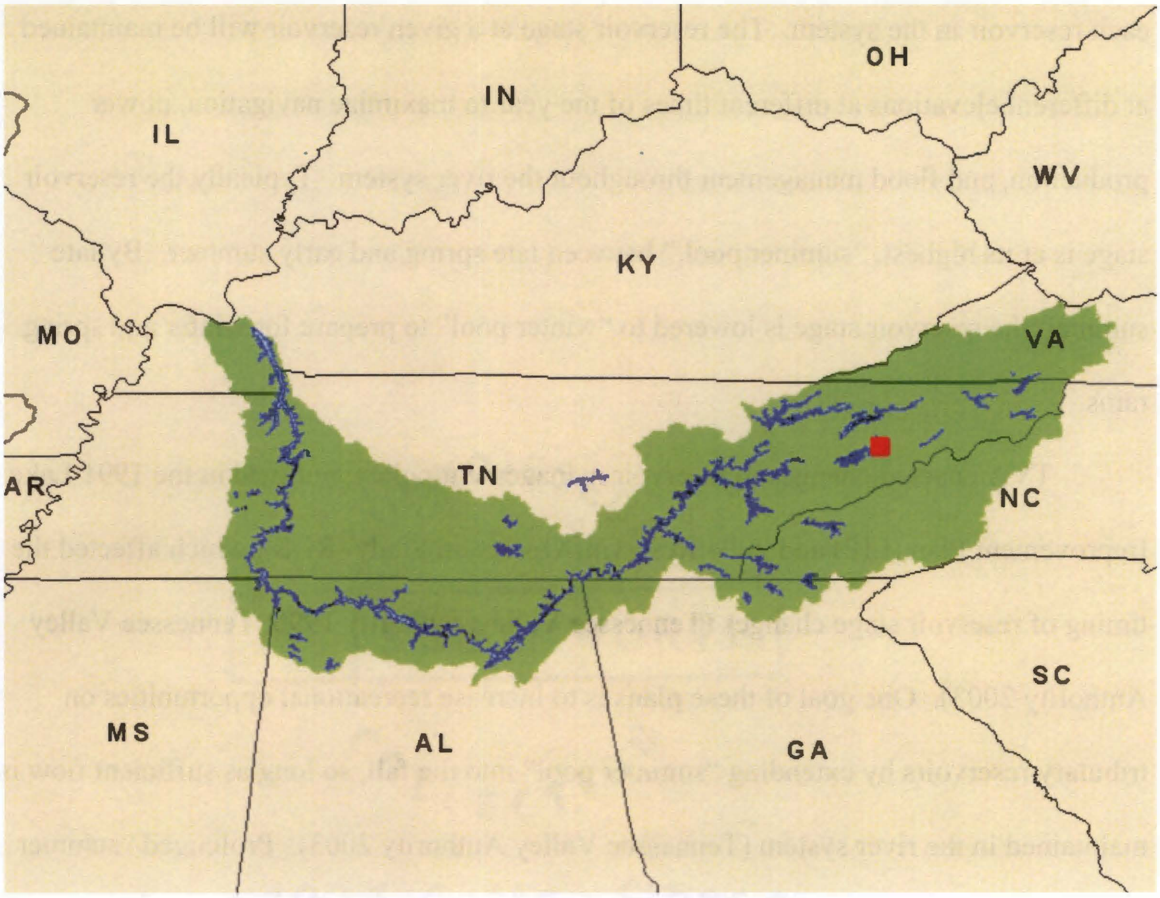


Figure 2: The Tennessee River Valley with TVA-managed reservoirs. The location of Rankin Bottoms is symbolized by the red square.

each reservoir in the system. The reservoir stage at a given reservoir will be maintained at different elevations at different times of the year to maximize navigation, power production, and flood management throughout the river system. Typically the reservoir stage is at its highest, "summer pool," between late spring and early summer. By late summer, the reservoir stage is lowered to "winter pool" to prepare for winter and spring rains.

TVA enacted changes in reservoir management policy, outlined in the 1991 Lake Improvement Plan (LIP) and 2004 Reservoir Operation Study (ROS), which affected the timing of reservoir stage changes (Tennessee Valley Authority 1990; Tennessee Valley Authority 2003). One goal of these plans is to increase recreational opportunities on tributary reservoirs by extending "summer pool" into the fall, so long as sufficient flow is maintained in the river system (Tennessee Valley Authority 2003). Prolonged "summer pool" is preferred by recreation enthusiasts, lakeside landowners, and recreation businesses that desire enhanced aesthetic views, increased property values, and improved lake access. Local government likewise supports the ROS management change in hopes that it might foster job creation and tax base expansion (Tennessee Valley Authority 2003).

These management changes have drawn criticism from natural resource managers and members of the ornithological community who cite possible impacts to waterfowl and shorebird habitat on TVA managed reservoirs (Davis 2004; Tennessee Ornithological Society 2004b). During fall migration shorebirds use mudflat habitat created by reservoir drawdown, and overwintering waterfowl feed on vegetation that becomes established on these flats (Davis 2004; Tennessee Ornithological Society 2004b). The concern is that maintaining elevated reservoir levels throughout much of the migration season may result in shorebird habitat remaining inundated and therefore unusable when birds arrive. This delay in exposure of mudflats also may impede the development of mudflat vegetation, one of the primary food resources for overwintering waterfowl. The U.S. Fish and Wildlife Service opposed ROS changes to the drawdown timing of Kentucky Reservoir because of possible impact on habitat availability at Tennessee National Wildlife Refuge. At this time Kentucky Reservoir will not be affected, but there has been much speculation that the changes dictated by the ROS will be detrimental to other key mudflat habitats, at Rankin Wildlife Management Area and elsewhere in the TRV (Davis 2004; Tennessee Ornithological Society 2004b).

The Final Programmatic Environmental Impact Statement (FEIS) prepared by TVA (Tennessee Valley Authority 2004) for the ROS addresses possible impacts to flood management, water quality, power production, wetlands, shoreline erosion, and the health of aquatic species (Tennessee Valley Authority 2003). However, impacts to migratory shorebird habitat and waterfowl habitat are not adequately addressed in this document. TVA must address these impacts in order to adhere to the Migratory Bird Treaty Act (U.S.C. 1918) and the Executive Order on Migratory Birds (E.O. #13186). As part of the ROS record of decision, TVA has undertaken a five-year monitoring program to assess impacts to shorebird species through biogeographic habitat research and annual migration counts at stopovers throughout the TRV.

This thesis examines the timing of mudflat exposure at Rankin Bottoms (Rankin Wildlife Management Area) (Fig. 3), relative to the timing of shorebird migration. I selected Douglas Reservoir and specifically Rankin Bottoms as a study site to explore

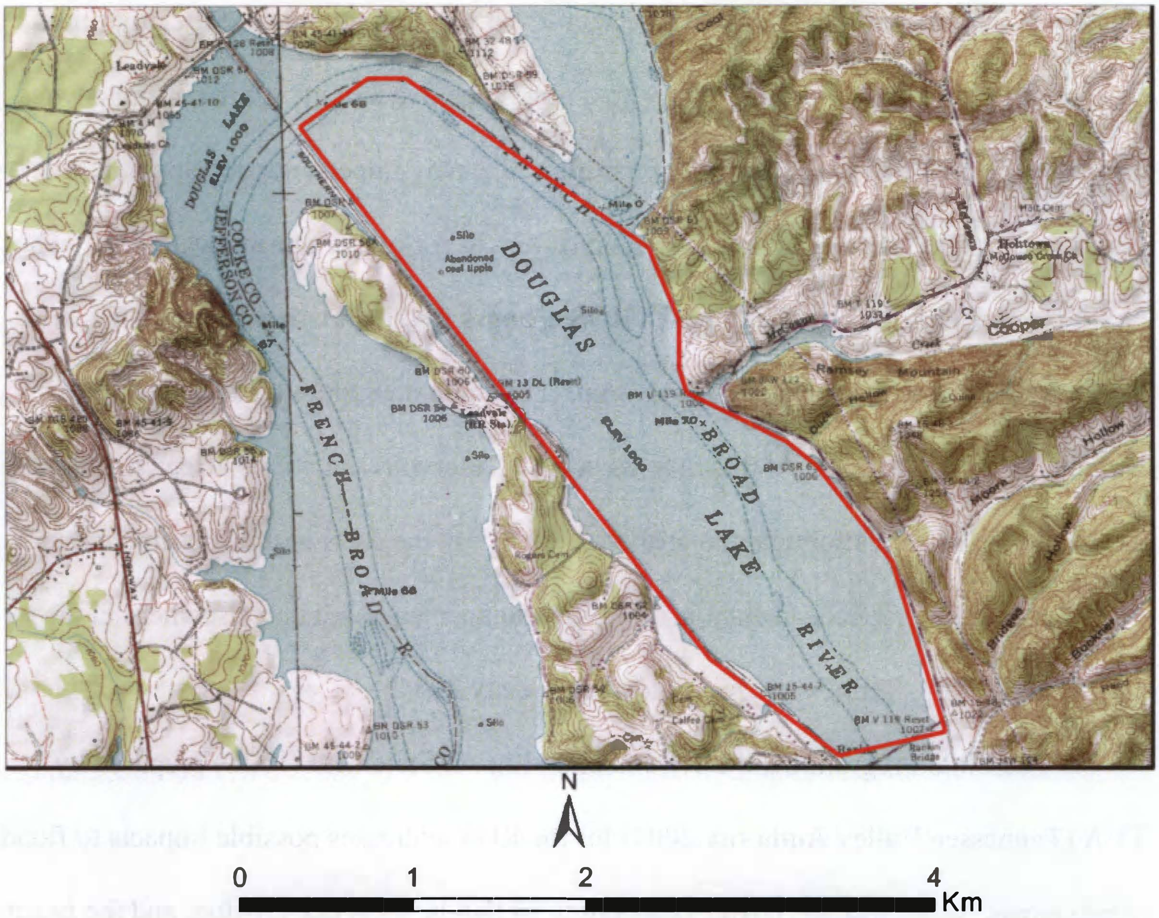


Figure 3: Rankin Wildlife Management Area (WMA). This wetland area is managed by the Tennessee Wildlife Resources Agency and is a key stopover for migrating shorebirds in East Tennessee. The boundary used to quantify habitat area in this study is outlined on this map. Adjacent mudflats exist on the Nolichucky River, but these areas were not surveyed by LiDAR and thus are not included in any of the habitat availability calculations.

methods for quantifying shorebird habitat availability in the TRV. Rankin Bottoms is a suitable stopover location for shorebirds, because it possesses large mudflats apt for foraging during fall migration. In late summer and early fall, daily counts of hundreds of migrating shorebirds are common (Tennessee Ornithological Society 2004a; Tennessee Valley Authority 1999). The mudflats at Rankin Bottoms are exposed by the fall drawdown of the reservoir in preparation for winter and spring rains. This fall drawdown period roughly corresponds with the timing of fall migration. The same areas provide very little habitat in the form of non-vegetated streambed and impounded pools during the spring migration period because the mudflats are vegetated by thick emergent groundcover (A. Mays unpublished data). During the summer, no habitat exists because the mudflat area is completely inundated by the headwaters of Douglas reservoir.

My study quantified the area of mudflat habitat exposed at Rankin Bottoms during fall drawdown under ROS and under past management regimes (Fig. 4). By modeling the timing and amount of potential shorebird habitat resource availability at key stopovers in the TRV relative to the timing of shorebird migration, we can begin to understand the cumulative impacts to shorebird resources made by different TVA reservoir management regimes. My research demonstrates a methodology for assessing the impacts of reservoir management on migratory shorebird habitat. These methods can be applied to other human controlled or human altered aquatic systems to assess the habitat consequences of different management strategies, or to determine the optimal management strategy for species of concern.

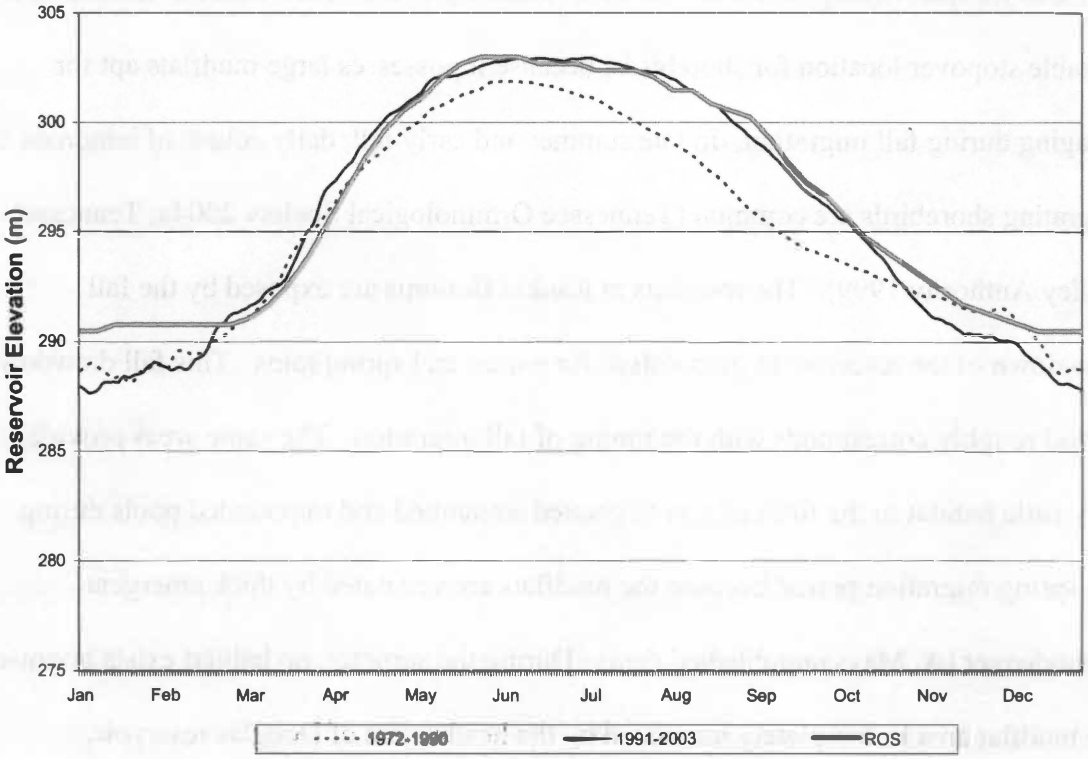


Figure 4: Averaged headwater reservoir stage values for Douglas Reservoir under three TVA management regimes.

1.2 Hypothesis and Justification

I hypothesize that shorebird habitat availability in the Tennessee River Valley will be negatively impacted by the changes in reservoir management outlined in the ROS and the 1991 Lake Improvement Plan (LIP). These changes include delay in reservoir drawdown and should therefore delay the seasonal exposure of mudflat habitat used by fall migrating shorebirds in the TRV. The issue is not that shorebird habitat will be destroyed, but that mudflat habitats will not be available when the majority of shorebirds arrive at migration stopovers in the TRV.

My research was designed to address concerns in the ornithological community that extending "summer pool" into the fall on Douglas Reservoir will cause much of the mudflat habitat at Rankin Bottoms to remain flooded during fall migration. I have seen and heard this sentiment expressed in forums, news articles, and through personal correspondence, but have found no systematic research to support or refute it (Davis 2004; Tennessee Ornithological Society 2004b).

The primary goal of my project was to demonstrate the development and application of a spatiotemporal model quantifying the amount of habitat available for migratory shorebirds at Rankin Bottoms at each reservoir stage during the migration period. This model has been applied to the ROS scenario, the LIP scenario (1991–2003), and the preceding reservoir management scenario (1972–1990) to quantify differences in the amount and timing of habitat availability. A secondary objective of this research was to develop a set of guidelines for TVA that would optimize shorebird habitat availability at Rankin Bottoms.

There are three fundamental questions:

1) When do shorebirds migrate through the Tennessee River Valley?
2) How much mudflat habitat is exposed as the migration period progresses under the different scenarios based on the predicted elevation values? Do ROS and LIP provide less habitat at critical times than the previous management strategy?
3) What reservoir management scenario would provide the most habitat overall for shorebirds at Rankin Bottoms?

The geographic analysis methods discussed in this document were designed to answer these questions so that environmental decision makers at TVA have the best data available to them for assessing the consequences of different reservoir management strategies. These methods will be applicable to other reservoir or river systems to support reservoir and wildlife managers there. For example, these methods may be adapted to study species composition in wetlands as a function of inundation duration and timing to aid managers in maximizing food resources for waterfowl and other target species. They may also be used by land managers to determine the best reservoir management practices aimed at stopping the spread of or eradicating invasive species that establish along river banks, or to manage for pest species that breed in backwater pools created during reservoir drawdown.

My study will contribute to the overall assessment of impacts to shorebird migration by developing habitat quantification methods applicable to other areas. Within TVA, these methods may be applied elsewhere in the TRV to assess how reservoir management changes have affected mudflat habitat availability; they may also be used in future planning efforts for the reservoir system as a whole or by other reservoir managers outside the region.

Shorebird management has not been a priority for TVA in the past, and the general public views mudflats as a detriment to the scenic beauty of TVA reservoirs. More recently, TVA has recognized the habitat creation benefits of fall drawdown and has partnered with the U.S. Fish and Wildlife Service and state Wildlife Agencies to improve conditions for wading birds by designating some lakefront properties as National Wildlife Refuges and State Wildlife Management Areas (Tennessee Valley Authority 1999). The data and methods generated in this study may assist TVA in properly managing these and other TRV stopover habitats.

From a hemispheric shorebird conservation perspective, my research may help to highlight shorebird resources that exist outside the primary migration routes. Losses of wetlands through human destruction such as dredging wetlands or diking large rivers has dramatically reduced the amount of wetland and shallow floodplain stopover habitat available for shorebirds migrating along traditional migratory routes (Brown et al. 2001; Dahl and Johnson 1991; Gosselink and Bauman 1980; Howe et al. 1989; de Szalay et al. 2000; Tiner 1984). For example, alterations made to the Ohio and Mississippi Rivers for navigation, flood control, and agriculture have significantly reduced the number of stopover locations on the Mississippi Alluvial Valley (MAV) migration corridor (de Szalay et al. 2000). This reduction in available stopover sites along traditional migration routes is a likely contributing factor to population declines in many shorebird species (Howe et al. 1989; Myers 1983). Increasing the availability of stopover sites, especially during fall migration, has been highlighted in the MAV as one of the greatest conservation needs for shorebirds (Loesh et al. 2000).

The best way to compensate for stopover habitat losses would be to create new shorebird habitats or incorporate shorebird management into the management priorities of existing sites (Loesch et al. 2000; Twedt et al. 1998). Managed wetland systems can be especially valuable at times when droughts or floods reduce the number or quality of available natural stopover habitats (Eldridge 1992; Helmers 1992). The Tennessee Valley Authority has the unique ability to manage wetland areas at a regional scale. Although not on a major migration corridor (Fig. 1.), TVA lands have hosted substantial numbers of shorebirds since the creation of the reservoir system (Tennessee Ornithological Society 2004a; Tennessee Valley Authority 1999). The drawdown of TVA reservoirs in the fall to prepare for winter and spring rains provides habitat that successive generations of migrating shorebirds have learned to exploit, extending migration corridors into the TRV. Fall drawdown exposes thousands of hectares of mudflats along the reservoir system. Many of these mudflats are rich in invertebrate food resources and have become stopovers frequented by migrating shorebirds when available (Brown et al. 2001; U.S. Fish and Wildlife Service 2004).

In late summer and early fall, daily counts of hundreds to thousands of migrating shorebirds are common on TRV stopovers (Tennessee Ornithological Society 2004a; Tennessee Valley Authority 1999). These numbers cannot compare to the tens of thousands of birds seen along traditional migratory routes such as the Mississippi flyway (Brown et al. 2001; Loesch et al. 2000), but individual migrants and shorebird habitat resources in the TRV should be considered when developing an effective and comprehensive shorebird conservation framework. Moreover, on-reservoir shorebird habitat resources in East Tennessee are especially important because there are relatively fewer wetlands present in this area than nearer the main migration corridor in West Tennessee. These habitats provide alternate routes for species displaced by adverse human activities along the traditional routes.

1.3 Scope and Limitations

In this study, I model habitat availability for a key stopover site in East Tennessee—Rankin Bottoms. Rankin Bottoms was selected because it has been affected by the ROS and past reservoir management changes to Douglas Reservoir (Fig. 4.), and it is one of the few large stopover sites in East Tennessee (T. Henry, unpublished data 2004). The LIDAR data coverage used for modeling in this study covers only Rankin Bottoms. Adjacent mudflats exist on the Nolichucky River, but these areas are not included in any of the calculations. Although this study is spatially limited to this particular area, the methods developed herein are applicable to other areas in the TRV and may be applicable at stopovers elsewhere.

In this modeling, I have had to make several assumptions to forecast the outcome of several different scenarios. The rationale used to justify my assumptions is detailed in the methods section of this thesis. I have approached this modeling effort by using averaged reservoir stage data for the 1972–1990 and LIP scenarios, and predicted reservoir stages for the ROS scenario. I report habitat availability based on these averaged and predicted reservoir stage data because I believe they are the most appropriate datasets to use for forecasting future changes to habitat availability brought on by changes in reservoir management policy. In the future after several years of data collection following implementation of the new ROS reservoir management scenario, it will be possible to test the validity of this model's prediction statistically by calculating habitat availability for each year under all the scenarios to determine if there is a statistical difference in the amount of habitat provided under each scenario. The model I have chosen is not statistically rigorous, but rather is a test which quantified the amount of shorebird habitat availability based on representative reservoir stage data for each period to predict how these changes in reservoir management will affect and have affected shorebird habitat availability. I have made this decision because the power of this study lies in the ability to predict how changes to policy will affect the dynamics of habitat availability, and the ability to develop and propose reservoir policy guidelines that optimize habitat availability.

Temporally this study is focused on the fall migration because it is during this time period that reservoir drawdown has historically provided mudflats. In the spring, available shorebird habitat is limited to perennial streambeds and impounded ponds. Also, shorebird survey data have consistently shown higher numbers of individuals in the TRV during fall migration relative to spring migration (T. Henry, unpublished data 2004). In this study I modeled habitat availability for Rankin Bottoms for average conditions under the 1972-1990 and LIP management regimes and used modeled reservoir elevation values to make future habitat availability predictions for the ROS management scenario. This study quantifies habitat for the 1972–1990 (72–90) management scenario, the 1991–2003 Lake Improvement Plan (LIP), and the 2004–present Reservoir Operation Study (ROS) management scenario based on representative reservoir stage data for each period. Reliable reservoir headwater elevation data for the management scenario before 1972 are unavailable.

1.4 Research Objectives

My research has the following objectives:

1) Research and document a chronology for shorebird migration in the TRV and identify the times of year when individual shorebird species are present.
2) Use a Geographic Information System (GIS) to model habitat availability throughout fall migration using LIDAR elevation data.
3) Confirm the accuracy of the mudflat exposure model using actual mudflat exposure, measured using Differential Global Positioning Systems (DGPS).
4) Model habitat availability and compare model results for three reservoir management scenarios (72–90, LIP, and ROS).
5) Develop a set of "shorebird optimal" reservoir management guidelines.
6) Produce maps and animations to accurately communicate the spatiotemporal nature of results generated by this study. Target audiences include TVA, other natural resource management agencies, non-governmental organizations, and interested private individuals.

1.5 Thesis Organization

My thesis is organized into five chapters: Introduction, Background, Methods, Results, and Discussion. Chapter Two reviews the literature covering shorebird migration, stopover habitat selection, shorebird conservation, and methodological literature pertaining to Global Positioning Systems (GPS), Aerial Photography, and Light Detection and Ranging (LiDAR) technologies. Chapter Three describes the methods used in this study and offers details about data collection, modeling parameters, and analyses. Chapter Four briefly presents the results of the study textually and then shows detailed results in a series of graphs and tables. Chapter Five discusses the significance of this study's findings from both local and hemispheric perspectives and discusses further research opportunities and how this methodology may be applied elsewhere.

I also present results, and demonstrate the model, more completely via the interactive *Rankin Wildlife Management Area Shorebird Habitat Viewer* included on the CD (Plate 1) accompanying this document. This application allows the viewer to explore the findings of this study in detail on screen. The habitat viewer contains information about project background, mudflat exposure animations and graphs and charts that summarize the findings of this study. The habitat exposure animations on the CD offer aerial views of reservoir drawdown at Rankin Bottoms that the viewer can interactively control. This product also automatically reports the area of shorebird habitat available under the three TVA management regimes and the number of possible shorebird species in the area as estimated from the migration chronology.

Chapter 2: Background

2.1 Shorebird Migration and Stopover

Each fall 47 species of shorebirds (Aves: *Charadrii*) embark on one of the most energetically costly migrations of any North American bird species. Traveling at speeds of up to 80 kilometers per hour and altitudes in excess of 3000 meters, these migrants complete their annual journeys through North America from arctic breeding grounds to Central and South American wintering grounds (Myers et al. 1983). Shorebirds migrate through North America by one or some combination of flyways along the Atlantic coast, Pacific coast, Great Plains and western Gulf of Mexico, and the Mississippi Alluvial Valley (MAV) (Myers et al. 1987) (Fig. 1). During spring and fall migration these diurnal migrants rely on visual cues to select refueling areas known as stopovers or staging areas to rest and feed so that they may complete their long journeys (Myers 1983).

Shorebird species have higher metabolic rates than other similarly sized nonpasserine species, so they spend the majority of their stopover time foraging to maintain energy and store fat (Ashkenazie and Safriel 1979; Drent and Piersma 1990; Kersten and Piersma 1987; Short 1999). Shorebird species may increase their body mass up to 100 percent at these stopover sites (Davidson and Evans 1989). The amount of energy accumulated en route sustains their long journeys, and following spring migration directly affects the reproductive potential of individual birds once they reach their breeding grounds in the arctic (Ashkenazie and Safriel 1979; Davidson and Evans 1989).

In coastal regions, shorebirds forage on intertidal mudflats, estuaries, deltas, and hypersaline lagoons (Helmers 1992; Johnsgard 1981; Meyers and Meyers 1979; Morris 1996). At these sites shorebirds feed on benthic marine polychaetes, mollusks, and crustaceans (Helmers 1992). In the North American interior shorebirds use wetlands, flooded agricultural areas, and mudflats along rivers, lakes, and reservoirs (Brown et al. 2001; Durell 2000; Hands 1991; Helmers 1992; Short 1999; Smith et al. 1991). These areas are selected because they commonly have high densities (~2g/m^2) of Chironomid larvae, the primary food source of interior migrating shorebirds (Brown et al. 2001; Hands 1991; Helmers 1992; Twedt et al. 1998). Areas used for foraging in both interior and coastal stopovers characteristically have less than 25% vegetation cover and less than 10 cm of water depth (Brown et al. 2001; Helmers 1992; Short 1999; Smith et al. 1991).

Coastal staging areas are generally more reliable than interior staging areas because predictable tides and seasonal food source availability at coastal staging areas coincide with the spatiotemporal patterns of migration (Helmers 1993; Myers 1983 Skagen and Knopf 1993). Coastal migration is characterized by large groups traveling long distances with few stopovers (Helmers 1993; Myers 1983; Wildlife Habitat Council 2000). Interior staging areas tend to be more ephemeral and therefore migration through the interior is characterized by smaller, more opportunistic groups flying shorter distances between many stopovers (Skagen and Knopf 1993; Skagen and Knopf 1994; Wildlife Habitat Council 2000). The interior staging areas are more predictable in the spring when heavy rains recharge wetlands leading to an abundance of surface water compared to fall (Brown et al. 2001). Migration patterns of some species suggest that they have adapted to avoid interior staging areas in the fall by assuming an elliptical migration pattern using coastal areas for fall migration and interior areas in the spring (Brown et al. 2001; Gratto-Trevor and Dickson 1994).

2.2 Stopover Habitats in the Tennessee River Valley

One place in the North American interior that offers predictable stopover habitat for fall migrants is the Tennessee River Valley (TRV). The TRV does not lie along one of the traditional migratory corridors, but still receives considerable numbers of migrants (Robinson 1990; Tennessee Valley Authority 1999). It is likely that some of these migrants are genetically distinct populations that have adapted to frequent stopovers along this interior path while others are diverted from other migration corridors by storm events or lack of habitat due to yearly variation. Migrants in the western TRV may have been diverted from the Mississippi Alluvial Valley which hosts approximately 500,000 shorebirds annually (Brown et al. 2001), while birds in the eastern TRV may have been diverted from more coastal routes. Given the evolution and genetics of migration (Berthold et al. 1992; Haig et al. 1997; Moore 1984; Woodrey 2000), and the dynamics of climate cycles changing the patterns of habitat availability (Skagen and Knopf 1994; Skagen et al. 1999) it is also likely that every portion of the landscape is visited by some birds, taking advantage of habitats along multiple routes. These opportunistic migrants move across the landscape governed by variable temporal and spatial patterns of habitat availability, and new migration routes become established when migrants find successful alternative routes.

The stability of fall habitat availability in the TRV is a function of the system of reservoirs constructed by the Tennessee Valley Authority (TVA). TVA is a multipurpose federal corporation that operates a system of dams and reservoirs in the TRV for flood control, year round navigation, electricity production, water supply, and recreation (Tennessee Valley Authority 2003). Most of the dams in the TVA system were constructed in the 1940s and since that time water flow and reservoir elevation have been managed by TVA (Tennessee Valley Authority 2003).

The seasonal drawdown of reservoirs in the TVA system has resulted in the development of mudflats now used by migratory birds as stopover habitat. Although other off-reservoir habitats such as flooded agricultural fields, fish hatcheries, sewage treatment facilities, and ash ponds have been identified as significant shorebird habitats (Hands et al. 1991; Neill 1992; Smith et al. 1991;), the vast majority of habitats in the TRV are on reservoir-created mudflats (T. Henry, personal correspondence 2004). As part of my research at TVA I created a geographic coverage of all the possible shorebird habitats along TVA reservoirs in the TRV. Potential shorebird habitats were identified from the U.S. Fish and Wildlife Service's National Wetland Inventory (NWI) data, and through personal correspondence with professionals. I then delineated mudflats in these areas using digital orthophotography of Tennessee. I identified 93 potential stopover sites on eight reservoirs in the TRV. These sites were spread across the TRV; 49 sites were in West Tennessee on Kentucky Reservoir, 13 were in Northern Alabama on Wheeler and Pickwick Reservoirs, and 31 were in Middle and East Tennessee on Douglas, Cherokee, Watauga, Nottely, Hiawassee, and Chickamauga Reservoirs. These areas are typically at the mouths of stream channels that feed into the reservoirs where streams lose energy and deposit suspended fine sediments in the form of mudflats and silt bars. The mudflats created in these areas are very fertile and when left exposed will develop emergent vegetation, but are inundated for enough of the growing season to prevent the establishment of persistent woody vegetation.

TVA recognizes the habitat development opportunities created by fall drawdown and has partnered with the U.S. Fish and Wildlife Service and state Wildlife Agencies to improve conditions for birds by developing national wildlife refuges and state wildlife management areas (Tennessee Valley Authority 1999). Rankin Wildlife Management Area (Rankin Bottoms), the focus of this study, is one of these where shorebird habitat is created by fall drawdown. Rankin Bottoms is located on Douglas Reservoir at the confluence of the Nolichucky and French Broad Rivers (Fig. 2). The Wildlife Management Area at Rankin Bottoms encompasses a thin peninsula and surrounding shoreline areas that are characterized by low relief with sparsely vegetated alluvial features composed of fine sediments.

2.3 Shorebird Foraging and Microhabitat Selection

All shorebird species subsist primarily on macro-invertebrates, but different species have different foraging methods. There are three primary feeding methods: probing, gleaning, and a combination of both (Durell 2000). Some species such as Godwits (*Limosa*) prefer to probe the substrate to collect subterranean invertebrates and larvae. Other species such as Yellowlegs (*Tringa*) glean invertebrates directly from the water surface and water column while others like Sandpipers (*Calidris*) feed using a combination of both methods. Different species of shorebirds are often sighted foraging together (Durrell 2000). Differences in bill length, bill shape, and foraging strategy between species partition the foraging niche among species. Mixed flocks of shorebirds can pursue different prey in the same area at the same time without competing with each other (Durell 2000). For example, varying bill lengths mean that each bird species probes for its food source at a different depth in the substrate.

It is useful to categorize shorebird species into foraging guilds to describe the water depth and/or vegetation height and density preferences of the species (Table 1). In *The Shorebird Management Manual,* Douglas Helmers defines shorebird habitat as wetland areas that are sparsely vegetated with low (half the height of the bird) vegetation and shallowly flooded, up to 24 cm deep, grading to areas of wet mud (Helmers 1992). This is because invertebrates are more abundant and more accessible in wet or shallowly flooded substrates and tend to burrow deeper or vacate as the mud dries out (Durell 2000; Goss-Custard 1984; White 1995). Drier mud is also more difficult for shorebirds to penetrate and probe with their bills (Quammen 1982).

On a reservoir system during fall drawdown shorebird habitat areas consist of a thin band of sparsely vegetated mudflat and shallow open water buffering the shoreline (Fig. 5). The majority of shorebird foraging activity occurs within this shoreline buffer as witnessed in the field by the high concentration of shorebird tracks and probe marks very near the shoreline. Large gleaners and probers may wander out into areas of deeper water to forage because their taller legs allows for this, while smaller probers and gleaners remain in shallower water and on wet mud (Helmers 1992). Figure 6 illustrates a hypothetical representation of this habitat partitioning by depth along the shoreline at Rankin Bottoms. However, depending on the rate of reservoir drawdown this thin buffer of habitat may widen. For example, a seemingly miniscule depth of water (tens of centimeters) may be drawn off the reservoir in a given day, exposing tens of hectares of

Table 1: Shorebird foraging guilds and habitat preferences.

Shorebird Group	Common Name	Scientific Name	Foraging Guild	Feeding Depth	Vegetation Density
Plovers	🟧 Black-bellied Plover	*Pluvialis squatarola*	terrestrial/aquatic gleaner	Dry-6cm	sparse
	🟩 Lesser Golden Plover	*Pluvialis dominica*	terrestrial/aquatic gleaner	Dry-6cm	sparse
	⬜ Snowy Plover	*Charadrius alexandrinus*	terrestrial/aquatic gleaner	Dry-6cm	sparse
	🟧 Semipalmated Plover	*Charadrius semipalmatus*	terrestrial/aquatic gleaner	Dry-6cm	sparse
	🟨 Piping Plover	*Charadrius melodus*	terrestrial/aquatic gleaner	Dry-6cm	sparse
	■ Killdeer	*Charadrius montanus*	terrestrial/aquatic gleaner	Dry-6cm	sparse
	⬜ Mountain Plover	*Charadrius montanus*	terrestrial/aquatic gleaner	Dry-6cm	sparse
Curlew	🟨 Whimbrel	*Numenius phaeopus*	terrestrial/aquatic gleaner/prober	Dry-18cm	sparse
	⬜ Long-billed Curlew	*Numenius americanus*	terrestrial/aquatic gleaner/prober	Dry-18cm	sparse
Small Sandpiper	🟧 Sanderling	*Calidris alba*	aquatic prober/gleaner	Wet-2cm	sparse
	🟩 Semipalmated Sandpiper	*Calidris pusilla*	aquatic prober/gleaner	Wet-2cm	sparse
	🟧 Western Sandpiper	*Calidris mauri*	aquatic prober/gleaner	Wet-2cm	sparse
	🟩 Least Sandpiper	*Calidris minutilla*	aquatic prober/gleaner	Wet-2cm	sparse
	⬜ White-rumped Sandpiper	*Calidris fuscicollis*	aquatic prober/gleaner	Wet-2cm	sparse
	🟧 Baird's Sandpiper	*Calidris bairdii*	aquatic prober/gleaner	Wet-2cm	sparse
Medium Sandpiper	⬜ Red Knot	*Calidris cantus*	aquatic prober/gleaner	Saturated-12cm	sparse
	🟩 Pectoral Sandpiper	*Calidris melanotos*	aquatic prober/gleaner	Saturated-12cm	sparse
	🟧 Stilt Sandpiper	*Calidris himantopus*	aquatic prober/gleaner	Saturated-12cm	sparse
	🟧 Dunlin	*Calidris alpina*	aquatic prober/gleaner	Saturated-12cm	sparse
	🟧 Short-billed Dowitcher	*Limondromus griseus*	aquatic prober/gleaner	Saturated-12cm	sparse
	⬜ Long-billed Dowitcher	*Limondromus scolopaceus*	aquatic prober/gleaner	Saturated-12cm	sparse
	🟩 Common Snipe	*Gallinigo gallinago*	aquatic prober/gleaner	Saturated-12cm	sparse
	🟨 Buff-breasted Sandpiper	*Tryngites subruficollis*	aquatic/terrestrial gleaner	Saturated-12cm	sparse
	🟧 Upland Sandpiper	*Bartramia longicauda*	aquatic/terrestrial gleaner	Saturated-12cm	sparse
Godwit	⬜ Hudsonian Godwit	*Limosa haemastica*	aquatic prober	2-13cm	sparse/moderate
	⬜ Marbled Godwit	*Limosa fedoa*	aquatic prober	2-13cm	sparse/moderate
Yellowlegs	🟧 Greater Yellowlegs	*Tringa melanoleuca*	aquatic gleaner	4-17cm	sparse/moderate
	🟩 Lesser Yellowlegs	*Tringa flavipes*	aquatic gleaner	4-17cm	sparse/moderate
	🟧 Solitary Sandpiper	*Tringa solitaria*	aquatic gleaner	4-17cm	sparse/moderate
	⬜ Willet	*Catoptrophorus semipalmatus*	aquatic gleaner	4-17cm	sparse/moderate
Turnstone	🟨 Ruddy Turnstone	*Arenaria interpres*	terrestrial/aquatic gleaner/prober	Dry-2cm	sparse
	🟩 Spotted Sandpiper	*Actites macularia*	terrestrial/aquatic gleaner/prober	Dry-2cm	sparse
Avocet/Stilt	⬜ Black-necked Stilt	*Himantopushimantopus*	aquatic gleaner/sweeper	8-24cm	sparse
	🟧 American Avocet	*Recurvirostra americana*	aquatic gleaner/sweeper	8-24cm	sparse/moderate
Phalarope	⬜ Wilson's Pharalope	*Phalaropus tricolor*	aquatic/pelagic gleaner	8-21cm	sparse/moderate
	⬜ Northern Pharalope	*Phalaropus lobatus*	aquatic/pelagic gleaner	8-21cm	sparse/moderate

Key	
⬜	Unconfirmed
🟨	Rare
🟧	Uncommon
🟩	Fairly Common
■	Common
From Helmers 1992	

Figure 5: A photograph taken on October 16, 2003 showing macro-invertebrate tubules and shorebird probing marks along the shoreline at Rankin Bottoms. Notice how areas that have been exposed for a longer period of time have begun to vegetate and no longer show evidence of shorebird or macro-invertebrate activity.

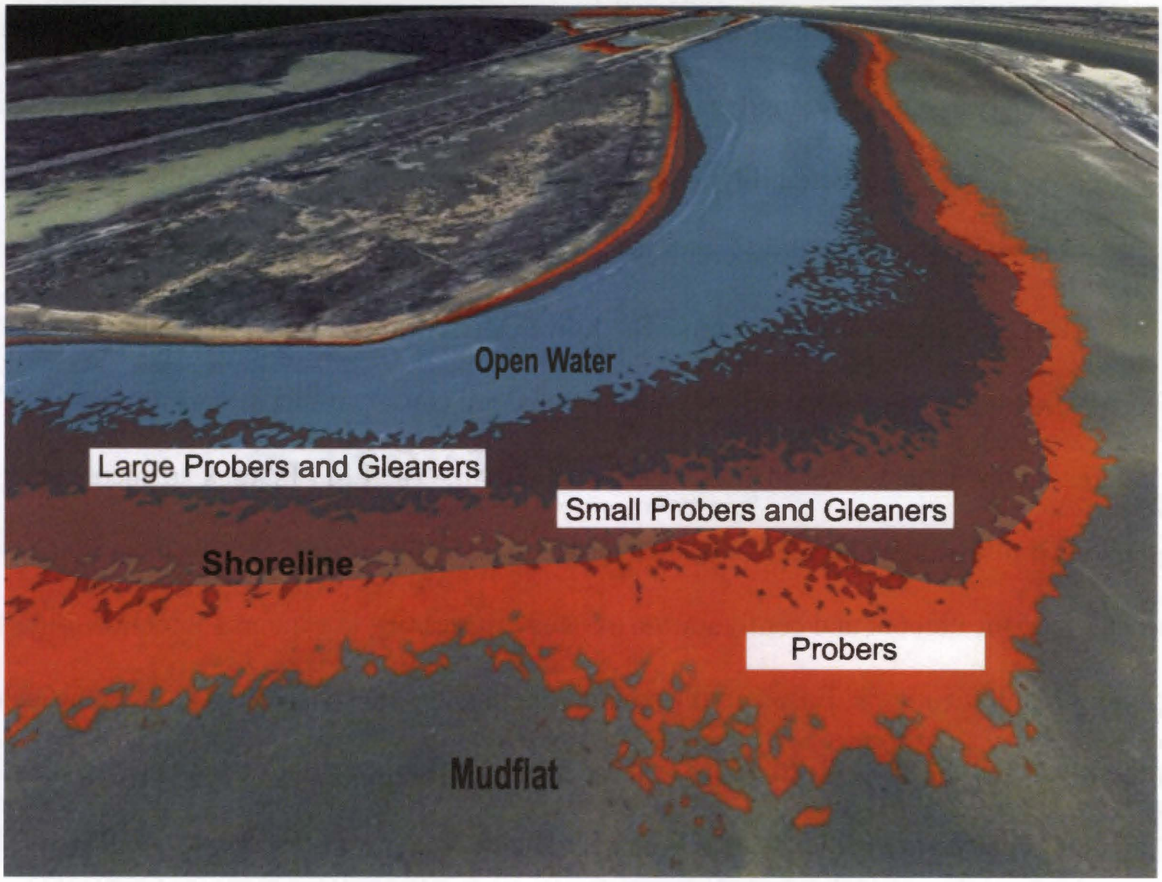


Figure 6: A hypothetical representation of habitat partitioning by shorebird feeding guilds at Rankin Bottoms. This graphic illustrates the habitat ` partitioning by feeding guilds based on depth. Larger species may prefer deeper water areas to feed while smaller species are limited to shallower areas, and some species prefer to probe in the exposed mudflat exclusively.

mudflat that until that morning were shallowly flooded. At this point there will be a large area of newly exposed wet mud that may contain the required food resources and have the proper degree of penetrability to be suitable habitat for foraging.

How much habitat do shorebirds need to complete migration? This is a very important but complicated question. The Lower Mississippi Valley Joint Venture (LMVJV), a non-regulatory private, state, and federal conservation partnership, has addressed this issue for the MAV (Loesch et al. 2000). The LMVJV took an energetics approach following the direction of the North American Waterfowl Management Plan to determine the amount and configuration of habitat necessary to support shorebird migration in their area. Based on the assumption that 500,000 shorebirds migrate through the MAV and the stopover duration of these species is 10 days, they concluded that the amount of necessary habitat is approximately 2023 hectares (5000 acres) (Loesch et al. 2000). In other words their calculations imply that the energy needs of 100 migrating shorebirds could be supported by ~0.4 hectares (1 acre) of foraging habitat, where habitat is defined as areas having ~2 g/m^2 of invertebrate food density (Loesch et al. 2000).

2.4 Technical Literature

This research uses several different technologies for data acquisition and analysis. Specifically, I needed to acquire highly accurate elevation data, in the form of a digital elevation model (DEM), for the study area so that analysis could be performed in a Geographic Information System (GIS). I also used aerial photography and global positioning system (GPS) receivers to delineate habitat and test the accuracy of the DEM. In this section, I will briefly define and discuss the three different technologies that I used in this data acquisition effort. These technologies are: the Global Position System (GPS), Aerial Photography, and Light Detection and Ranging (LiDAR).

Global Positioning System (GPS)

GPS is a satellite based navigation system developed by the U.S. Department of Defense in the 1970s. A minimum of 24 GPS satellites orbit the Earth at an altitude of approximately 11,000 miles providing users with accurate information on position, velocity, and time anywhere in the world (El-Rabbany et al. 2002). The basic idea behind GPS is that a point on the earth can be determined by calculating the distances from at least three satellites if the locations of those satellites are known. A GPS receiver acquires the microwave radio signal transmitted by the satellites and uses built-in algorithms to decode the signal and determine the distance to the satellites and their coordinates (El-Rabbany et al. 2002).

Several technological advancements have led to handheld GPS receivers that can provide real time acquisition of highly accurate position data. In the U.S., GPS users now have access to GPS signal corrections made possible by the Federal Aviation Administration's Wide Area Augmentation System (WAAS). WAAS consists of approximately 25 ground reference stations across the U.S. which monitor the GPS satellite data (Trimble 2001). Each of these precisely surveyed reference stations then calculates the position error of the GPS signal and transmits these data to one of the two master stations located at either coast. The master stations generate correction algorithms to account for GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere. The correction (differential) message is then broadcast through one of two geostationary satellites using the basic GPS signal structure so that

WAAS-enabled GPS receivers can use the differentially corrected signal in real time (Trimble 2001).

In this study I used a Trimble GeoXT DGPS unit with ArcPad 6.0.2 software. This mapping-grade GPS unit is an example of a GPS/GIS integrated system which allows the user some of the functionality of a GIS within the GPS receiver. For this project the accuracy of the horizontal positions captured by the GPS receiver was very important. Therefore I set several data quality standards. First, I set the unit so that data would only be recorded in Differential (DGPS) mode using the WAAS correction. Second, I enabled averaging so that the coordinates of 50 raw position fixes would be averaged to create one set of x, y coordinates for any point feature collected by the GPS unit. Third, I set the unit to only collect data when the PDOP (position dilution of precision, a measure of the quality of satellite geometry) value was less than 6. Lower PDOP values indicate better relative geometry which corresponds to more accurate positional data.

Aerial Photography

Aerial photography is commonly used by photo interpreters to delineate different land cover types. The data derived from this process can be geo-rectified and entered into a GIS for analysis of landscape patterns or to inventory the amount of various land cover types. Land cover classification is often performed on infrared photography or multi-spectral satellite imagery because various signatures apparent in datasets can offer insights to the environmental conditions on the ground. Certain signatures for example can allow an interpreter to differentiate broadleaf deciduous from evergreen vegetation types, or to differentiate wet areas from dry ones. Photo interpretation of land cover types can be accomplished using either black and white photography or color photography.

For this project I used color aerial photography flown by Tuck Mapping, Inc. in the winter of 2004. I used the photography as a means to differentiate mudflat areas from surrounding areas with persistent vegetation. I also used aerial photography as a base layer in the GIS for displaying reservoir drawdown at the study site. For our purposes we chose to use two-meter resolution true-color orthophotography because it was sufficient for photo interpretation and the most affordable option.

Light Detection and Ranging (LiDAR)

LiDAR is an airborne laser scanning method primarily used to acquire elevation data. LiDAR combines three technologies into a single data acquisition system for the generation of accurate digital elevation models (DEMs): a Laser range finder, Global Positioning System (GPS), and Inertial Navigation Systems (INS) (Katzenbeisser 2003). The LiDAR system laser emits optical pulses in a sweeping motion below the aircraft that are reflected from objects on the earth's surface and returned to the receiver. The receiver measures the round trip travel time of the optical pulse. These pulses travel at the speed of light and their travel times can be converted into ranges or distances to the receiver. The LiDAR system captures the ground coordinates of each reflected laser pulse by combining the laser range value with the receiver position from the onboard GPS unit and the laser orientation (i.e., "look angle") from the INS (Katzenbeisser 2003).

LiDAR systems are primarily used to generate high-accuracy DEMs. This system offers increased efficiency over traditional ground survey techniques when surveying large areas. LiDAR has been used to generate DEMs of sandy shorelines to estimate rates of beach erosion or to quantify the impact of storm surge events (Carter and Shrestha 1997). It has also been used as a tool to ascertain the best path for highways and to quantify changes in continental ice sheet thickness (Berg and Ferguson 2001; Krabill et al. 1995).

I have found two cases in which LiDAR has been used to map emergent wetlands. The technology was used to assess the impacts to Cape Sable seaside sparrow nesting sites if natural sheet flow were to be restored to an area in the Everglades (Carter et al. 2001). The Cape Sable seaside sparrow is an endangered species that builds nests in grass, just above the surface of the water. U.S. Park Service personnel were concerned that the restoration project could inundate the nesting sites of this species. A LiDAR system was used to scan the area and analyze the strength of reflections to differentiate water from grass and produce a sub-decimeter-precision measurement of the height of the water surface (Carter et al. 2001).

LiDAR was also used on the Pacific coast to assess the impact of invasive grasses on shorebird habitat (Stralberg et al. 2004). Non-native cordgrass (*Spartina alterniflora*) is invading the San Francisco Bay where 70% of California's shorebird habitat exists. This area constitutes one of the most important stopover sites for Pacific coast migrant shorebirds within the contiguous United States. *S. alterniflora* has a higher inundation tolerance than native grasses and threatens to encroach onto the mudflats, making them unsuitable for shorebird foraging. LiDAR was used in this project to produce a high resolution DEM of the area to model the potential spread of *S. alterniflora* as a function of tidal inundation (Stralberg et al. 2004).

For this project TVA contracted Tuck Mapping Solutions, Inc. for the LiDAR survey. The contractor used a helicopter-based LiDAR mapping system. A helicopter's ability to fly at slow speeds and low altitudes is advantageous because it allows for greater efficiency and higher point density. The LiDAR system acquires 15,000 points per second to achieve a final density of 1 point every square meter on the ground (Tuck Engineering, personal correspondence 2004). The system differentiates multiple returns so that the recorded ground elevation is not obscured by reflections from vegetation cover.

Chapter 3: Methods

3.1 Developing a Migration Chronology

To model the dynamics of habitat availability at Rankin Bottoms, I needed to develop a clear understanding of the timing of migration in the Tennessee River Valley (TRV), including arrival and departure times and the relative abundance of each species throughout the fall migration period. To develop a baseline chronology to use for this project I sought out the best available data for shorebird migration in our area. I began by summarizing the timing of shorebird arrival and departure in the TRV using Robinson's "An Annotated Checklist of the Birds of Tennessee" which lists arrival and departure times for birds in Tennessee (Robinson 1990). I then gathered all of the listings of Rankin Bottoms shorebird sightings on the Tennessee Ornithological Society's TNBirds forum from 2002-2003 (Tennessee Ornithological Society 2004b), along with some preliminary TVA monitoring data for 2004, to validate the list I had compiled. The finished migration chronology that I have used as an approximation of shorebird arrival times in the TRV and specifically at Rankin Bottoms is summarized in Figure 7. This chronology as stated previously has been developed by observations made by birdwatchers across Tennessee not by a systematic monitoring effort. This chronology is the best approximation I could develop for arrival and departure times for all the possible shorebird species that may visit Rankin Bottoms and the TRV as a whole.

Future trends in shorebird migration through the TRV will be recorded by a systematic shorebird monitoring program established by TVA in 2004. This program is a partnership between TVA, the US Fish and Wildlife Service (USFWS), other state

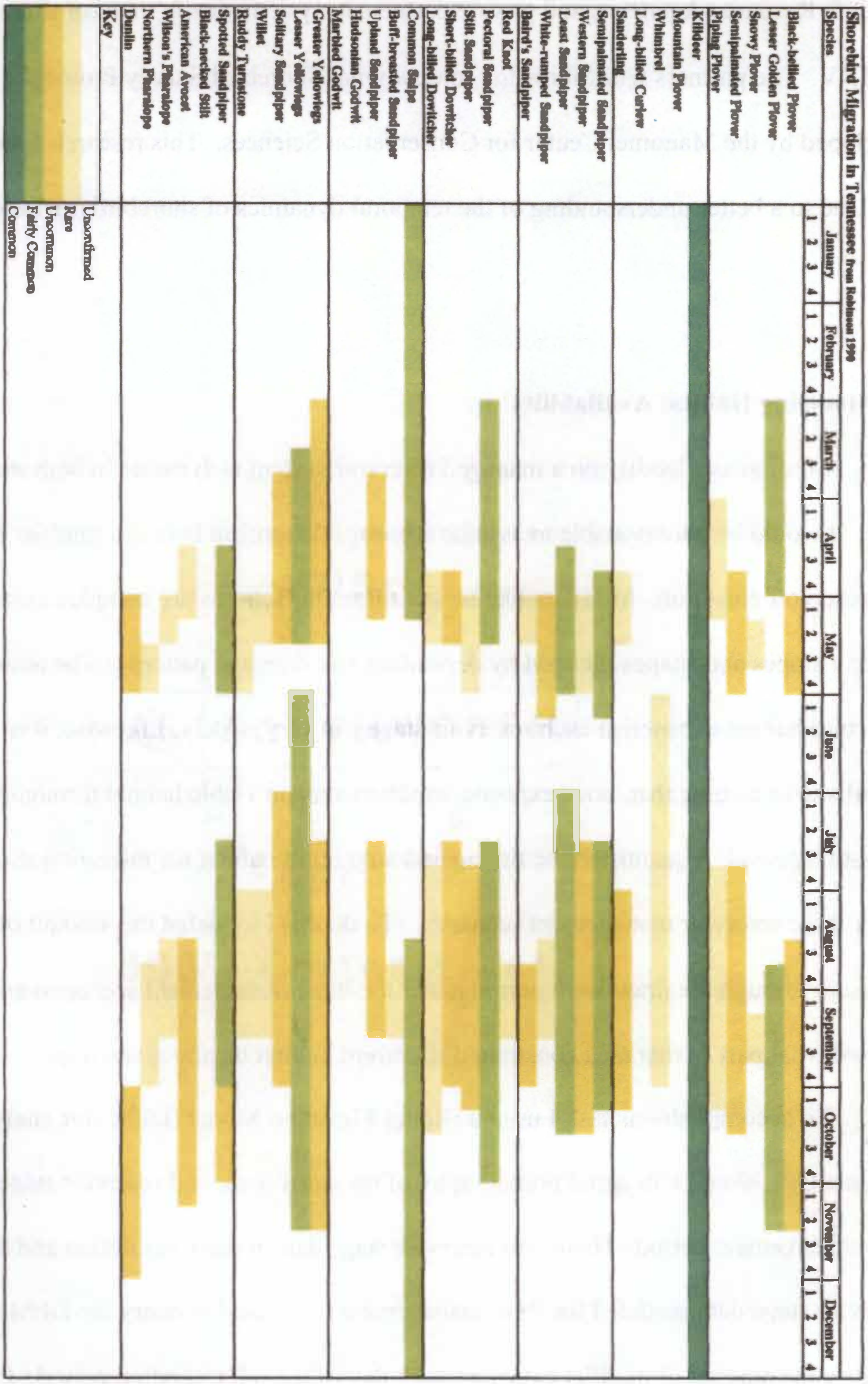


Figure 7: Shorebird migration chronology for the Tennessee River Valley.

Wildlife Resource Agencies, and private partners to systematically monitor shorebirds in the TRV. The partners will follow the International Shorebird Survey Protocol developed by the Manomet Center for Conservation Sciences. This research endeavor will lead to a better understanding of the temporal dynamics of shorebird migration in the TRV.

3.2 Modeling Habitat Availability

Mudflat availability on a managed reservoir system is dynamic in both space and time. It would be unreasonable to assume a linear relationship between mudflat exposure and reservoir elevation. Mudflats like those at Rankin Bottoms are complex systems with varying slopes and shapes dictated by deposition and drainage patterns. The amount of shorebird habitat exposed at each reservoir stage can vary widely. Likewise, it is unrealistic to assume that, once exposed, mudflats remain viable habitat throughout the migration period. I quantified the timing and amount of habitat for migrating shorebirds under three reservoir management scenarios. To do this I modeled the amount of mudflat exposure through the drawdown period under the three management scenarios and defined what part of that area constituted shorebird habitat on any given day.

To accomplish this task I used a Digital Elevation Model (DEM) for analysis within a GIS, along with aerial photography of the study area, and reservoir stage data for each management period. Historical reservoir stage data at daily resolution and estimated reservoir stage data modeled for ROS management were used to query the DEM to quantify the amount of mudflat exposure each day of the fall migration period. Photo interpretation and GPS-assisted field observations were used to differentiate vegetated and otherwise unsuitable locations from suitable habitat when calculating available habitat area. I verified the accuracy of this photo-interpretation exercise in the field using GPS and traditional surveying techniques. Using these datasets the amount of mudflat exposed at Rankin Bottoms can be quantified very precisely. The difficulty is determining how much of that area actually represents usable habitat for the species in question such that habitat availability can be modeled accurately. For this model, I adopted a definition of shorebird habitat widely used in shorebird literature which best defines the pattern of habitat found at my study site through space and time (see below).

My model gives an estimate of available habitat area based on averaged reservoir stage data for the two previous reservoir management scenarios and predictive reservoir stage values for the current ROS reservoir management scenario. This model can be recalculated to statistically show differences in habitat availability once several years of ROS management have been completed. The model may also be refined by determining the length of time that mudflat areas can remain exposed before they become uninhabitable for invertebrates or too impervious for shorebirds to probe. Future research planned by a cooperative effort between TVA and The University of Tennessee to study invertebrates and soil penetrability will likely result in more accurate estimates of how long a mudflat can be exposed and remains usable. Values for how long it takes for invertebrates to desiccation or disperse from an area of exposed mud or for the mud to become too hard for shorebirds to probe can be entered back into the model to refine model results.

3.2.1 Defining Shorebird Habitat

The first step in this process was to develop a definition of shorebird habitat that accurately reflects real world habitat selection and can be modeled in a GIS. I decided to adopt the definition of shorebird habitat used in *The Shorebird Management Manual* by Douglas Helmers (Helmers 1992). Helmers defines shorebird habitats as sparsely vegetated mudflats extending from shallowly flooded areas (24 cm deep) up to and including areas of wet mud above the edge of the water. There is no simple definition of how dry is too dry, or how quickly soils dry out. Several equations such as the Penman-Monteith equation (Monteith 1965) are helpful in determining the rate of evapotranspiration from a given soil under a defined set of environmental conditions, but these equations have many parameters that will be unknown, such as humidity or precipitation. To avoid adding too many parameters that may confuse the model without improving the accuracy of the result I chose to use a fixed number of days for the amount of time mudflat can be exposed and still be considered useable habitat.

I selected the temporal extent of habitat exposure based on observations I made while participating in a vegetation study in the fall of 2004 for TVA. During the course of this study, Alan Mays, a TVA soil scientist, and I collected soil samples across the mudflats to gather data about soil moisture. We established sampling plots along three transects that ran across the mudflats perpendicular to the shoreline. On every visit we added a sampling plot to the transect at the current shoreline and then collected samples from each plot every seven days. In this way we were sampling all established plots at seven-day intervals after exposure. During this study we kept notes about the presence or absence of macro-invertebrate tubules: castings in the substrate left by the vertical burrowing of invertebrates. We found that in some cases tubules were still present after one week of exposure, making it evident that invertebrates were still active in the area. After two weeks, however, tubules were no longer present at any of the sample locations. Additionally, after two weeks vegetation was becoming established on some of the plots.

Based on these observations I assumed that the temporal limit for shorebird habitat was somewhere between seven and fourteen days after exposure. Since this limit was based on observations not quantitative sampling I decided to perform several iterations of the analysis using five, ten, and fifteen day values and found that no changes in pattern, but only proportionate changes in habitat area were evident using these durations (Fig. 8). In other words, the peaks of habitat availability occur at the same time independently of what value is chosen. Therefore, some flexibility in selecting a value is acceptable since the same relative pattern of habitat availability results from different time limit values. I decided to select ten days as the time limit value to use in the model because it is roughly the median between the seven and fourteen day observations.

3.2.2 Historic Reservoir Management Data

The second step in this process was to obtain reservoir stage values for each day under the three management scenarios being assessed by this study. I obtained historical daily records of headwater elevation measurements from the TVA River Operations team. These data are available to the public through the TVA Lake Information website (lakeinfo.tva.gov). I averaged the reservoir stage value across years for each day of the year under the 1972–1990 and 1991–2003 reservoir management scenarios. I used these

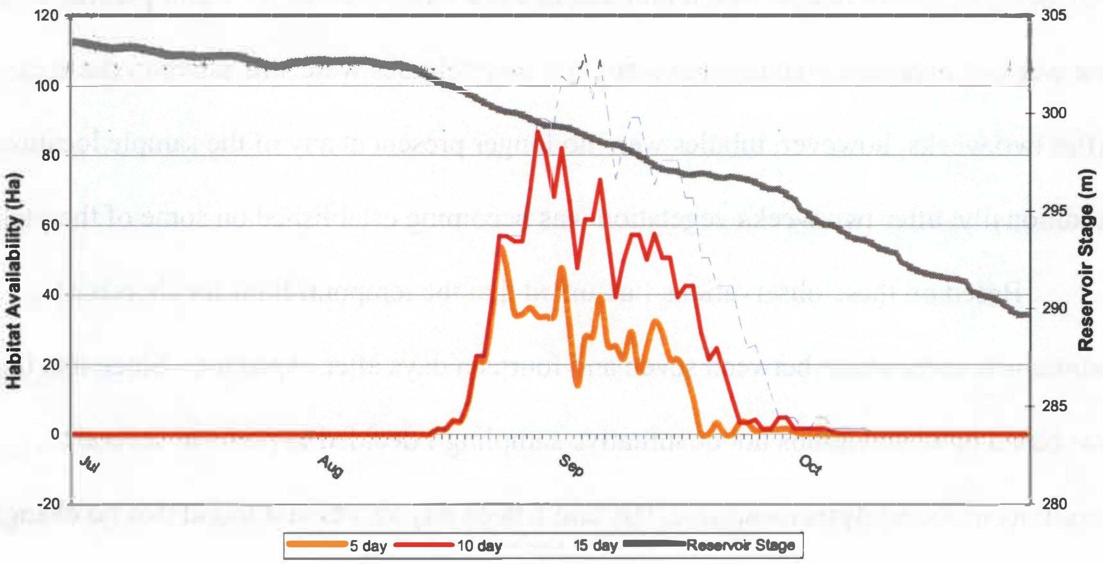


Figure 8: A comparison of habitat availability using a five-, ten-, and fifteen-day exposure window. This is an example of a model iteration using 1999, a relatively typical drawdown year, to explore the changes in modeled habitat availability values using different temporal limits of mudflat exposure. It is obvious that changing the exposure limit creates proportional changes in habitat area, but does not affect the relative timing or temporal pattern of habitat availability.

two datasets as the base cases for each of the respective management periods. During these two management periods, the reservoir stage on a given day often varied widely from the averaged profile curve due to weather events or maintenance at the dam facility, so these averaged datasets are used as the best estimates of daily reservoir stage values during those periods.

The ROS management scenario has just been implemented in 2004 and therefore only two complete years of reservoir stage data exist for this scenario. Instead of using the limited real-world reservoir stage data for these years, I have elected to use the modeled average guide curve generated for ROS management by the TVA River Operations team. This dataset was modeled based on stream inflow values to attain probable average elevations for each day of the year with ROS management guidelines applied. I have assumed that these modeled reservoir stage data are the best prediction of long-term average reservoir stage curves under the ROS management regime.

3.2.3 Delineating Habitat

The next step in the process was to distinguish mudflat areas from persistently vegetated areas, which are not preferred by most shorebird species (Helmers 1992). Unsuitable areas include bottomland hardwood forest and areas dominated by shrubby vegetation. These types of areas are not preferred by foraging shorebirds (Helmers 1992) and are generally found above the "summer pool" reservoir stage, because the substrate is not inundated long enough during the growing season to prevent the establishment of woody vegetation. Delineating these vegetated areas is necessary so that they are not included in habitat availability quantification. I used a color orthophotograph of the field area to separate areas of exposed mud from woody vegetated areas in the GIS (Fig. 9). The orthophotograph used in this effort was taken during “winter pool” conditions so that the entire extent of mudflat is evident in the photograph. I verified the results of this photo-interpretation effort in the field by walking the mudflats and recording observations using a GPS unit and manually on a printed map.

3.2.4 Querying Mudflat Exposure by Date

In order to quantify the amount of habitat exposure for the three different scenarios, I needed to query the DEM using the average daily reservoir stage values. I chose to automate this process in the GIS using Arc Macro Language (AML) programming language in the ArcGIS GRID module (ESRI 2005). Using AML, I was able to reference elevation values stored in tabular format to query the DEM grid and record the available habitat area as a new field in an output table. For this model, shorebird habitat is defined as mudflat areas that have been exposed during the last ten days of reservoir drawdown, and inundated areas less than 24 centimeters in depth.

The reservoir stage data (section 3.2.2) are a daily-resolution dataset, where water elevation values are stored as individual records for each day of the year. The DEM is a raster format dataset with 61 cm horizontal resolution (nominally, 2-foot) and 1 cm vertical resolution. In this dataset the mudflat surface is represented by a regular grid of 61 cm by 61 cm (2 ft by 2 ft) square pixels.

In the GIS, the calculation is made by selecting all records in the DEM elevation table that are greater than or equal to the current reservoir stage value minus 24 cm, and

data covering the total area of mudflats which do not support woody

vegetation.

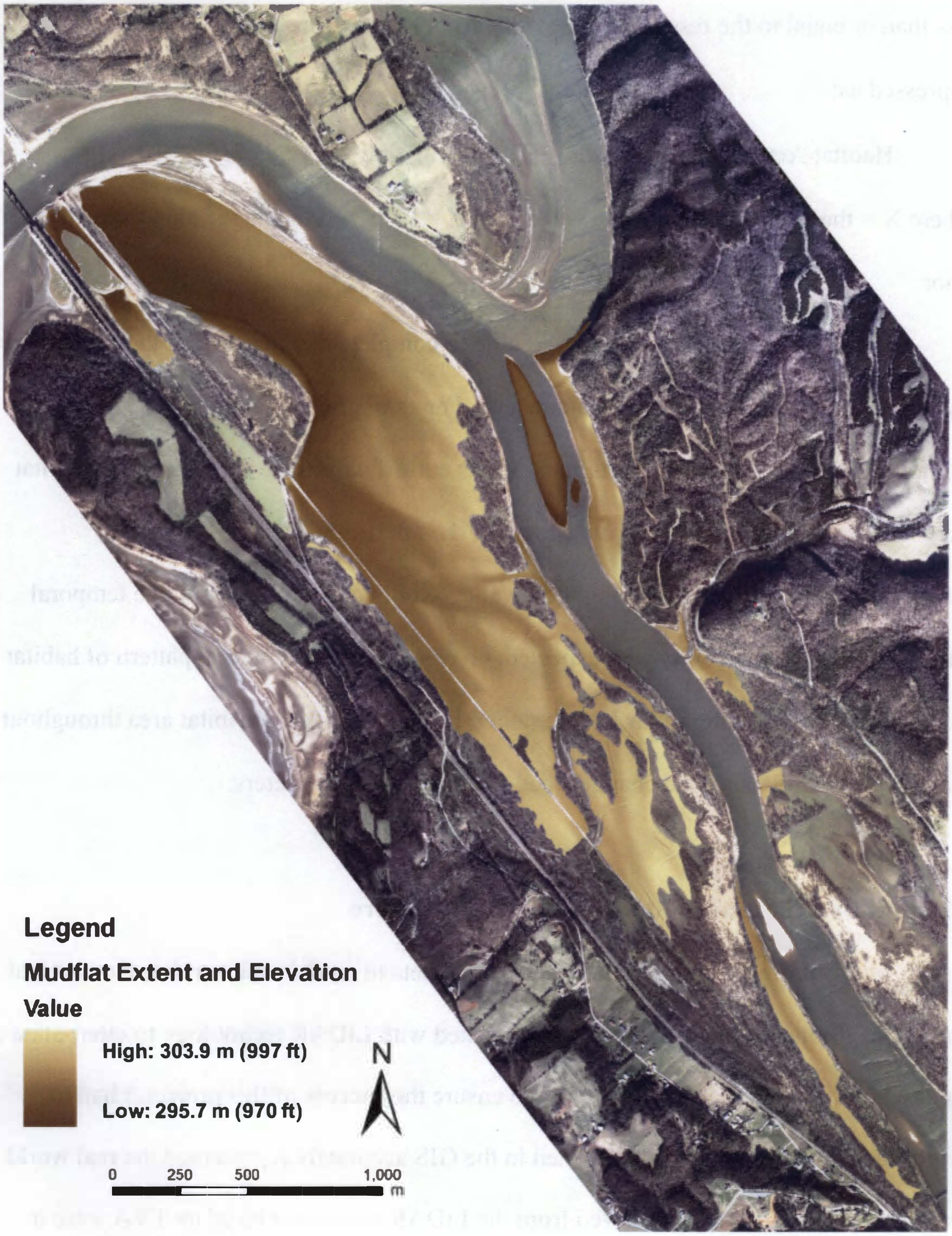


Figure 9: An aerial photograph of Rankin Bottoms overlaid with digital elevation data covering the total area of mudflats which do not support woody vegetation.

less than or equal to the reservoir stage value from ten days previously. This can be expressed as:

$$\text{Habitat Area (ha)} = \Sigma\ [(\text{pixels} \geq (X - 24\text{ cm}) \text{ and} \leq Y) * (3.7161 * 10^{-5})]$$

where X = the daily reservoir stage value, and Y = the reservoir stage value from 10 days prior.

By automating this process, I was able to complete this iteration of the model and try several others with alternative parameters. For example, model runs were completed using varying foraging depth limits and various cut-off values for the duration of habitat exposure as explained at the end of section 3.2.1. I performed this exercise as a sensitivity analysis to see if varying these values would cause a change in the temporal pattern of habitat availability. As expected, no changes in the temporal pattern of habitat were evident from the iterations I tried; rather, I found changes in habitat area throughout that were proportional to the changes made in the model parameters.

3.2.5 Field Verification of Modeled Mudflat Exposure

In this project I used remotely sensed datasets to model real world environmental conditions through time. I used the DEM created with LiDAR technology to interpolate the predicted location of the shoreline. To ensure the success of this project, I had to determine that the shoreline interpolated in the GIS accurately represented the real world feature. The elevation data received from the LiDAR contractor hired by TVA were in the form of a completed DEM that reported elevation values in feet above mean sea-level. To make valid recommendations to TVA about habitat availability, the elevation model must reflect the geography of the shoreline at a given gauge elevation for the reservoir. This gauge is downstream of Rankin Bottoms at Douglas Dam, and it was possible that the reservoir stage value at the gauge would be different than the reservoir stage value in the headwaters at Rankin Bottoms.

I hypothesized that the reservoir stage value at the study site would likely be slightly higher than the gauge reading because of a hydrological gradient created by inflow from rivers in the headwater and outflow from the dam at the gauge. To address this issue I decided to record the difference between the gauge elevation and the actual elevation of the water at Rankin Bottoms using two different methods. First, I employed an optical level and surveyed a profile from a benchmark down to the elevation of the reservoir on-site. I found that the value I calculated for the reservoir elevation was within thirty centimeters (~1 foot) of the elevation reported at the gauge for the time that I conducted the survey, a value within the margin of error for this type of optical surveying. I also overlaid several GPS points at the shoreline that I had taken on four separate days during the drawdown period with the LiDAR data and found that every data point correlated with the LiDAR generated DEM values within one foot. As an extra measure to assure that the correct geometry of the shoreline could be generated from the DEM I walked the shoreline of the mudflats on two occasions in the spring of 2004 with a Trimble GeoXT© Differential Global Positioning System (DGPS) to capture the coordinates of the shoreline as the reservoir stage elevated towards "summer pool." After comparing the shoreline feature collected through GPS surveying with the shoreline interpolated from the DEM I concluded that the correct geometry of the shoreline could be interpolated from the DEM (Fig. 10).

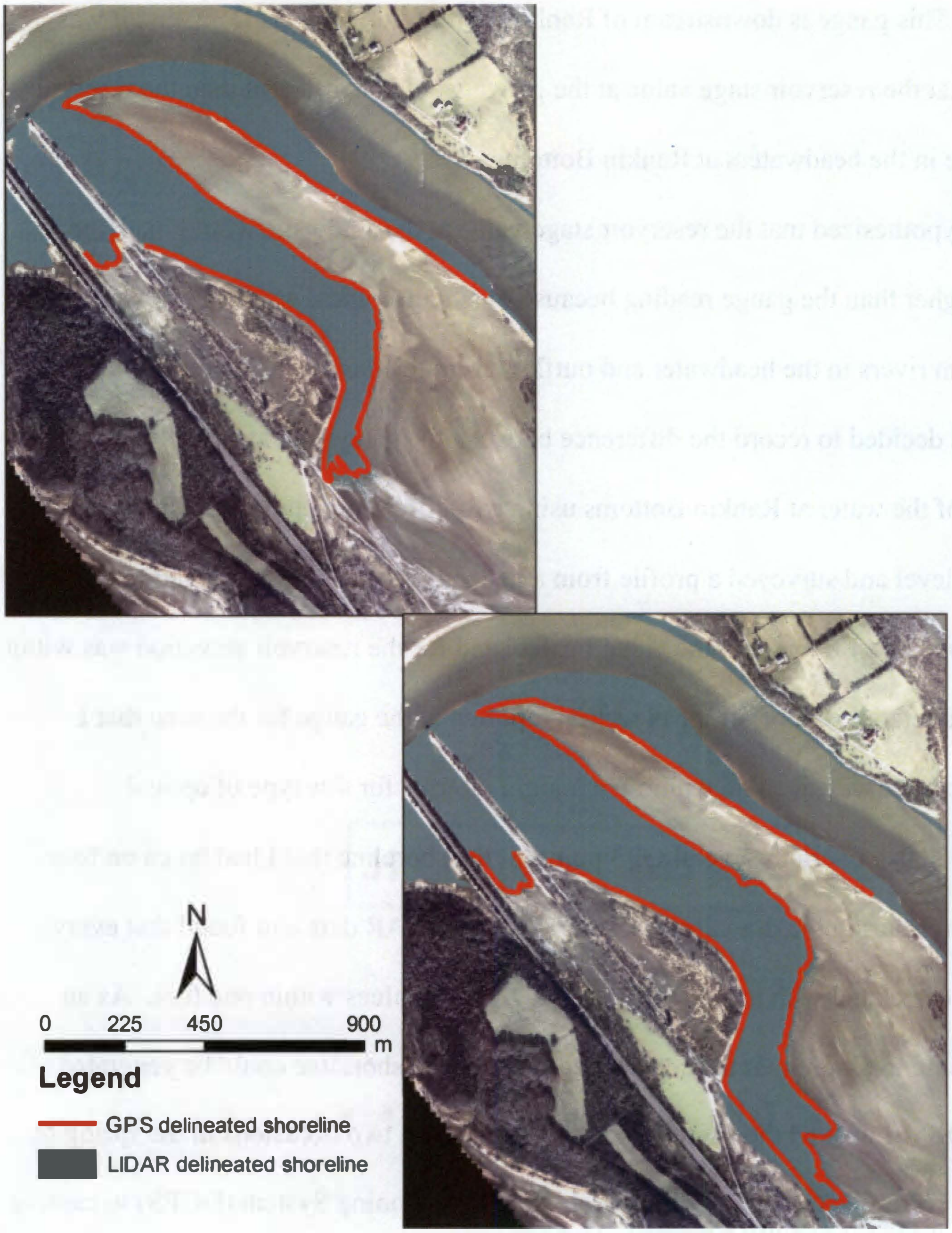


Figure 10: Overlay of LiDAR and GPS delineated shorelines for April 7, 2005 and April 11, 2005. The straight segment in the Southeast corner of the April 11, 2005 map (lower right) follows the shoreline at the former railroad embankment, the shoreline adjacent to this area was not recorded with GPS.

Based on these data, I felt confident in assuming there was no measurable hydrological gradient between the field area and the gauge location. I also decided that the LiDAR-generated DEM was appropriate for interpolating the shoreline at any given reservoir stage. This confirmed to me that the methodology that I had selected was appropriate for this application.

3.3 Developing Visual Display Methods

To disseminate my results effectively, I needed to find favorable ways to communicate the purpose of this study along with the findings to the public. It has been shown in several studies that spatial relationships are best communicated through visual media (Wilhelm 1996; Williams 1993). It has also been shown that visual storyboards are a very effective means of providing a meaningful context for unfamiliar material (Wilhelm 1996).

Most members of the public do not have access to a GIS capable of viewing and manipulating the visual products created in this study, therefore I decided to make a stand-alone application with which individuals can explore the findings of the study on-screen regardless of software. I used Macromedia Flash Studio MX 2004. Using the Flash Developer Suite, I was able to make a stand-alone application that presents the background information for this study as a storyboard with minimal text, accompanied by graphs and 3-dimensional animations of shorebird habitat availability. This product, *Rankin Wildlife Management Area Shorebird Habitat Viewer*, is located on the CD (Plate 1) accompanying this document.

3.4 Alternate Methods for Elevation Data Acquisition

To model the dynamics of shorebird habitat availability at Rankin Bottoms I needed an elevation dataset for the study area with high vertical accuracy. Ultimately TVA contracted Tuck Mapping, Inc. to fly LIDAR of the site. LIDAR is a relatively new and expensive method for acquiring elevation data. Before deciding on accepting this data acquisition option Roger Tankersley and I reviewed several data acquisition alternatives. Each alternative displayed some strengths and weakness in terms of feasibility, cost, and accuracy. I have distinguished two alternative methods which are especially well-suited for smaller areas, or for projects with limited budgets. These methods are: time-series aerial photography, and a non-traditional GPS surveying method. I have chosen to discuss these methods in the hope that they may be of benefit to other resourceful researchers or managers whose budgets or sites necessitate a thrifty approach to elevation data acquisition.

As discussed earlier in section 3.2.5 of this thesis and illustrated in Figure 10, I walked the shoreline of Rankin Bottoms on two occasions to verify the interpolation of shoreline created by the LiDAR DEM. On these occasions I was fundamentally capturing a contour of known elevation, because I knew the elevation of the water in the reservoir provided by the gauge in Douglas Dam. A series of elevation contours collected in this way could be compiled in a GIS and used to create a continuous elevation surface through statistical interpolation methods. Using GPS in this way is advantageous because it does not require the use of survey-grade GPS hardware and multiple transects. This method can be accomplished with a handheld GPS receiver using real time WAAS or post processing correction methods on the horizontal data which is acquired. At Rankin Bottoms it was only feasible to walk the shoreline in the spring, during reservoir recharge rather than drawdown, because the mudflat had sufficient time to vegetate and become firm enough to travel on.

Another method that could be used to create contours at multiple reservoir stages is to use air photos from different years and at different elevations combined into a total picture of mudflat shape and extent. For a given mudflat, there may be enough images taken at different reservoir levels to allow you to draw the shorelines and compile them into an elevation surface. For example, I have included two photographs of the Blood River Embayment on Kentucky Reservoir taken at different reservoir stages (Fig. 11). These photos can be converted to a digital format usable in a GIS by scanning and geo-rectifying the printed images. The shoreline from each of these images can then be traced to capture an elevation contour to be labeled with the reservoir stage that was recorded for the day the photography was taken. This method is only plausible if accurate reservoir stage data has been recorded for the site, and is of course subject to the availability of aerial photography.

A combination of these methods may be suitable for smaller sites, in instances where good aerial photograph coverage exists, reservoir stage data is recorded, and a GPS receiver is accessible. Using existing photos can save time in the field, but you are at the mercy of previously flown missions which may have had little to do with mudflats and therefore may not provide good coverage. In the TRV, photography is commonly taken during leaf-off conditions in the winter months which coincide with the time when TVA reservoirs are at their lowest "winter pool" stage. This provides a snapshot of mudflat extent, but photography taken earlier in the fall or spring is necessary to gain a

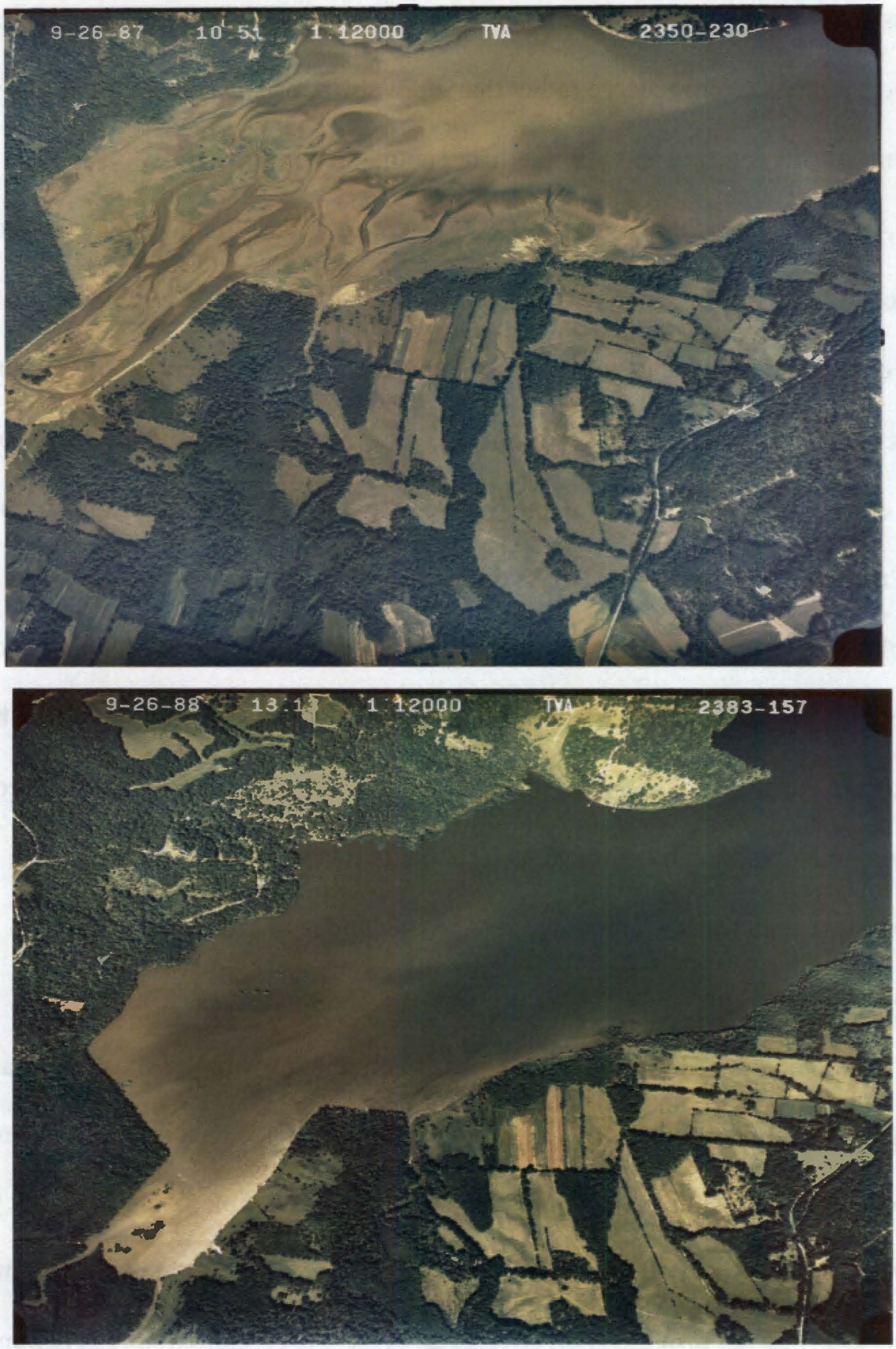


Figure 11: Aerial Photographs of the Blood River Embayment on Kentucky Reservoir, TN. These images could be used to photo-interpret shoreline contours to create an elevation dataset of the area.

better coverage of contour data using photo-interpretation methods. Another caveat to this approach is that mudflats are generally depositionally active systems which may change shape over time in response to hydrologic events. Some field verification of the photo-interpreted contours would be necessary to ensure that they still accurately describe site elevation.

Chapter 4: Results

This thesis models shorebird habitat availability at Rankin Wildlife Management Area under three TVA reservoir management regimes, based on representative reservoir stage data for each scenario. I found that changes in reservoir management made in 1991 and 2004 have moved the timing of habitat availability later in the year relative to the timing of shorebird arrival in the Tennessee River Valley (TRV). The biggest impact to shorebird habitat identified in this study was when TVA implemented the 1991 Lake Improvement Plan (LIP). This change in management moved the timing of first mudflat exposure back from mid-June to the beginning of August. From 1972 through 1990, the fall drawdown started earlier and was also more gradual than more recent management scenarios. This gradual drawdown cycle provided habitat throughout the migration season. The transition from 1972–1990 management to the 1991–2003 LIP management scenario eliminated habitat availability in July for the 15 species that can potentially arrive in the TRV in that month.

The current River Operations Study (ROS) plan further delays drawdown and thus mudflat exposure slightly more than the 1991 Lake Improvement Plan management change. Under ROS management, drawdown at Douglas reservoir will be limited from June 1 through Labor Day, so that by the beginning of August only four hectares (10 acres) of shorebird habitat will be exposed, and thereafter the area of exposed habitat will increase dramatically through September. The ROS plan keeps the reservoir stage elevated longer into the fall but then releases more rapidly than previous scenarios. The result of this is less habitat area available during the beginning of migration relative to the two previous management scenarios, but abundant amounts of habitat at the peak of migration and relatively more habitat remaining nearer the end of the migration window.

As stated previously, mudflat exposure is not linear in relation to reservoir stage. The relationship between mudflat area and reservoir stage at Rankin Bottoms is illustrated in Figure 12. Notice that the slope of the curve is at its greatest between 301 and 287 meters, meaning that the slope of the mudflat in general is least steep in this range and therefore more mudflat will be exposed per unit drop.

The primary goal of this study was to quantify the amount of habitat available for migratory shorebirds at Rankin Bottoms during the fall migration under the three TVA management scenarios discussed above. The modeled results of this effort are summarized in Figure 13 which graphically depicts the amount of habitat available under each scenario versus the number of species which may possibly be present according to the migration chronology used in this study. Using this graph we may qualitatively compare the results of each model run to see the temporal pattern of habitat availability created by the representative reservoir stage data for each scenario. Notice that all of the scenarios at some point during fall migration fail to provide habitat. The two most recent scenarios, the LIP and ROS, have delayed the timing of habitat availability to later in the migration period. I have also presented the model results opposite the number of individual shorebirds posted on the TNBirds forum for the fall of 2002 to 2003 (Fig. 14). These shorebird survey data were not collected systematically and likely contain bias in that higher numbers of birds were recorded during periods when birdwatchers spent more effort. The final graph in this series, Figure 15, shows the differences in habitat area

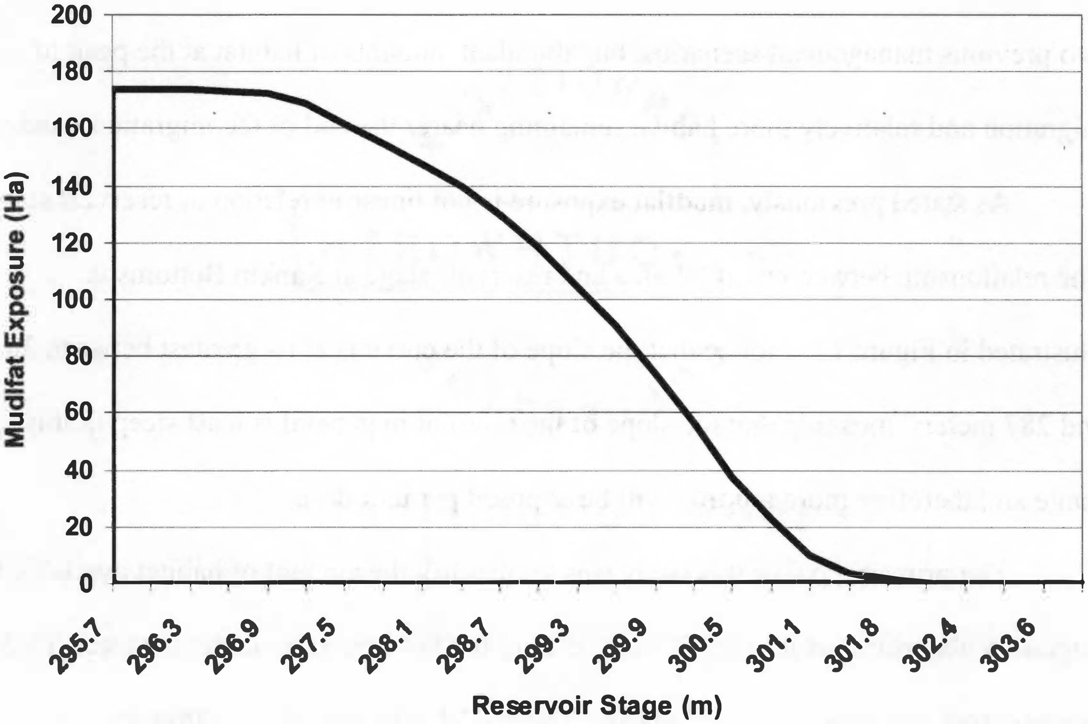


Figure 12: Mudflat exposure at every reservoir stage encountered during reservoir drawdown at Rankin Bottoms. Below 297 m mudflat areas give way to the old river channel, which reactivates at low stages. Areas above "summer pool" 302.6 m elevation experience insufficient inundation to suppress persistent woody vegetation and therefore never function as mudflats.

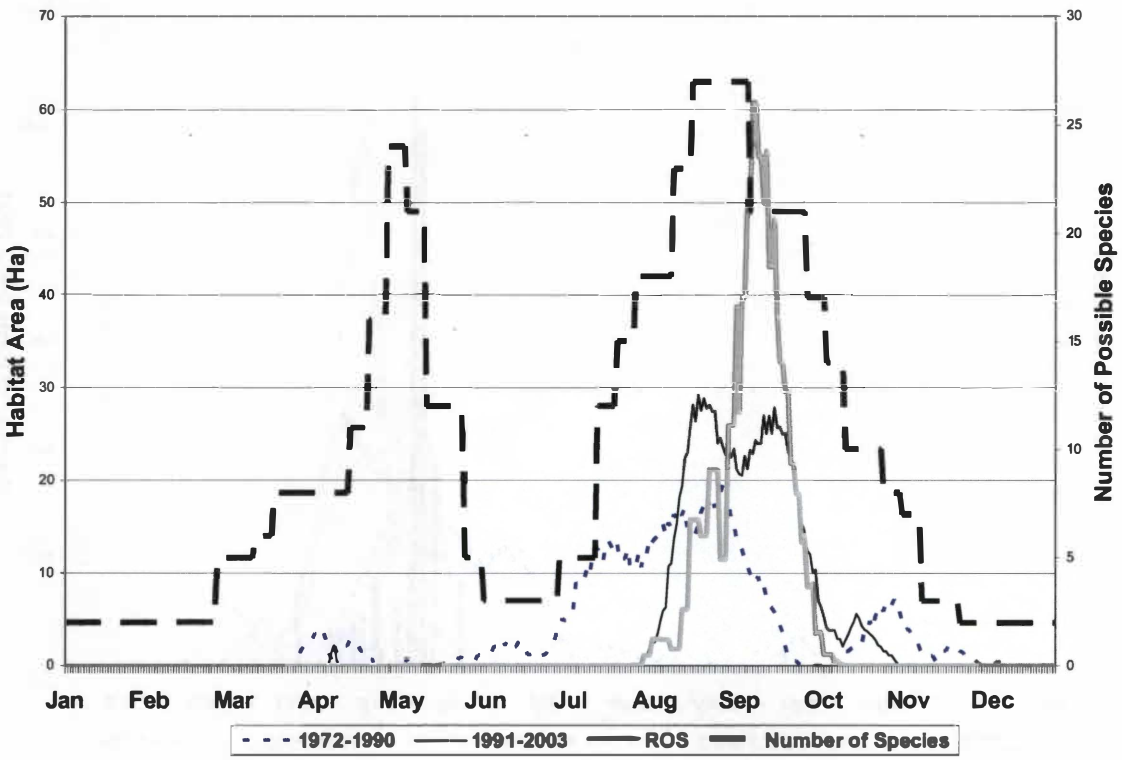


Figure 13: Shorebird habitat availability for the three scenarios versus the number of species possibly present.

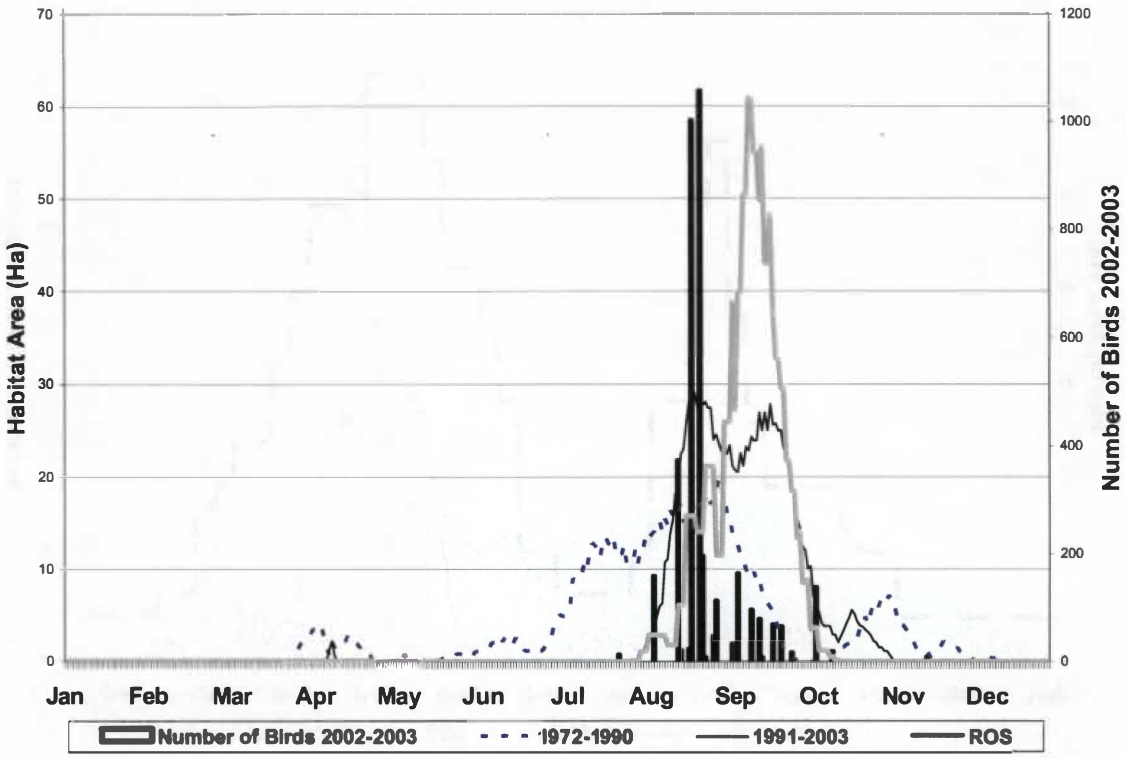


Figure 14: Shorebird habitat availability for the three scenarios versus the number of individual birds observed during fall migration 2002–2003. The shorebird survey data were not collected in an organized and systematic sampling effort, and therefore are temporally biased towards the times of greatest effort. High numbers of bird sightings likely coincide with periods when birdwatchers decided to visit this site.

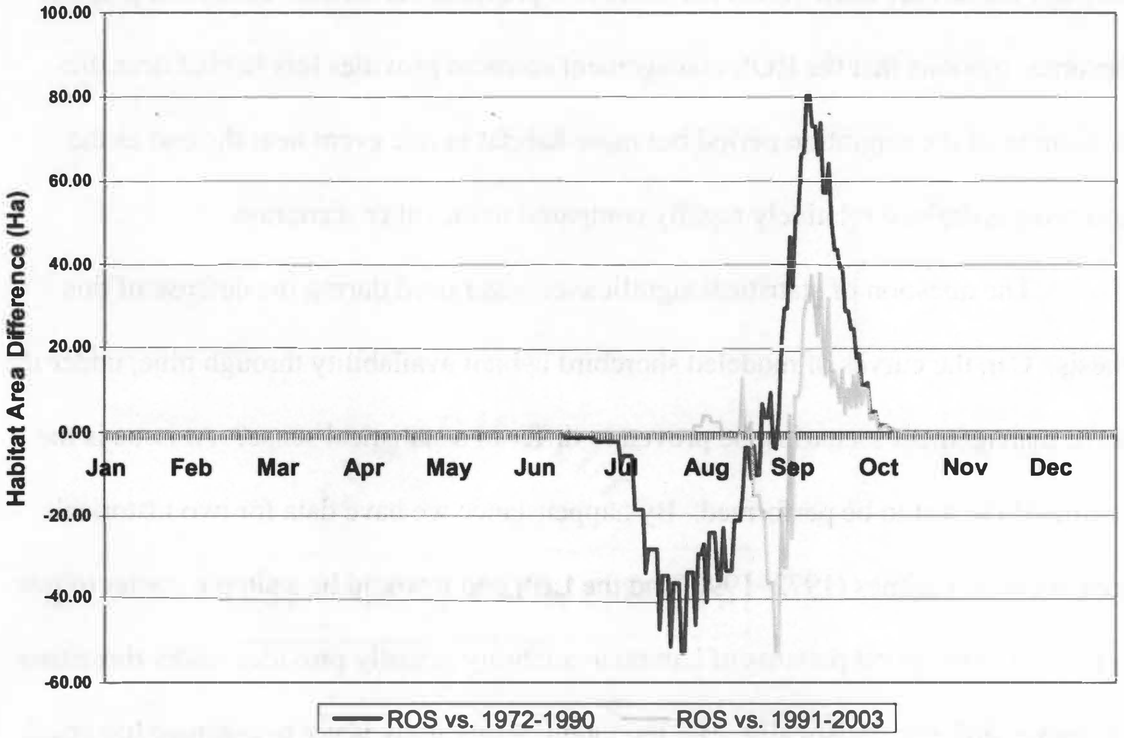


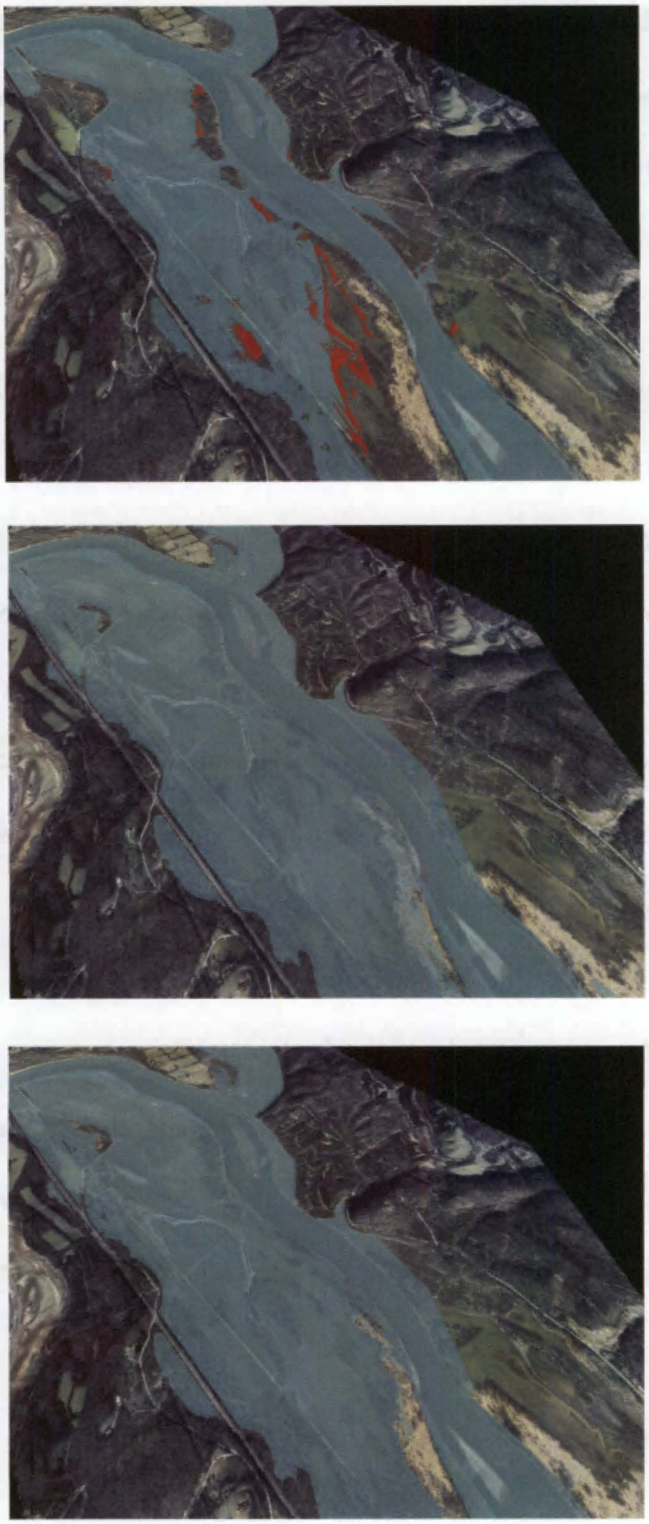
Figure 15: The difference in habitat availability between ROS and the past management scenarios.

through the fall for ROS versus the other two previous scenarios. Using this graph it becomes obvious that the ROS management scenario provides less habitat near the beginning of the migration period but more habitat in one event near the end as the reservoir is drained relatively rapidly compared to the other scenarios.

The question of statistical significance was raised during the defense of this thesis. Can the curves of modeled shorebird habitat availability through time, under the three management scenarios, be proven to differ in a statistical sense? At issue is the nature of the test to be performed. By happenstance we have data for two historical management regimes (1972–1990, and the LIP) and it would be a simple matter to test whether the temporal patterns of habitat availability actually provided under those two scenarios differed statistically. But the intent of this study is not to compare historical regimes, but to demonstrate how to make inferences regarding untried, proposed regimes. Any management regime, whether it is the LIP, ROS, or some other, is only a prescription. When put into practice each will be affected by weather, downstream river-level requirements, power-generation requirements, changes to the time of concentration within the watershed, and more. The practical result will invariably differ from the prescription. We know the impact of management under the LIP only because that particular prescription remained in force for more than a decade and we can examine the annual reservoir stage curves that actually resulted. Short of performing decade-long experiments with ROS or other proposed management regimes, we cannot acquire meaningful datasets to which to rigorously compare historical regimes. After consulting faculty experts in statistical analysis of geographic problems, I reached the conclusion supported by them, that although my 1972–1990, LIP, and ROS curves obviously differ, there is no inherently meaningful way to statistically demonstrate that difference, because the historical data represent actual populations of resultant impacts of the respective prescriptions, whereas modeled ROS impacts reflect the idealized prescription only, not the combination of prescription and other influences that will define actual results comparable to historical annual reservoir stage curves.

I have summarized these data in a series of images to allow readers to visually explore and understand the changing pattern of habitat availability on the mudflat as the water recedes (Fig. 16). This series of graphics shows available shorebird habitat at bi-weekly resolution for the fall migration period (July–September). These images were generated in a GIS using aerial photography of Rankin Bottoms overlain with model outputs. These graphics display habitat areas in red and provide area values in hectares and acres. Additionally the number of shorebird species that may possibly be present is reported based on the shorebird migration chronology.

There is also an interactive shorebird habitat viewer, the *Rankin Wildlife Management Area Shorebird Habitat Viewer*, included on the CD (Plate 1) accompanying this document. That application allows you to interactively explore the findings of this study on-screen. The interactive shorebird habitat viewer offers weekly-resolution, animated 3-dimensional views of reservoir drawdown at Rankin Bottoms like those found in Figure 16.



July 1
Possible # of Species Present: 3

1972-1990
Habitat Area:
2.4 hectares
(6 acres)

1991-2003
Habitat Area:
0 hectares

ROS managment
Habitat Area:
0 hectares

Figure 16: Graphical representation of habitat availability at Rankin Wildlife Management Area.

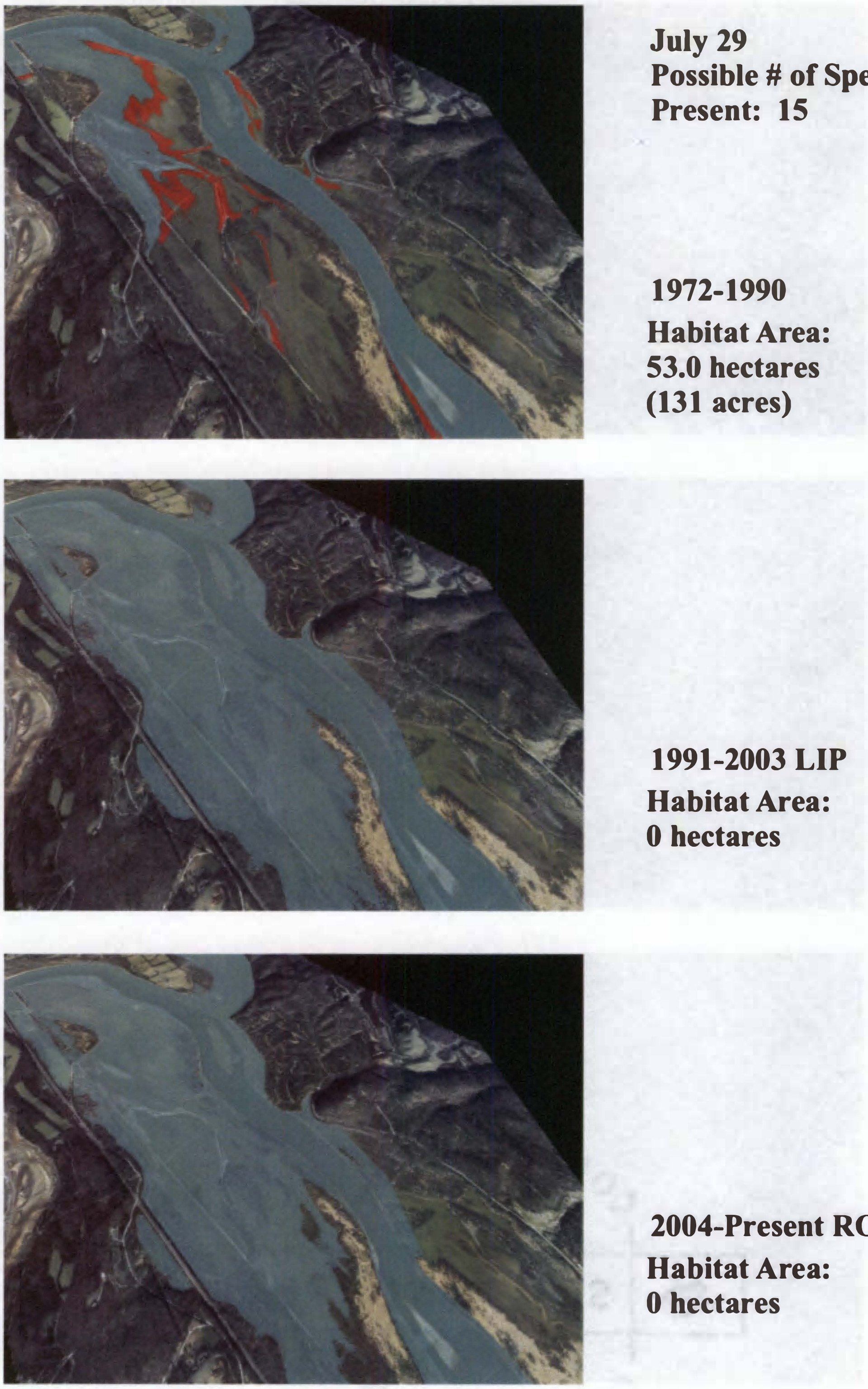
July 15
Possible # of Species
Present: 5

1972-1990
Habitat Area:
34.0 hectares
(84 acres)

1991-2003 LIP
Habitat Area:
0 hectares

2004-Present ROS
Habitat Area:
0 hectares

Figure 16: Continued.



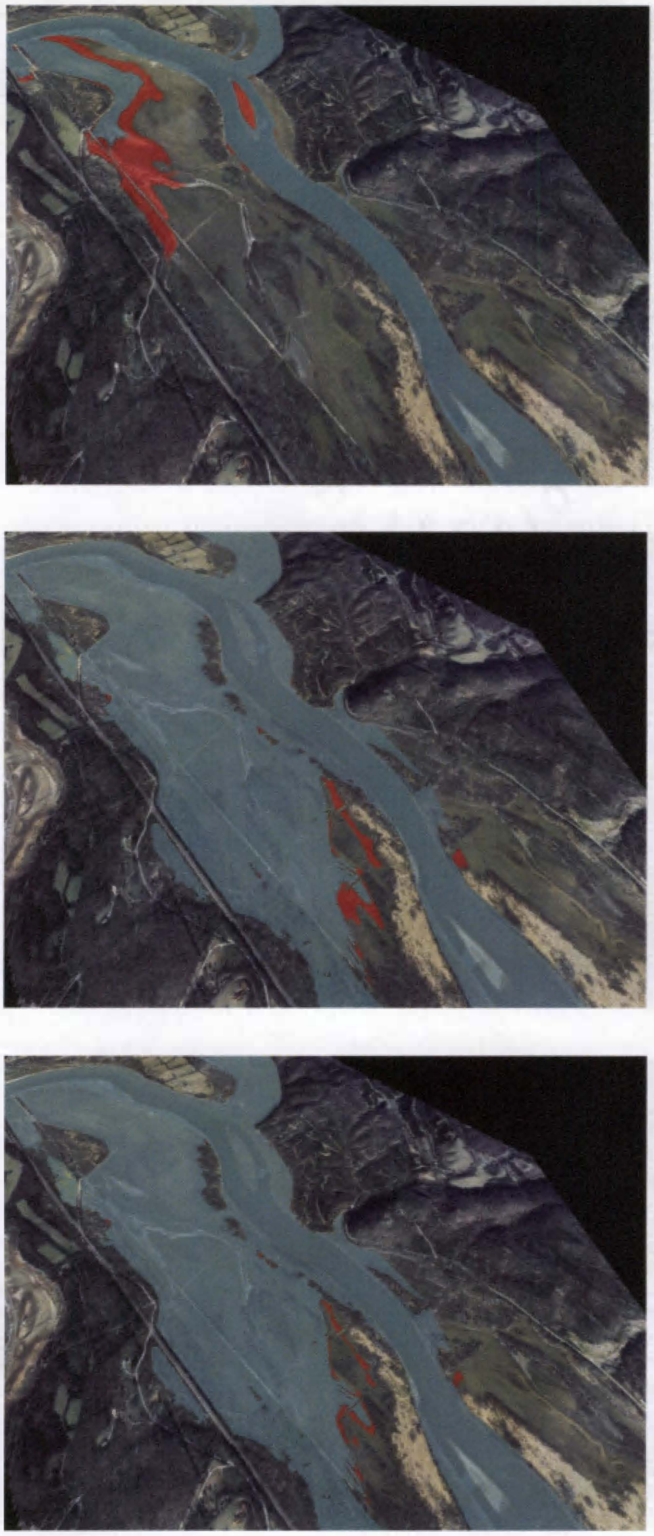
July 29
Possible # of Species
Present: 15

1972-1990
Habitat Area:
53.0 hectares
(131 acres)

1991-2003 LIP
Habitat Area:
0 hectares

2004-Present ROS
Habitat Area:
0 hectares

Figure 16: Continued.



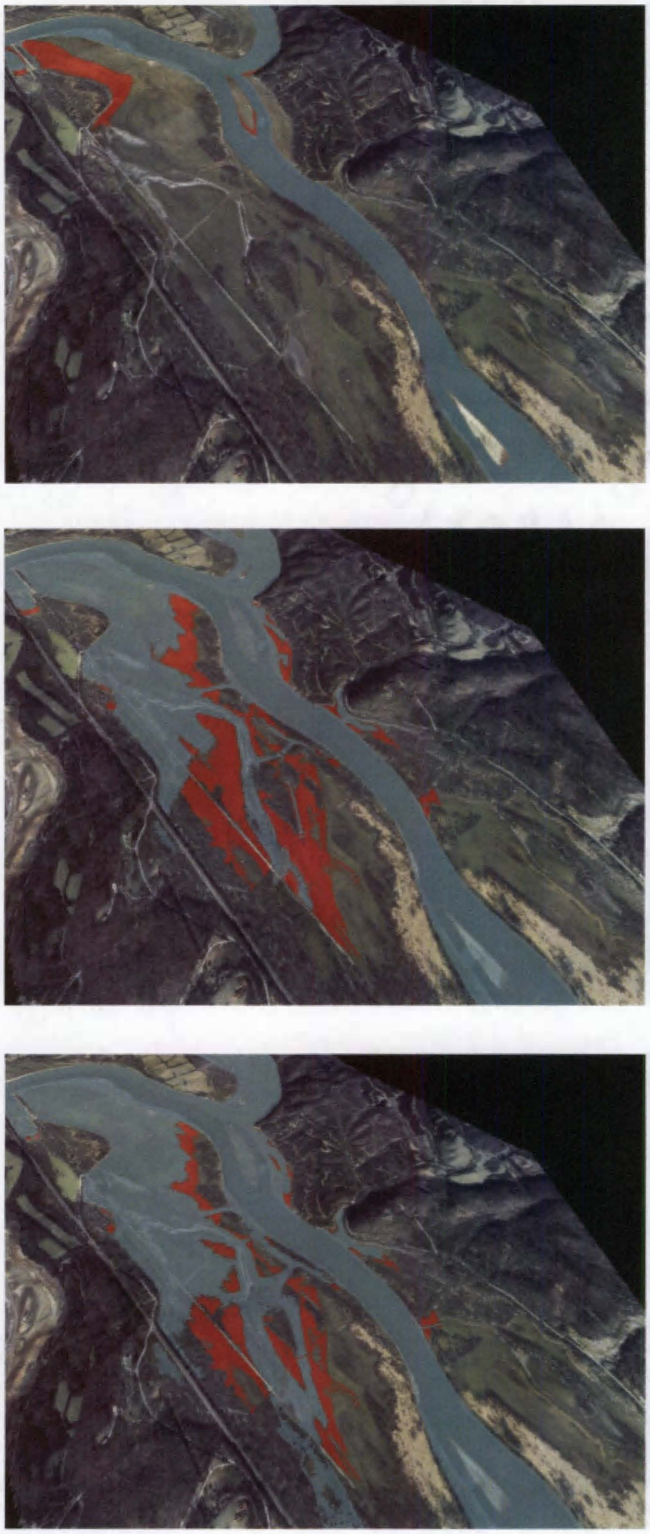
August 12
Possible # of Species Present: 18

1972-1990
Habitat Area:
25.5 hectares
(63 acres)

1991-2003 LIP
Habitat Area:
3.6 hectares
(9 acres)

2004-Present ROS
Habitat Area:
2.4 hectares
(6 acres)

Figure 16: Continued.



August 26
Possible # of Species Present: 27

1972-1990
Habitat Area:
21.4 hectares
(53 acres)

1991-2003 LIP
Habitat Area:
47.3 hectares
(117 acres)

2004-Present ROS
Habitat Area:
27.9 hectares
(69 acres)

Figure 16: Continued.

September 9
Possible # of Species
Present: 27

1972-1990
Habitat Area:
0.8 hectares
(2 acres)

1991-2003 LIP
Habitat Area:
55.8 hectares
(138 acres)

2004-Present ROS
Habitat Area:
66.7 hectares
(165 acres)

Figure 16: Continued.

September 23
Possible # of Species
Present: 21

1972-1990
Habitat Areas:
0 hectares

1991-2003 LIP
Habitat Area:
32.0 hectares
(79 acres)

2004-Present ROS
Habitat Area:
39.2 hectares
(97 acres)

Figure 16: Continued.

Chapter 5: Discussion

I have found that none of the reservoir management scenarios analyzed in this study were optimal for shorebird species migrating through the TRV. A truly optimal scenario would be one where some habitat is available throughout the migration window. Based on the findings of this study, I have created a set of generalized shorebird-optimal guidelines. The guidelines state that shorebird habitat exists at Rankin Bottoms on the Douglas Reservoir between the reservoir gauge elevations of 302.6 and 295.6 meters (993 and 970 ft) AMSL. To optimize the shorebird habitat resource at Rankin Bottoms the reservoir level should be below 302.5 meters (989 ft) by the first of July to provide habitat for early migrants. From July 1 forward, the reservoir should be lowered as slowly as possible between 302.5 and 296.9 meters (989 and 974 ft) through October to provide habitat for migrants throughout the migration period. In this manner some habitat is always available at Rankin Bottoms throughout the migration period.

Using the methods developed in this study, a shorebird habitat alternative could be created for the TVA system or systems elsewhere. The first step in developing a shorebird optimal alternative would be to define optimal. For example, is the goal of management to maximize species richness, population size, or is it more focused on species of management priority, or balancing habitat availability for species with several habitat preferences?

In this study we have developed our guidelines such that some habitat is available throughout the migration period. Shorebirds are diurnal migrants relying on visual clues to select appropriate stopover locations (Hayman et al. 1986). Providing some habitat throughout the migration period for shorebirds to locate seems to be the most appropriate way to address the needs of all possible migrant species, including species of management concern, at this stopover. This definition of optimal is used for our site due to the relatively low number of individuals who presently visit the site versus the amount of habitat available. The greatest number of individual shorebirds at Rankin Bottoms recorded during TVA's 2004 weekly monitoring effort was 371 individuals of 8 species (A. Trently, unpublished data 2005). If we assume that habitat at Rankin Bottoms provides the same density of food resources (~2 g/m^2) as sites analyzed in the Mississippi Alluvial Valley by the Lower Mississippi Valley Joint Venture (LMVJV), then the amount of fall habitat appears excessive for the number of individual migrants present on any given day. According to this rationale, so long as a few hectares of habitat are available, the habitat requirements of the individuals in this area will be met. Based on this information I believe that the guidelines presented in this study are suitable for addressing the relatively low populations recorded at Rankin Bottoms.

I have created an idealized reservoir drawdown guide-curve for Rankin Bottoms and used it as input for modeling habitat availability to illustrate how reservoir drawdown timing and rate can be adapted to optimize shorebird habitat availability. I have graphed data opposite the habitat and reservoir stage curves for the ROS (Fig. 17). In the "optimal" scenario I have fundamentally modeled the guidelines recommended by this study previously; reservoir drawdown begins prior to July when shorebird species begin to arrive at this site, and the reservoir stage is lowered gradually from 302.5 to 296.9 meters (989 and 974 ft) through October. This "optimal" reservoir stage curve is purely

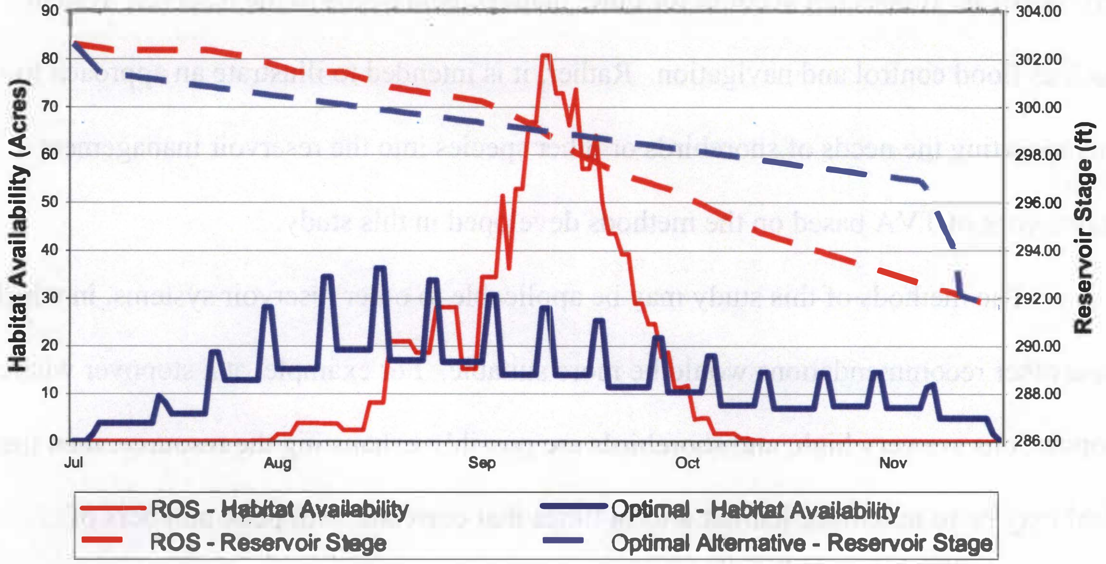


Figure 17: Reservoir stage and habitat availability for the shorebird optimal reservoir management scenario versus the ROS management scenario. The peaks and valleys evident in the habitat availability curve for the "optimal" scenario are a function of the ten day mudflat exposure limit; they are very apparent due to the linear nature of the "optimal" curve.

hypothetical. It does not account for other management needs in the reservoir system such as flood control and navigation. Rather, it is intended to illustrate an approach to incorporating the needs of shorebirds or other species into the reservoir management framework of TVA based on the methods developed in this study.

The methods of this study may be applicable to other reservoir systems, in which case other recommendations would be more suitable. For example, at a stopover where populations are very high, and shorebirds are possibly exhausting the resource, then the goal may be to maximize habitat area at times that correlate with peak numbers of individuals arriving to exploit foraging areas. In this case habitat availability data may be combined with modeled reservoir inflow to generate a reservoir stage curve that attempts to maximize habitat area at times when shorebird foraging is expected to be most intensive. There is no equation or mathematical function which can describe the amount of habitat generated per unit of drop of reservoir stage, due to the temporal dynamic of habitat availability. This makes the generation of a shorebird-optimal drawdown curve a more empirically driven process. Figure 18 shows habitat availability as a simple 30 centimeter buffer above and below the shoreline at a given reservoir stage. A graph like this one, reporting habitat area based on a non-temporal definition of habitat, is a good tool to rapidly estimate the amount of habitat area exposed during reservoir drawdown. This information can be used as a baseline for beginning to develop a guide-curve that would maximize habitat at target times during the migration period. At other sites, monitoring data may suggest that certain species of management priority arrive at particular windows of time that occur before or after the arrival of the majority of other species. In such a scenario modeling efforts may be aimed at generating a drawdown

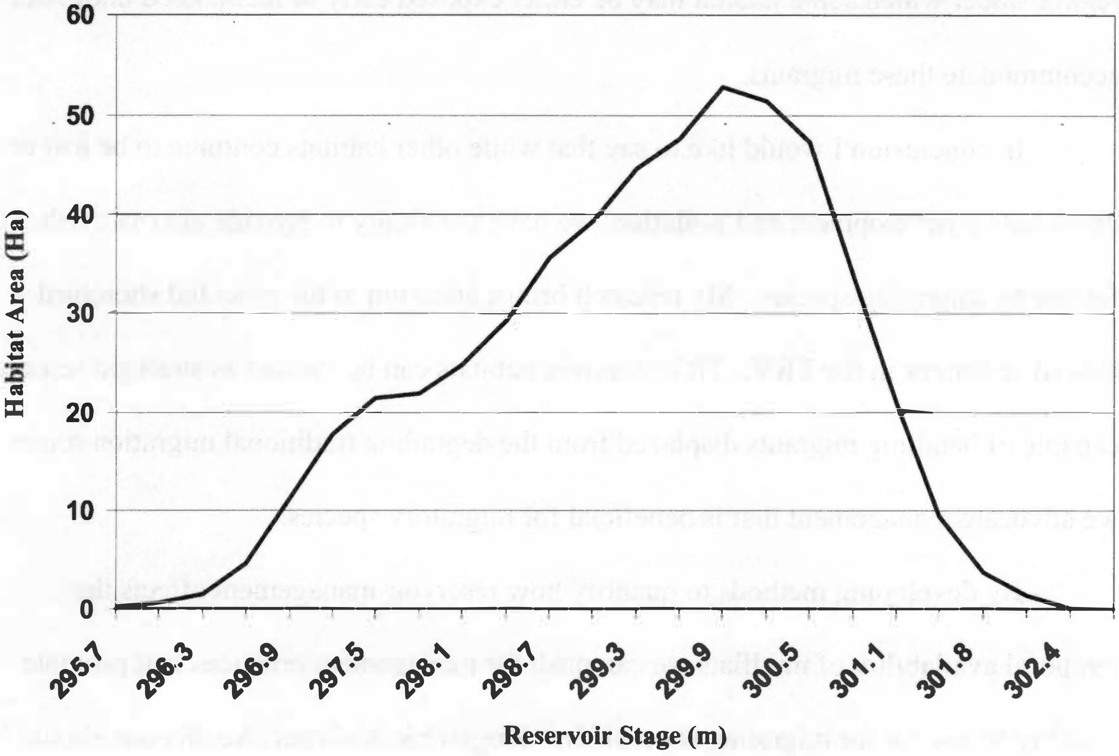


Figure 18: Habitat area at Rankin Bottoms based on a simple 30 centimeter buffer above and below the shoreline at each reservoir stage. This graph provides a rapid assessment of the quantity of mudflat at various reservoir stages.

regime under which some habitat may be either exposed early or maintained until later to accommodate these migrants.

In conclusion I would like to say that while other habitats continue to be lost or degraded by development and pollution, we have the ability to provide alternate habitats for use by migrating species. My research brings attention to the potential shorebird habitat resources in the TRV. TRV stopover habitats can be viewed as strategic reserves capable of handling migrants displaced from the degrading traditional migration routes if we advocate management that is beneficial for migratory species.

By developing methods to quantify how reservoir management affects the temporal availability of mudflats we can push for management practices that promote stability of habitat for migrating shorebirds. Geographic analyses like this one should be undertaken elsewhere within or outside of traditional migratory routes to help incorporate shorebird needs into reservoir management policy. Certainly shorebird habitat is not the only consideration when managing a reservoir system in the TRV or elsewhere, but it is definitely one important piece of a comprehensive management framework and our duty to consider as stewards of the environment.

I hope that this research may be useful elsewhere whether it is applied to shorebirds or used as a model for approaching similar geographic analysis of other temporally dynamic natural resource issues related to reservoir management. The effects of altering the timing of seasonal shifts in reservoir stage has some impacts to almost all the species both terrestrial and aquatic that inhabit shallow water or near-shore environments.

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Appendix

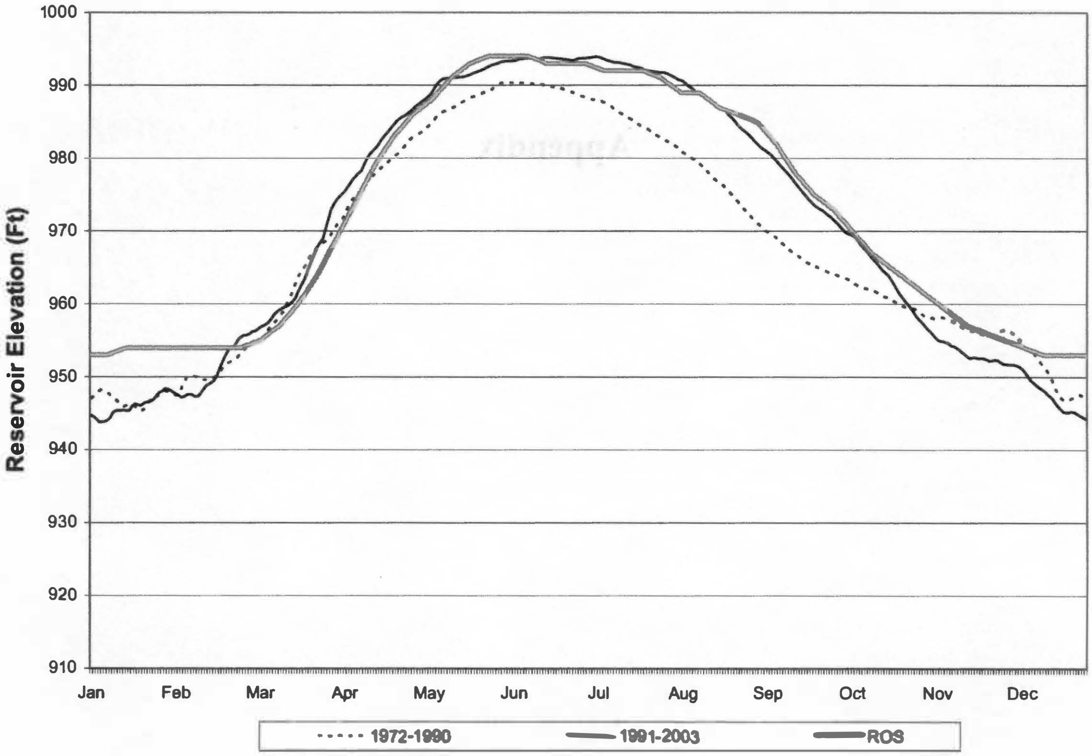

Figure 19: Averaged headwater reservoir stage values for Douglas Reservoir under three TVA management regimes (U.S. units).

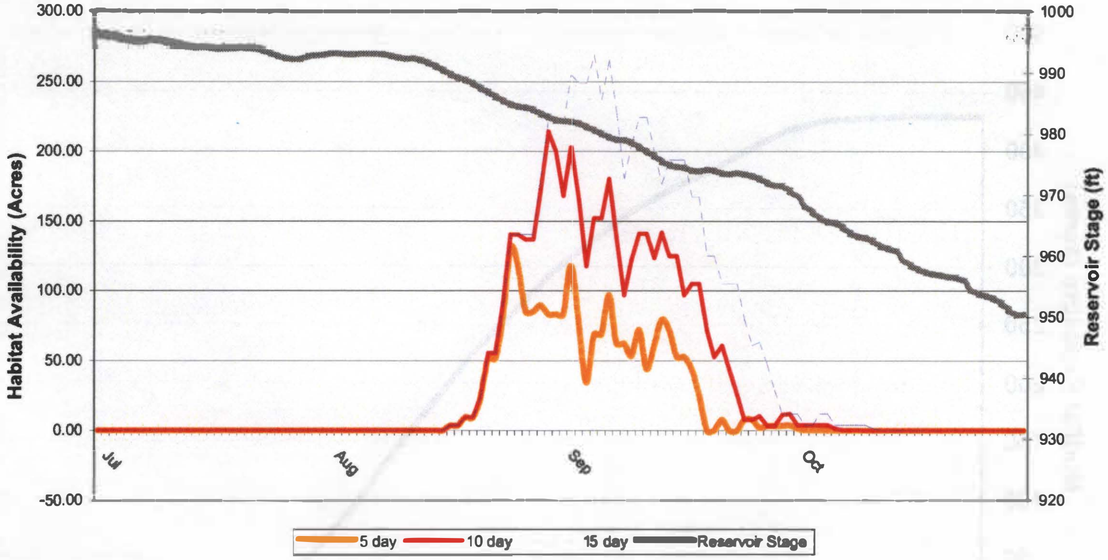

Figure 20: A comparison of habitat availability using a five-, ten-, and fifteen-day exposure window (U.S. units). This is an example of a model iteration using 2003, a relatively typical drawdown year, to explore the changes in modeled habitat availability values using different temporal limits of mudflat exposure. It is obvious that changing the exposure limit creates proportional changes in habitat area, but does not affect the relative timing or temporal pattern of habitat availability.

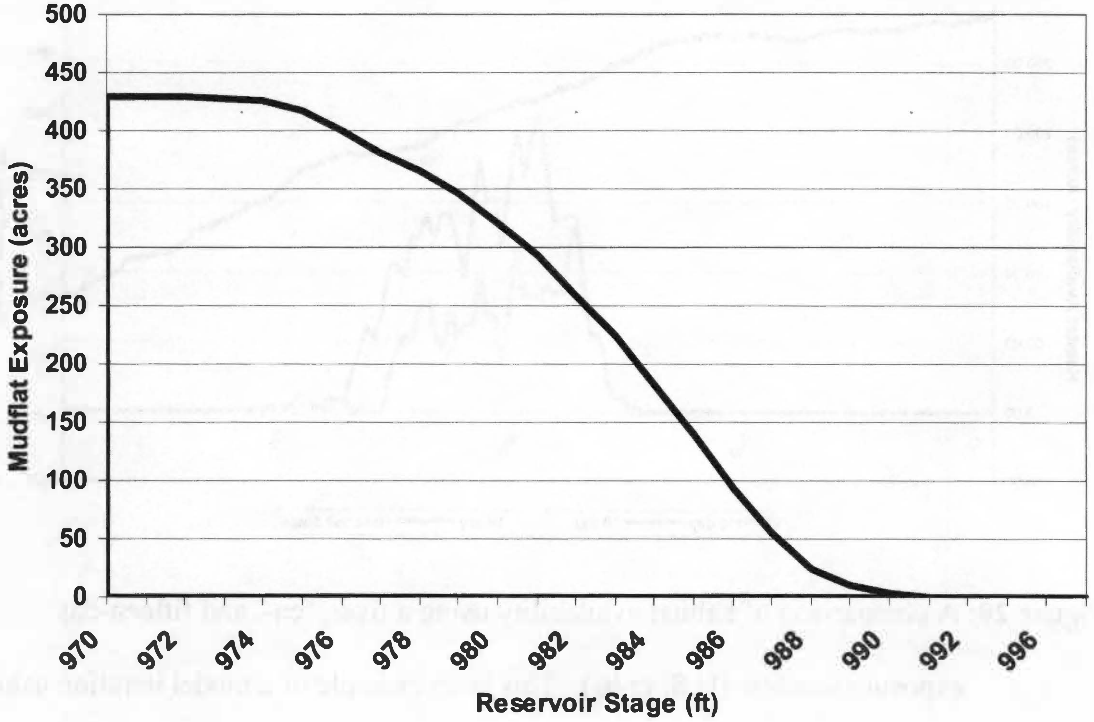

Figure 21: Mudflat exposure at every reservoir stage encountered during the fall reservoir drawdown (U.S. units). Below 975' (~297m) mudflat areas give way to the old river channel, which reactivates at low stages. Areas above "summer pool" 993' (~302.6 m) elevation experience insufficient inundation to suppress persistent woody vegetation and therefore never function as mudflats.

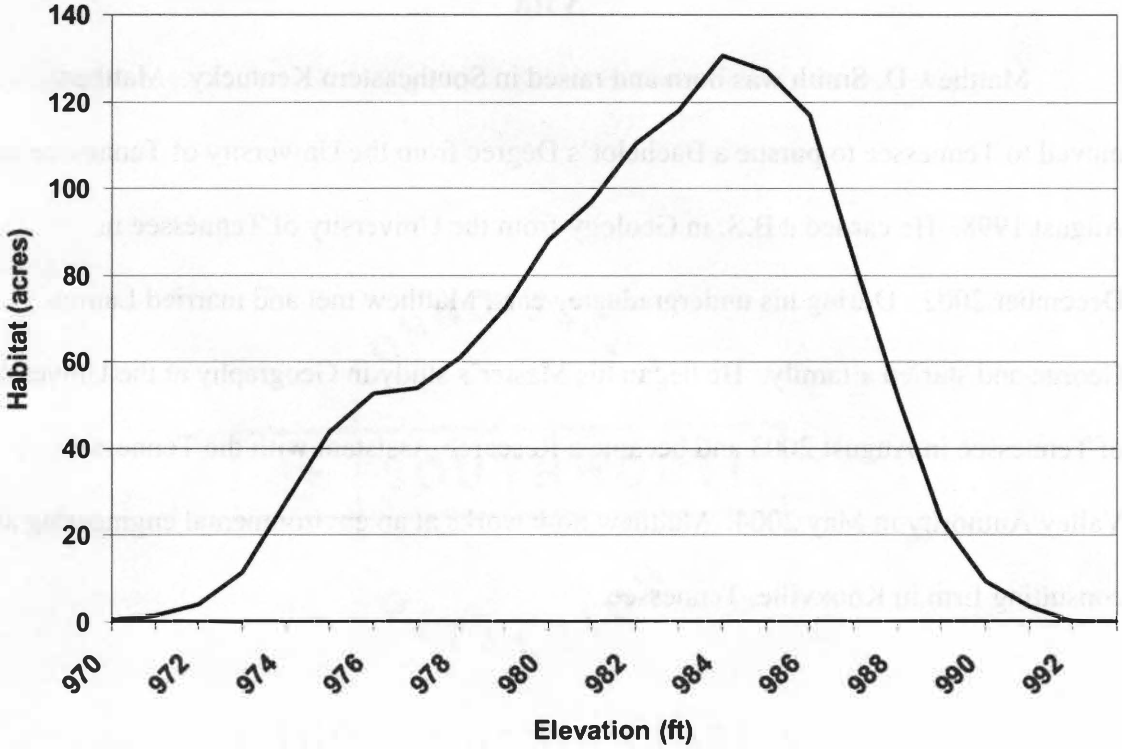

Figure 22: Habitat area based on a simple 30 centimeter buffer above and below the shoreline at each reservoir stage (U.S. units). This graph provides a rapid assessment of the quantity of mudflat at various reservoir stages.

Vita

Matthew D. Smith was born and raised in Southeastern Kentucky. Matthew moved to Tennessee to pursue a Bachelor's Degree from the University of Tennessee in August 1998. He earned a B.S. in Geology from the University of Tennessee in December 2002. During his undergraduate years, Matthew met and married Lauren George and started a family. He began his Master's study in Geography at the University of Tennessee in August 2003 and became a Research Assistant with the Tennessee Valley Authority in May 2004. Matthew now works at an environmental engineering and consulting firm in Knoxville, Tennessee.