PROTECTION OF FLOODPLAIN WETLANDS ASSOCIATED WITH MINIMUM FLOW AND LEVEL DEVELOPMENT IN SOUTHWEST FLORIDA

By

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PROTECTION OF FLOODPLAIN WETLANDS ASSOCIATED WITH MINIMUM FLOW AND LEVEL DEVELOPMENT IN SOUTHWEST FLORIDA

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Floodplain wetlands, associated with river systems, have been recognized as important components of the ecologic community of river corridors. However, the importance of out-of-bank flows to the riverine ecosystems is often not recognized by instream methods used to assess flow requirements. Quantification of potential differences in floodplain inundation associated with differences between minimum flow requirements and natural hydrologic regimes should be a critical component of regulatory programs that are intended to protect or restore riverine habitat. The Southwest Florida Water Management District uses the historic flow records to produce a temporal measure of habitat loss when developing minimum flow requirements for floodplain wetland protection. In this dissertation an alternative approach, employing a measure of spatial loss by examining the change in top width at each cross section modeled under different flow conditions, is compared to the temporal measure

Both spatial and temporal measures of habitat loss can be related to percent flow reduction in a river channel. However, both serve as a proxy to evaluate the extent of the river-floodplain connection. This connection has not yet been fully described on any river studied by the District because complicated floodplain geometry is presently represented by a limited number of floodplain cross-sections.

This dissertation concludes with an analysis of the role Geographic Information Systems (GIS) coupled with hydraulic models can play in MFL development by providing data concerning floodplain inundation under different flow scenarios. Riverine ecosystems benefit from spatial analysis since it provides data in three temporally dynamic spatial dimensions. The coupling of a one-dimensional hydraulic model and spatial information from GIS results in a powerful tool for relating variations in floodplain inundation with variations in river flow. When developing minimum flows, topographic data, in a geographic information system, can provide detailed information about riverine floodplain connection and lead to better understanding of river floodplain interaction.

CHAPTER 1
INTRODUCTION

For many years, surface water in Florida was drained to support development. Channelization of rivers, development of canals, and draining of wetlands were the foundation of early water management in Florida (Anderson and Rosendahl 1998, Egozcue 2001, Purdum et al. 1998). In more recent years, ground water use has increased as water demands have grown. Under these conditions, the importance of natural systems and their linkage to the economy of Florida and its potable water supply have become more evident. In more recent times, the water related resources of the state have been offered some protection through the requirement that minimum flows and levels (MFLs) be established.

The 1972 Florida Water Resources Act (Chapter 373, Florida Statutes (F.S.)) represents the initial legislation calling for development of MFLs in the state of Florida. Aimed at protecting the ecology of natural systems from "significant harm" associated with water withdrawals, MFLs represent an attempt to quantify the hydrologic requirement of aquifers, rivers, lakes, and wetlands. Initially, MFL development was somewhat sparse because of uncertainties in the legislative language, among other factors. It was not until 1997, when the Florida legislature enacted several major changes to Florida water law in an attempt to improve water resource planning and protection, that MFL development became a key component in water resource regulation in the state. The five water management districts of Florida responded to the changes in the law by prioritizing water bodies within their boundaries and developing MFLs for water bodies as identified on each priority list.

A number of rivers in the Southwest Florida Water Management District (SWFWMD) were considered potentially impacted by withdrawals and thus to be high value candidates for MFL development and as such were placed on the priority list. The District subsequently

developed a multi-parameter approach to determining MFLs on the freshwater portions of these rivers that included evaluation of loss of floodplain habitat. This action was concurrent with the development of approaches by other water management districts in the state. Although floodplains have long been recognized as seasonally important riverine habitat, floodplain inundation has historically not been addressed in most minimum flow determinations (Postal and Richter 2003). Middleton (1999) also points out that regulation of water regimes has not always fully appreciated the interaction between floodplains and rivers via the flood pulse. Regulation of river flows can, however, result in decreased stage fluctuations and alteration of inundation patterns of floodplain wetlands (Poff et al. 1997, Woltemade 1997). Quantification of potential differences in floodplain inundation associated with differences between minimum flow requirements and natural hydrologic regimes should, therefore, be a critical component of regulatory programs that are intended to protect or restore riverine habitat.

Compared to instream evaluations of minimum flows requirements, there has been relatively little research on river flows necessary for meeting the requirements of floodplain species, communities or functions. However, periodic inundation of riparian floodplains by high flows is closely linked with the overall biological productivity of river ecosystems (Crance 1988, Junk et al. 1989). Further evidence exists suggesting that floodplain inundation benefits fish (Ainsle et al. 1999, Hill and Cichra 2002, Wharton et al. 1982), supports high rates of primary production (Brinson et al. 1981, Conner and Day 1979), is critical to food webs (Gregory et al. 1991, Vannote et al. 1980) and results in development of wetland soils that are important to the overall function of the river ecosystem (Kuensler 1989, Stanturf and Schoenholtz 1998, Walbridge and Lockaby 1994, Wharton et al. 1982).

The Southwest Florida Water Management District (District) has developed an approach which recognizes that fundamental to the development of MFLs is the realization that a flow regime is necessary to protect the ecology of the river system (Hill et al. 1991, Hupalo et al. 1994, Richter et al. 1996, Stalnaker 1990). The high flow component of the flow regime is intended to protect the connection between the floodplain and the river. The resource management goal identified for the seasonally predictable wet period is maintenance of seasonal hydrologic connections between the river channel and floodplain to ensure floodplain structure and function.

Minimum flows developed for the high flow season are intended to protect ecological resources and values associated with floodplains by maintaining hydrologic connections between the river channel and floodplain and maintaining the natural variability of the flow regime. These goals are quantified through use of the Hydrologic Engineering Centers-River Analysis System (HEC-RAS) and the alteration of long-term flow records to evaluate floodplain feature inundation patterns associated with channel-floodplain connectivity.

A temporal measure of habitat loss has been employed by the District in establishing MFLs on freshwater river systems in southwest Florida, during the high flow season of the year. This reduction in number of days of inundation is a temporal measure of loss based on how many days, annually, a specified water-surface elevation was reached compared to how often that elevation would have been reached if flow conditions had been reduced by a given amount.

Data and methods used to develop minimum flows for seasonal, high-flow periods for the Alafia River, Myakka River, and Peace River are used in this study to illustrate this approach to quantifying habitat change associated with temporal difference in floodplain inundation patterns. An alternative approach, employing a measure of spatial loss by examining the change in top

width at each cross section in a hydraulic model under different flow conditions, is also explored. The use of a temporal measure of habitat loss for establishing MFLs during high flows is compared to the spatial loss of habitat for the same flow reduction. The applicability of both is discussed and the results compared to determine which is more restrictive in terms of allowable flow reduction.

However, as Mertes (1997) points out, floodplain vegetation development and persistence may not, however, necessarily depend wholly on inundation from the river channel. Groundwater seepage, hyporheic inputs, discharge from local tributaries, and precipitation can also lead to floodplain inundation. Recent work on the upper segment of the Peace River and the Alafia River in central Florida suggests that direct and continuous inundation of floodplain wetlands by river flows is insufficient to account for inundation needs of the dominant species found in the wetlands (SWFWMD 2002).

After comparing the temporal and spatial measures of habitat loss, being employed in the minimum flow and level process, this dissertation examines an alternative means to measuring habitat. The use of high-density remotely gathered data to generate a digital elevation model is explored. This terrain model is then used in the development of cross-sectional data for use in a one-dimensional hydraulic model. Beyond this, data generated in the hydraulic model can be processed in a Geographic Information System (GIS) environment to produce inundation maps which are not limited to the one dimensional cross-sections. The coupling of a one-dimensional hydraulic model and spatial information from GIS results in a powerful tool for relating variations in floodplain inundation with variations (or reductions) in river flow.

The objectives of this dissertation include reviewing the history of water management in Florida with an emphasis on decisions culminating in the 1997 legislation requiring the

development of minimum flows and levels. Attention is paid to water quantity issues and policies and the natural and anthropogenic factors influencing them. The measures of riverine floodplain habitat loss use in response to the minimum flows and levels mandate are also examined and temporal loss measures are compared with spatial loss measures. Finally, a method of examining inundation changes in a GIS system environment is presented as an alternative to current approaches.

CHAPTER 2
DETERMINING MINIMUM FLOWS AND LEVELS IN FLORIDA: A LEGISLATIVE MANDATE

Introduction

On average, Florida receives 140 cm of rainfall annually (Carriker 2000, Henry 1998). This precipitation feeds Florida's diverse hydrologic systems and makes it the second wettest state in the United States. Florida has more than 7,700 lakes, ranging from 0.4 ha to over 180,000 ha (Shafer et al. 1986). Thirteen major rivers originate in, or flow through, the state with a combined mean annual discharge of nearly 1700 m^3s^{-1} (Henry 1998). Contributing to this total are 27 first magnitude springs that discharge a total average flow of 272 m^3s^{-1} or more than 22 billion liters day^{-1} (Rosenau et al., 1947). Florida also contains significant areas of wetlands, which at one time covered 54 percent of the state and still comprise about 30 percent of the total land area (Henry 1998, SWFWMD 2001).

In a state with such abundant water resources, stringent water supply management may seem unnecessary. This was the presumption for many years, as surface water systems were drained to support development. Channelization of rivers, development of canals, and draining of wetlands were cornerstones of early water management in Florida (Anderson and Rosendahl 1998, Egozcue 2001, Purdum et al. 1998). In more recent years, ground water use has increased as water demands have continued to grow. Under these conditions, the importance of natural systems and their linkage to the economy of Florida and its potable water supply has become more evident.

The 1972 Florida Water Resources Act (Chapter 373, Florida Statutes (F.S.)) represented the initial legislation calling for development for minimum flow and levels (MFLs) in the State. Aimed at protecting the ecology of natural systems from "significant harm" associated with water withdrawals, MFLs represent an attempt to quantify the hydrologic requirement of

aquifers, rivers, lakes, and wetlands. Though some water management agencies did proceed with the development of regulatory flows and levels, it was not until 1997 that legislation was enacted which propelled MFLs from a stand-alone statute to an integral part of water resource management and regulation.

The objectives of this chapter include providing a brief review of the history of water management in Florida with an emphasis on decisions culminating in the 1997 legislation requiring the development of minimum flows and levels. Attention is paid to water quantity issues and policies and the natural and anthropogenic factors influencing them. Also examined are the effects of the 1997 law on water management and the efforts that have been made to comply with the legislative mandates.

History of Water Management in Florida (1824-1972)

In the early years of Florida's governance, there was little activity that could be said to constitute a statewide water policy. With respect to water management and use, local communities and landowners were free to do as they chose with little interference. Water was abundant, often too much so for most settlers, and prior to statehood in 1845, only minor concern seems to have been given to regional or statewide water management issues. Although not enacted, an 1824 proposal by the legislative council calling for the construction of a canal across Florida for ship passage represents one exception to the dearth of early large-scale water management and planning (Purdum et al. 1998).

Florida was granted statehood in 1845 and was given 202,344 ha of land by the federal government for “internal improvements”. In 1850, the U.S. Congress additionally conveyed all swamps and inundated lands, over 8 million ha in total, to state ownership through the Swamp Lands Act (U.S. Congress 1911). In subsequent years, public lands granted to the state by Congress were sold and the resulting funds were funneled through the state's Internal

Improvement Fund and used to invest in railroads and guarantee railroad bonds. However, the outbreak of the Civil War devastated Florida's railroads, and with the prospect of railroads failing, future sales of public lands went to funding canals to drain the Everglades (Egozcue 2001). The legislature looked to the south Florida Everglades for reclamation and settlement, believing these lands offered suitable areas for cultivation of sugar, rice, cotton and tobacco (Egozcue 2001).

In 1881, the state sold four million acres of land to Hamilton Disston for $1 million. A businessman from Philadelphia, Disston began channelization of the Caloosahatchee and the Upper Kissimmee River basins in south and central Florida (Purdum et al. 1998). Numerous other companies were given charters to dredge canals throughout the state and were given public lands in compensation for their efforts. The land was subsequently sold to farmers as it was drained. Under pressure from farmers, the legislature encouraged the creation of additional canals and dykes to drain more land for development (Egozcue 2001). In 1883, Lake Beauclair and Lake Apopka in central Florida were connected to reduce Lake Apopka's water elevation by approximately one meter and enhance the farming ventures on the northern shore of the lake (Shofner 1982). During the years leading up to the 20th century, additional canals were completed between Lakes Apopka, Dora, Eustis, Griffin and the Ocklawaha River. These canal projects reinvigorated the dream of a cross-Florida shipping canal, which had been considered earlier but had been set aside in favor of railroad development.

In 1902, Congress heeded a United States Army Corp of Engineers (USACOE) recommendation and a federal navigation project was initiated on the Kissimmee River. Other regional projects, developed to de-water the Everglades, led to the creation of the Everglades Drainage District in 1907 (Figure 1). This was the first regional authority created by the state to

implement water policy. The District constructed six major canals totaling over 700 km, which still connect Lake Okeechobee to the Gulf of Mexico and the Atlantic Ocean. As had central Florida's earlier trend, the drainage of land for agriculture in south Florida continued to be encouraged. In 1913, the General Drainage Act gave landowners the right to form districts to reclaim their lands. Over 100 such districts were created in the Everglades area; some still operate today (Anderson and Rosendahl 1998, Purdum et al. 1998).

The 1920's saw a marked shift in state water management goals. Until that time, lands had been drained and canals created to reclaim land and foster the development of both agriculture and urban areas. During the 1920s, four major hurricanes hit south Florida and during the 1928 hurricane, Lake Okeechobee overflowed, killing over 2,000 people. This catastrophe led to an increase in Federal assistance for water management projects and spurred the state to establish the Okeechobee Flood Control District in 1929 (Anderson and Rosendahl 1998; Figure 1). While the methods remained largely the same, the stated goal, which brought in federal help from the USACOE, became one of flood protection, which had the ancillary benefit of providing continued drainage for agriculture and urban development.

By the 1940s, the legislature began to act under mounting recognition that state-level oversight of water management was necessary. In 1945, the Florida legislature created the State Board of Conservation. The board was tasked with the protection of the state's marine, mineral and water resources. In 1947, the legislature created the Water Survey and Research Division, whose records were later forwarded to the Florida Geological Survey in 1955 when the division was dissolved (Purdum et al. 1998). Political willingness to move towards increased state oversight was matched by the public sentiment of the times. Concern over the adequacy of environmental protection was growing as newspapers reported fish kills in lake Apopka

(Bachmann et al. 1999) and publication of *The Everglades: River of Grass* (Douglas 1947) raised considerable concern for the state's water resources.

As had happened earlier in the 1920s, natural disasters influenced the course of state water policy. In 1947, two hurricanes caused substantial flooding in Miami. The Central and South Florida Flood Control District was established in 1949 to coordinate the efforts of the federal government's Central and South Florida Flood Control Project. The district's plan had many components, including flood control, water control, water conservation, prevention of salt water intrusion into freshwater reservoirs and aquifers, preservation of fish and wildlife, improved navigation, and pollution abatement (Maloney et al. 1968). A decade later, two floods within a two-year period, followed by Hurricane Donna in 1960, inundated over 1 million acres of land east of Tampa and caused $29 million in damages. The state enlisted federal aid through the USACOE, and with a price tag of $100 million, the Four Rivers Basin Project was conceived. The Southwest Florida Water Management District (SWFWMD; Figure 1) was created in 1961 to manage the project and to oversee Florida's $40.5 million share of the expenses (Blake 1980).

Clearly, flooding turned the focus and the resources of the state to flood control and canalization and diluted the mounting desire for environmental regulation and natural systems protection. However, the era of canalization and drainage began to come to an end as 1970 saw a demand for a reevaluation of the Four Rivers Basin Project, and work on the project was halted (Purdum et al. 1998). Under mounting public pressure and with concern that drainage of regional surface waters was causing environmental harm, the SWFWMD requested that the USACOE undertake an environmental impact assessment of the Four Rivers Basin Project, an action that eventually led to abandonment of the project.

By the early 1970s, public demands for environmental protection were again gaining momentum and the state was committed to implementing more comprehensive forms of water management. Florida had been struggling with a need for statewide water management and several divisions and boards were established as a result of committees established by various governors. The state's executive office made environmental issues a major policy platform. Under greater state scrutiny, the number of approved dredge-and-fill projects decreased from 2,000 to 200 a year (Blake 1980, Derr 1989, Kallina 1993). Several environmental laws were passed in 1971, including the Environmental Protection Act, which allowed Florida citizens to sue the state when environmental laws are not enforced. However, it wasn't until 1972 that the state finally developed a coherent water policy through passage of the Florida Water Resources Act.

Water Resources Act of 1972

The Florida Water Resources Act of 1972 was an important step forward for state water policy. Previously, water had been managed regionally in a disjointed manner. Agencies had often been created in response to recent weather events or local economies, and their policies were so narrowly focused on one issue that other problems were often exacerbated by their activities. However, the task of creating centralized agencies and passing the laws that would empower them to conduct more comprehensive planning for water resources, was daunting. To this end, Florida lawmakers turned to *A Model Water Code* (Maloney et al. 1972).

Prior to the adoption of the code, Florida adhered predominately to eastern water law. Eastern water law is a common law riparian system, which largely restricts water rights to landowners whose property is directly adjacent to water bodies. Further, water rights are subject to reasonable use. Historically, there was a lack of administrative guidance on reasonable use, leaving litigation, and it's uncertain outcomes, as the only means of determining reasonableness.

This uncertainty of future water availability can discourage industrial investment in areas with no guarantees of meeting future needs (Maloney et al. 1972).

Believing that Florida's water resources would not be protected unless statewide control and long-term, scientifically based planning was adopted, the drafters of the Model Water Code stated three purposes:

> to take into account the hydrologic interrelationship of all types of water resources in the state; to provide greater certainty than is possible under a court-administered reasonable use approach; yet to retain sufficient flexibility to make possible realistic long-range plans for the conservation and wise use of water resources and the elimination of waste. (Maloney et al. 1972)

To achieve these goals, multipurpose water planning was essential. The state had a long history of single-purpose special districts. The majority of entities actually vested with regulatory or management authority were local forms of government, including drainage districts, irrigation districts, water supply districts, aqueduct districts, sewer districts and mosquito control districts (Maloney et al. 1980). In contrast, the state had a short history of multi-purpose special districts; the first having been the Central and South Florida Flood Control District whose charge was multifaceted (Maloney et al. 1968). The state had also established, in 1961, the SWFWMD. This was the first water resource district in the state whose name reflected the broad multifaceted functions it was tasked with, rather than a single function, such as drainage or flood control.

To achieve multipurpose water planning at a state level (multipurpose water planning was implemented 10 years earlier at the federal level by the Water Resource Planning Act), A Model Water Code (Maloney et al. 1972) identified four requirements for success. First, centralized planning was considered necessary. Lack of centralized control could lead to state programs that could contradict each another and diminish management efficiency. Second, the planning must be based in science; the hydrologic cycle and the effects of pollution, land use, recharge loss, and development must all be considered as well as their interrelationships. Third, planning must

recognize relationships between water pollution and water use and these relationships must be considered when developing long-term plans. Finally, consumptive use must be regulated (Maloney et al. 1972).

The Model Water Code (Chapter 373, Florida Statutes) envisioned statewide planning, but also envisioned scientific planning based on hydrologic boundaries rather than political boundaries. This seeming contradiction was resolved by the creation of five regional water management districts, collectively covering the state. These districts would be responsible for local issues within their boundaries but would not have the authority to prepare independent water-use plans (Tjoflat and Quincey 2001). Therefore, scientific research could be conducted and district water control structures and lands could be owned and managed on a regional basis, but a single state entity would be responsible for adopting a state water plan. The five districts are the Northwest Florida (NWFWMD), Suwannee River (SRWMD), St. John's River (SJRWMD), Southwest Florida (SWFWMD), and South Florida Water Management (SFWMD) Districts (Figure 1). Statewide oversight was initially granted to the Division of Natural Resources and now resides with the re-named Florida Department of Environmental Protection (DEP).

Water Management in Florida; Quality not Quantity (1972-1997)

The 1972 Water Resources Act gave broad powers to the regional Water Management Districts (WMDs) and to the Division of Natural Resources (now, DEP). The new law allowed for consumptive use permitted on a reasonable-beneficial use basis. Defining reasonable and beneficial use proved to be difficult however, and before the turn of the 21st century some areas of the state would be over-permitted for withdrawals. The law also required that each district formulate a water shortage plan and establish minimum flows and levels (MFLs) for surface waters and minimum levels for aquifers.

District MFLs programs were not, however, implemented with any sense of immediacy. A Model Water Code (Maloney et al. 1972) had called for minimum flows and levels to establish a "harm" threshold to protect water resources from withdrawals. As Ross (2001) points out, this linked the MFLs program to the consumptive-use permitting program, which was designed to prevent "harm" to the water resources of the state. However, when enacting the 1972 law, the passage concerning MFLs was modified slightly to protect the water resources from "significant harm". This difference is notable because although neither term is defined, the law establishes that there is a difference between "harm" and "significant harm", and suggests some separation of the consumptive use and MFLs programs. Ross (2001) further pointed out that the linkage between MFLs and the State Water Use Plan, though present in the original 1972 legislation, was removed in 1973 when the MFL requirement was moved into a stand-alone statue (F.S. 373.042). These changes from the Model Water Code reduced MFLs to a more marginal role than was likely intended by the authors of the Code.

While water quantity policies were still evolving, water quality concerns took center stage. The 1970s saw the state acquire 141,640 ha of environmentally sensitive lands, often for the protection of adjacent water bodies. In 1975, the Department of Environmental Regulation (now, DEP) was formed and given the task of controlling pollution, permitting dredge and fill activities and supervising the WMDs. Water resource legislation in the 1980s included the 1983 Florida Water Quality Assurance Act and, in 1984, the Warren Henderson Wetlands Protection Act, which provided additional protection for wetlands by including criteria for the evaluation of dredge and fill permits (Purdum et al. 1998). Florida also passed the 1987 Surface Water Improvement and Management Act. This act focused on the restoration and protection of surface water bodies of regional significance.

The 1990s saw the continued support for public land acquisition and, by 1998, Florida had acquired more than 849,840 ha of land for conservation purposes. Combined with lands protected by federal and local programs or owned by private conservation groups, the total amounted to 3 million ha or 22 % of Florida (Purdum et al. 1998). Florida also continued to revisit water management decisions of the past, eventually passing the Everglades Forever Act, continuing restoration work around Lake Apopka, remaining engaged in discourse regarding the restoration of the Ocklawaha River, and with the help of the USACOE, initiated restoration of the Kissimmee River (Anderson and Rosendahl 1998, Bachmann et al. 1999, Canfield et al. 2000, Lowe et al. 1999, Purdum et al. 1998).

Perhaps the clearest indication of a growing recognition that water quantity as well as water quality was an important management concern comes from the difference between a statement made in 1985 and one a decade later in 1995. In 1985, the legislature adopted the state comprehensive plan, which stated:

> Florida shall assure the availability of an adequate supply of water for all competing uses deemed reasonable and beneficial and shall maintain the functions of natural systems and the overall present level of surface and ground water quality. Florida shall improve and restore the quality of waters not presently meeting water quality standards. (F.S. Chapter 187)

While this statement is reasonably strong, it is imprecise. Its only mention of water quantity is to note that Florida shall maintain an “adequate” supply to meet the needs of consumers who's proposed use must meet the permitting criteria of being reasonable and beneficial. It suggests that the function of natural systems and the “overall” level of water quality shall be maintained. This statement maintains the theme in the 1980s of protection of water quality, which it seeks to “improve and restore.” In 1995, a similar statement was made in the Florida Water Plan adopted by DEP:

> water must be managed to meet the water needs of the people while maintaining, protecting, and improving the state's natural systems. (DEP 1995)

This statement reflects a shift in perception and understanding and acknowledges that Florida's water resources are not boundless. It maintains that the goal of water supply is to meet the needs of the people of the state and that this must be accomplished in conjunction with the protection and improvement of natural systems. In this statement, no distinction is made between the need to manage water quantity and water quality. This shift in management goals seems to be indicative of the growing and prevailing need to address water quantity issues, which had been playing a larger and larger role in regional politics.

Florida has large populations in relatively small areas of the state. This has led to localized problems, especially in coastal areas where the local water supplies are most vulnerable to salt water intrusion and surface water bodies are frequently affected by groundwater levels. Highly localized demand raised concern in some counties that their water would be exported to more developed counties, leaving them with degraded environmental resources and reduced ability to enhance development. These factors, coupled with generally low surface water levels throughout the state in the late eighties and early nineties, led to a number of law suits and complaints being filed against many of the WMDs. These complaints from citizen groups and local governments led to a number of actions. In 1993, a decision involving the SJRWMD found that the water management district must establish MFLs and determined that it should be done within a reasonable time period. At the same time, the SFWMD responded to complaints filed against it by initiating MFL development for the Everglades. A few years later in 1996, the Florida Legislature responded to local concerns in the SWFWMD by requiring a priority list be established for MFL development within the district and that once developed, MFLs should be subject to independent scientific peer review (F.S. 373.042).

In that same year, a Governor's task force on water supply and funding was convened (Exec. Order No. 96-297). A core assumption adopted by the task force was that water demand was increasing and that the increased demand needed to be met (Matthews and Nieto 1998). Though the task force put forth approximately fifty recommendations, its primary theme was that increasing the supply of available water was necessary to ensure continued population and economic growth. This would lead to new responsibilities for all the water management districts and new protections for the environment.

The 1997 Law and Water Quantity

The recommendations from the Governor's task force provided the building blocks for legislation referred to as the “1997 Water Act”. This law represented the first major revision of state water policy since the Model Water Code was utilized to create Chapter 373 of the Florida Statutes in 1972. Perhaps the best summary of the changes in policy is taken from the statute itself, which was amended to “promote the availability of sufficient water for all existing and future reasonable-beneficial uses and natural systems" (F.S. 373.016 (2) (d)). This statement is significant because it denotes a fundamental shift in the state’s water policy. Until this juncture, the state's primary goal was the allocation of the existing water supply among uses and, recently, consumptive uses and natural systems. The Districts would now be responsible for allocating portions of available water between users and natural systems, and would also be charged with promoting expansion of the water supply, through water resource development.

Though other topics were covered, the 1997 changes to Chapter 373 were strongly focused on water quantity issues and consumptive uses. The new law more clearly defined the role of the WMDs and local governments in supplying water to the public. The water management districts were tasked with "water resource development" and technical support. "Water resource development" was defined as the formulation and implementation of regional water resource

management strategies and includes the task of data collection, construction and operation of structural components for flood control, surface and underground water storage, and ground water recharge augmentation (F.S. 373.019 (19)). Local governments, or utilities were charged with "water supply development", which was defined as design, planning, construction and operation of the infrastructure necessary to collect and distribute water for sale, resale or end use (F.S. 373.019 (21)).

The primary goal of this shift in policy, which aimed to increase the volume of water available, was to avoid pitting consumptive users against each other and against natural systems (Matthews and Nieto 1998). To accomplish these goals, the legislature stated that projects which create sustainable water sources but require financial assistance to complete, and projects that implement reuse, storage, recharge, or conservation of water be given priority funding by the water management districts (F.S. 373.0831 (4) (a) (3)). Further, if a priority project is expected to bring an MFL water body into compliance, it is given "first consideration" for funding assistance (F.S. 373.0831 (4) (b)).

Along with establishing funding priority for water resource development, the 1997 law also clarified the role of water resource planning in water management. The DEP is required to produce the Florida Water Plan in conjunction with the WMDs, regional water supply authorities, and others (F.S. 373.036). The Florida Water Plan includes the district Water Management Plans that are called for in the 1997 legislation. These plans are based on a 20-year planning horizon and are to be updated at least every five years (F.S. 373.036 (2)). The plans include, among other items, methodologies for establishing minimum flows and levels, water supply assessments, anticipated future needs, projections of water supply adequacy, and Regional Water Supply Plans which are developed for areas determined to have an insufficient

supply to meet the needs of projected reasonable-beneficial uses and to sustain the water resources and related natural systems (F.S. 373.036 (2) (b)). This last clause is important because it means that when the water needs of natural systems are projected to be inadequate (i.e., a minimum flow or level is expected to be violated), the WMDs must implement regional water supply planning. Incorporation of the five Water Management District water management plans into the Florida Water Plan provides for greater consistency among statewide and regional planning efforts.

Another important change to Chapter 373 in 1997 concerned development of minimum flows and levels (MFLs). While the Model Water Code was developed with MFLs as an integral part of consumptive water use permitting, Chapter 373 (F.S.) did not explicitly incorporate MFLs into the permitting process. Some efforts had been made by the WMDs to determine ecologically sensitive water levels for selected water bodies. For example, implementation of the SWFWMDs Lake Levels program, had led to the adoption of management levels for nearly four hundred lakes by 1996 (SWFWMD 1996). Yet MFLs remained an undefined and relatively abstract concept. In large part, this dilemma stemmed from the phrase "significant harm" which was included in the statute (F.S. 373.042). Because the language was changed from the original "harm" standard contained in the Model Water Code, it was clear that legislators intended to differentiate "harm" from "significant harm." Compounding the issue was the lack of guidance provided by the legislature regarding factors that should be considered when establishing MFLs. This is important because many of the state's surface water basins have been substantially altered, and a return to higher historic levels in these basins would require major restoration efforts and often result in the flooding of privately owned lands and structures, including homes. Another basis for the lack of action could be attributed to uncertainty regarding the purpose of

MFLs in the WMDs regulatory framework. Even if "significant harm" had been defined, the MFLs statute remained isolated from consumptive use permitting criteria, and thus served no immediately evident role in the district's regulatory charge.

In 1997, the Florida Legislature provided guidance regarding factors to be considered when establishing minimum flows and levels. The language the legislature sought was one of compromise and practicality. It sought to protect the water resources of the state from water withdrawals that would cause significant harm. However, they acknowledged that reestablishing historic water flows or levels was not necessarily desirable in all cases and that structural changes in the watersheds should be considered during the development of MFLs (F.S. 373.0421 (1) (a)). They also provided exemptions for water bodies smaller than 25 acres in size, those that have been constructed or ones that no longer serve their historic function (F.S. 373.0421 (1) (b)). A list of both cultural and scientific factors to be considered when establishing minimum flows or levels was developed, and incorporated into the Florida Administrative Code (Ch. 62-40.473 F.A.C.). Identified factors include recreation, fish and wildlife habitats and passage, estuarine resources, maintenance of freshwater storage and supply, aesthetic and scenic attributes, filtration and absorption of nutrients, water quality, and navigation. However, determination of the precise methodology for establishing MFLs was left up to each WMD and has, to date, resulted in the development of different approaches for establishing minimum flows and levels.

The 1997 Water Act also provided criteria for actions to be implemented when a minimum flow or level is not met or projected to be unmet in the next 20 years. The statute directs that the DEP or the WMD governing boards shall implement a recovery or prevention strategy, which includes the development of additional water supplies and conservation concurrently with, to the extent practical, reductions in permitted withdrawals (F.S. 373.0421 (2)). This strategy became

part of the regional water supply plan and, thus, eventually the Florida Water Plan. It is this language, from F.S. 373.0421 (2), that explicitly gave great weight to the minimum flows and levels developed by the water management districts. Violation of a flow or level can result in reduction of permitted withdrawals, and by extension, denial of proposed withdrawals that are projected to cause a violation of a minimum flow or level. Thus, the 1997 statute corrected a variance between the minimum flows and levels requirement and consumptive water use permitting. Matthews and Nieto (1998) pointed out that the WMDs must attempt to develop alternative water sources in conjunction with any reductions in permitted withdrawals. They contended that combining the obligation to engage in environmental restoration with the requirement for water resource development should protect the environment without inequitably reducing water use or stunting economic development. Therefore, a balance between maximizing water resource benefits for both consumptive use and natural systems protection may be achieved.

Response to the 1997 Law

The mandate to give priority funding to water supply projects has been well implemented and, in fiscal year 2001, the five water management districts spent between 17.7 % of their total budget in the Northwest District and 40.1 % of their budget in the Southwest District with all five districts committing $287 million, or 26.9 % of their combined budget on water resource development (DEP 2000). In 2002 the total climbed to $344 million, representing 28.0 % of the combined WMD budgets. Fiscal year 2003 budgets included approximately $372 million for water supply activities (DEP 2003a). Funds budgeted between 2001 and 2006 are projected to exceed $1.4 billion (DEP 2002a).

The 1997 amendments to Chapter 373 require all five water management districts to implement regional water supply planning in areas where water supplies are inadequate to meet

the projected water needs on a 20-year horizon. Water demand in the state is expected to increase from approximately 27.2 billion L day^{-1} in 1995 to 34.8 billion L day^{-1} by the year 2020 (DEP 2002a). Based on this projected demand, four of the five water management districts anticipate water deficits in at least a portion of their jurisdictional boundaries and have been required to submit regional water plans to the Florida DEP. As of August 2001, all the required plans were complete (DEP 2002a).

While it will take years to measure the effectiveness of major water-resource planning efforts, there is some evidence to suggest at least partial success. Planning and funding priorities guide the districts towards water resource development goals, which will need to be achieved to meet future water demands while protecting Florida aquatic ecosystems. Planning has helped quantify the future needs and focus water supply development on cost effective solutions, including seawater desalinization and aquifer storage and recovery. While these technologies hold promise and are being actively developed, they have yet to fully reach their potential role in Florida's water supply. Other strategies such as reclaimed water and conservation efforts are currently contributing cost effective alternatives to potable water use (DEP 2002b). For example, reclaimed water systems in Florida supplied 2.2 billion L day^{-1} in 2002 and system capacity is currently in excess of 4.2 billion L day^{-1} (DEP 2003b).

While the 1997 Water Resource Act made considerable progress in clarifying the role that MFLs are to play in state water policy, it also left many technical questions involved in the development of MFLs unanswered. Considerable work has been done on lotic systems, such as rivers and streams. Much of this work centers on protection of habitat by identifying necessary flow regimes using tools such as Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation System (PHABSIM) (Poff et. al. 1997, Postel and Richter 2003, Richter et. al

1997). Work on MFL development for lentic systems is less extensive. Further complicating MFL development is the need to account for both natural systems and cultural values during development. Cultural factors, such as aesthetic and scenic attributes, are difficult to quantify and like many natural systems values, are related to and affected by numerous other factors, such as water quality.

While all five water management districts seek, through MFLs, to prevent significant harm to the natural systems in their region, those that have initiated the process are employing different approaches (Ch. 40C-8, 40D-8 and 40E-8, F.A.C.). While this process has not yielded a uniform methodology, it may be appropriate for each WMD to establish its own methods since each faces different challenges; some need to protect water resources that are not highly influenced by consumptive uses, while others must develop MFLs for water resources that are severely impacted by withdrawals. As of 2002, three of the five WMDs have established MFLs on a total of 132 lakes, 9 rivers and streams, 46 wetlands, 20 aquifers, and 2 estuaries (DEP 2003c).

One of the greatest strengths of the 1997 law has been tying compliance with MFLs to water planning, funding of water resource development and regulatory oversight of consumptive use. In the SWFWMD, this interaction between MFLs, planning, funding and water-use permitting is evident. Regional, public-supply wellfields in the Northern Tampa Bay area are believed partially responsible for reducing water levels in some area water bodies. To meet MFLs in the region, an agreement calling for a combination of permit reductions, water supply development, and funding assistance was entered into by the SWFWMD, the regional water supply authority (Tampa Bay Water), and its member governments. Specifically, the agreement required ground water withdrawals at 11 regional wellfields to be reduced, in stages, from 158

mgd to 346 mgd by December 31, 2007. An intermediate reduction to 121 mgd was set for December 31, 2002 and has been met. To help offset reductions of wellfield pumping, 85 mgd of new water supply will be needed. The SWFWMD is providing, following funding priority directives, up to $183 million in funding assistance between 1995 and 2007 for alternative water supply development (DEP 2000). Alternative source projects underway, include surface water source development, indirect potable reuse, and seawater desalination.

Summary

The 1997 Water Act improved and enhanced the tools available to water managers and provided needed emphasis on water quantity and consumptive-use issues (Hamann 2001). The minimum flows and levels component asks the question, presuming we are going to harvest as much as water as we can, "How much can we harvest without significantly harming the natural resources of the state?" The planning requirements ask managers to determine where projected shortages may be expected during the next 20 years, and how the shortfalls can be met with alternative sources and conservation efforts. The priority-funding requirement attempts to assure that the alternative sources identified in regional and state plans receive necessary economic support.

The challenge, as we move forward, is for scientists, engineers, policy makers and citizens to respond to the 1997 legislation with ingenuity. The groundwork for future success has been established through the legal acknowledgement of clean water as a limited resource. When establishing consumptive-use limits, managers must consider scientific parameters such as absorption of nutrients and estuarine resources, as well as cultural parameters such as recreation, aesthetics, and scenic attributes. Water resource managers and policy makers must also determine what constitutes "significant harm", and identify the "practicable" steps needed to

develop alternative water resources to offset withdrawal reductions. Thus far, Florida has responded to these challenges.

Conclusions

In keeping with the 1972 vision of regional water management, the 1997 legislation retained flexibility for each of the water management districts to address regional water resource issues. The 1997 legislative changes have directly impacted state water management by mandating the development of MFLs and assuring that they are met by tying them to water planning, funding of water resource development and regulatory oversight of consumptive use. Planning has helped quantify the future needs and focus water supply development on cost-effective solutions. The Water Management Districts' commitment to water supply planning is evident in the district budgets, which demonstrate a steady increase in funding for water supply projects. Floridians have had the resourcefulness to ask, "How much water is there"? This means that water will no longer be a limited resource in some abstract or theoretical future, but will have real limitations defined for its use.

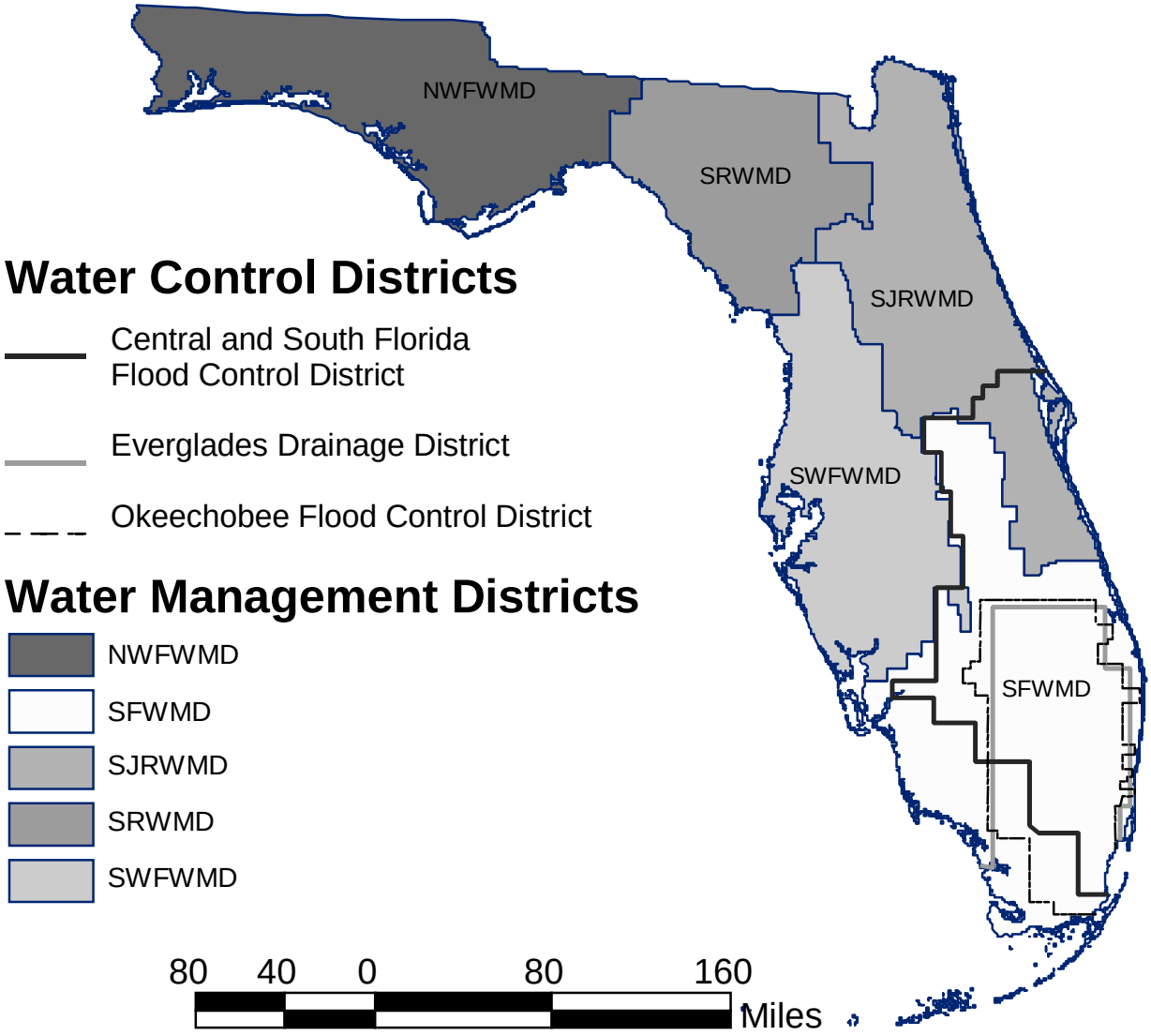

Figure 2-1. Map of the State of Florida showing the three early water management districts and the five current water management districts.

CHAPTER 3
CURRENT TECHNIQUES UTILIZED FOR THE QUANTIFICATION OF FLOODPLAIN HABITAT LOSS ASSOCIATED WITH REDUCTIONS IN WETSEASON FLOW

Introduction

Although floodplains have long been recognized as seasonally important riverine habitat, floodplain inundation has historically not been addressed in most minimum flow determinations (Postal and Richter 2003). Middleton (1999) also points out that regulation of water regimes has not always fully appreciated the interaction between floodplains and rivers via the flood pulse. Regulation of river flows can, however, result in decreased stage fluctuations and alteration of inundation patterns of floodplain wetlands (Poff et al. 1997, Woltemade 1997). Quantification of potential differences in floodplain inundation associated with differences between minimum flow requirements and natural hydrologic regimes should, therefore, be a critical component of regulatory programs that are intended to protect or restore riverine habitat.

Compared to instream evaluations of minimum flows requirements, there has been relatively little research done on river flows necessary for meeting the requirements of floodplain species, communities or functions. Junk et al. (1989) noted that the "driving force responsible for the existence, productivity, and interactions of the major river-floodplain systems is the flood pulse". Periodic inundation of riparian floodplains by high flows is closely linked with the overall biological productivity of river ecosystems (Crance 1988, Junk et al. 1989). Many fish and wildlife species associated with rivers utilize both instream and floodplain habitats. During inundation of the river floodplains, the habitat and food resources available to these organisms greatly expands (Ainsle et al. 1999, Hill and Cichra 2002, Wharton et al. 1982). Inundation during high flows also provides water and nutrients that support high rates of primary production in river floodplains (Brinson et al. 1981, Conner and Day 1979). This primary production generates large amounts of organic detritus, which is critical to food webs on the floodplain and

within the river channel (Gregory et al. 1991, Vannote et al. 1980). Floodplain inundation also contributes to other physical-chemical processes that can affect biological production, uptake and transformation of macro-nutrients, and development of wetland soils that are important to the overall function of the river ecosystem (Kuensler 1989, Stanturf and Schoenholtz 1998, Walbridge and Lockaby 1994, Wharton et al. 1982).

Floodplain vegetation development and persistence may not, however, necessarily depend wholly on inundation from the river channel. Groundwater seepage, hyporheic inputs, discharge from local tributaries, and precipitation can also lead to floodplain inundation (Mertes 1997). Recent work on the upper segment of the Peace River and the Alafia River in central Florida suggested that direct and continuous inundation of floodplain wetlands by river flows is insufficient to account for inundation needs of the dominant species found in the wetlands (SWFWMD 2002). However, because river channel-floodplain connections are important, can be influenced by water use, and may be a function of out-of-bank flows, it is valuable to characterize this connectivity. As with most other floodplain-related water management issues, technically sound development of minimum flows and levels requires such characterization.

The Southwest Florida Water Management District (District) has developed an approach which recognizes that fundamental to the development of minimum flows and levels (MFLs) is the realization that a flow regime is necessary to protect the ecology of the river system (Hill et al. 1991, Hupalo et al. 1994, Richter et al. 1996, Stalnaker 1990). The recognition of a seasonal flow regime as an essential component of this task led the District to develop minimum flow criteria for three distinct annual-flow periods; periods of low, medium and high flows. The District approach also acknowledges the effects of climatic oscillations on regional river flows

and includes identification of two distinct benchmark flow periods that are consistent with effects of the Atlantic Multidecadal Oscillation (AMO) (Enfield et al. 2001, Kelly 2004).

Because the methodologies employed by the District in the low and medium flow periods are commonly applied, consisting of components such as wetted perimeter analysis and physical habitat simulation analysis, they are not examined in the context of this chapter. Further, the focus of this paper remains on the connection between the floodplain and the river, which most frequently occurs during the high flow season. The resource management goal identified for the seasonally predictable wet period is maintenance of seasonal hydrologic connections between the river channel and floodplain to ensure floodplain structure and function

Minimum flows developed for the high flow season are intended to protect ecological resources and values associated with floodplains by maintaining hydrologic connections between the river channel and floodplain and maintaining the natural variability of the flow regime. These goals quantified through use of the Hydrologic Engineering Centers-River Analysis System (HEC-RAS) and the alteration of long-term flow records to evaluate floodplain feature inundation patterns associated with channel-floodplain connectivity.

The reduction in number of days of inundation is a temporal measure of loss based on how many days, annually, a specified water-surface elevation was reached compared to how often that elevation would have been reached if flow conditions had been reduced by a given amount. This temporal measure of habitat loss has been employed by the District in establishing MFLs on freshwater river systems in southwest Florida, during the high flow season of the year. It is applied by reducing historic flows iteratively until the percent of flow reduction that results in a 15% reduction in the number of days of inundation is found. The use of a percent of flow

reduction in establishing MFLs assures protection of the natural hydrograph (Flannery et al. 2002, Kelly at al. 2005a, b, c).

In Florida, regional Water Management Districts, by virtue of their responsibility to permit the consumptive use of water and a legislative mandate to protect water resources from "significant harm" have been directed to establish MFLs for streams and rivers within their boundaries (Section 373.042, Florida Statutes; Munson et al. 2005). The Southwest Florida Water Management District has developed methods for establishing MFLs that acknowledge the importance of seasonal flow regimes, including flows necessary for floodplain inundation. A temporal measure of habitat loss based on changes in inundation is used to develop minimum flows for seasonal high-flow periods. An alternative approach, employing a measure of spatial loss, by examining the change in top width at each cross section in the model under different flow conditions, is also explored. The use of a temporal measure of habitat loss for establishing MFLs during high flows is compared to the spatial loss of habitat for the same flow reduction. The applicability of both is discussed and the results compared to determine which is more restrictive in terms of allowable flow reduction.

The Alafia River, Myakka River and Peace River are used in this chapter to illustrate the temporal approach to quantifying habitat change associated with temporal difference in floodplain inundation patterns (Figure 3-1). All three rivers are located in southwest Florida. The Alafia River originates as a series of creeks that combine to form two branches of the Alafia River know and the North Prong and the South Prong. The North prong drains a swampy area and is characterized by low-lying wetlands. The South Prong is drains a highly mined area and is more incised. The Alafia River downstream of the confluence is more highly incised as well. The Alafia River above the Lithia gage (USGS# 02301500) drains approximately 335 mi$^{\wedge 2}$. The

Myakka River drains approximately 229 mi^2 above the Sarasota gage (USGS# 02298830). The Myakka River is a shallow river with broad flat floodplains. Two wide shallow lakes are near the gage site as well as substantial grass prairies. It is the lease incised of the three rivers studied. The Peach River at Arcadia gage (USGS# 02296750) captures approximately 1,392 mi^2 of the Peace River watershed. The channel is well defined upstream of Arcadia and widens downstream of Arcadia. In some areas of the river the floodplain is over a mile wide.

Methodology

The District's approach to protection of flows associated with floodplain habitats, communities, and functions involves consideration of direct connection between the river channel and the floodplain. As part of this process, plant communities and soils were identified across river floodplains at a number of sites on the Alafia River, Myakka River, and Peace River in central Florida (Figure 3-1), and periods of inundation/connection with the rivers were reconstructed on a seasonal basis. These data were used to characterize the inundation of these communities/soils by out of bank river flows, and to develop criteria for establishing minimum flows for the seasonal period of high flows**.**

Floodplain cross-sections were selected based on the location of vegetation communities identified from the USGS Gap Analysis Program maps within the Alafia, Myakka, and Peace river corridors. Attention was also made of the location of shoals in the river in an attempt to capture the hydraulic control points in the model. Eight, twelve, and ten representative floodplain/vegetation cross-sections were established perpendicular to the river channel within dominant National Wetland Inventory vegetation types for the Alafia, Myakka, and Peace rivers, respectively. Cross-sections were established between the 0.5 percent exceedance levels on either side of the river channel, based on previous determinations of the landward extent of floodplain wetlands in the river corridor. Ground elevations were determined at 50-foot intervals

along each cross-section. Where changes in elevation were conspicuous, elevations were surveyed more intensively (Kelly et al. 2005a b c).

To characterize forested vegetation communities along each cross-section, changes in dominant vegetation communities were located and used to delineate boundaries between vegetation zones. At each change in vegetation zone, plant species composition, density, basal area and diameter at breast height (for woody vegetation with a diameter at breast height > 2.5 cm) were recorded. Soils were characterized within each vegetation zone as hydric, organic, peat, or mineral by obtaining at least three soil cores. The cores were examined to a depth ranging from 51-152 cm to classify the soils. Special consideration was placed on locating elevations of the upper and lower extent of mucky soils (> 20 cm in thickness) at cross-sections where they occurred (Berryman and Henigar 2004).

Steady-state HEC-RAS modeling was used to determine corresponding flows at a downstream gage that would be necessary to inundate specific floodplain elevations (e.g., mean vegetation zone and soils elevations) along the floodplain/vegetation cross-sections. Version 3.1.1 of the HEC-RAS model released by the U.S. Army Corps of Engineers Hydrologic Engineering Center in November 2002 was utilized for all three rivers. The HEC-RAS model is a one-dimensional hydraulic model that can be used to analyze river flows. For subcritical flows, it operates as a typical step-back model, resolving the energy equation between adjacent cross-sections. Profile computations begin at a cross-section with known or assumed starting condition and proceed upstream (US Army Corps of Engineers 2001). Models for each river were based on cross-sectional data collected by the United States Geologic Survey and the floodplain/vegetation data collected by the District (Hammett et al. 1978, Kelly et al. 2005 a, b, c, Murphy et al. 1978).

For development of minimum flows, the year is categorized into three distinct flow periods or "blocks". Based on flow records for long-term United States Geological Survey (USGS) gage sites at the Myakka River near Sarasota (USGS# 02298830), the Alafia River at Lithia (USGS# 02301500), the Peace River at Arcadia (USGS# 02296750), and the Hillsborough River at Zephyrhills (USGS# 02303000, The Hillsborough River was used to develop the season block for the region but is not otherwise discussed in this chapter), the seasonal blocks were determined as periods corresponding to dates when specific exceedance flows occurred. On an annual basis, a low-flow period, Block 1, was defined as beginning when the median daily-flow fell below and stayed below the annual 75% exceedance flow. Block 1 was defined as ending when the high-flow period, or Block 3, began. Block 3 was defined as beginning when the median daily flow exceeded and stayed above the mean annual 50% exceedance flow and ending when the flow fell below and stayed below the mean annual 50% exceedance flow. The medium-flow period, Block 2, was defined as extending from the end of Block 3 to the beginning of Block 1.

Between these rivers, there was little difference in the dates that each defined flow period began and ended (Table 3-1). Block 1 is defined as beginning on Julian day 110 (April 20 in non-leap years) and ending on Julian day 175 (June 24). Block 3 is defined as beginning on Julian day 176 (June 25) and ending on Julian day 300 (October 27). Block 2, the medium-flow period, extends from Julian day 301 (October 28) to Julian day 109 (April 19) of the following calendar year (Kelly et al. 2005a, b, c). Though the District has developed MFLs for all three blocks, this paper focuses on the criteria for developing minimum flow standards for Block 3, which runs from June 25 to October 27 of each year.

For development of MFLs, it is necessary to identify a benchmark period from which flow deviations may be evaluated. Often changing flow trends are presumed to be the result of anthropogenic stresses on a system. This is possibly because variation in flow is frequently assumed to be the result of random independently and identically distributed random variables such as rainfall in flood risk analysis (Olsen et al. 1999). However, the effect of multidecadal oscillation on river flow patterns must also be recognized as natural climatic variations. As Enfield et al. (2001) observe, the Atlantic Multi-decadal Oscillation has a pronounced effect on rainfall in the continental United States and wet-season rainfall in peninsular Florida is negatively correlated with the Atlantic Multi-decadal Oscillation (McCabe and Wolock 2002). Kelly (2004) examined stream flows in Florida and identified a step-trend similar in timing to the step-trend describing the AMO (Enfield et al. 2001). This resulted in the identification of two benchmark periods, one from 1940-1969 and one from 1970-1999, which are characterized by relatively higher and lower wet season river flows in peninsular Florida, respectively. For determination of minimum flows, records from both benchmark periods are analyzed, and used to develop percent-of-flow reduction criteria. Minimum flows are determined by calculating the percent flow reduction for each benchmark period that would result in no more than a 15% reduction in habitat. For the Block 3 period, this means identifying the flow reduction that would result in no more than a 15% loss in the number of days of days that floodplain features are inundated by the river, during each of the two benchmark periods and utilizing the more limiting of the two.

In establishing minimum flows, the District defines a 15% change in habitat availability as a criterion for identifying significant harm, or unacceptable change. For the high-flow period or Block 3, this change is expressed as a temporal difference in the number of days specific water

surface elevations are reached. Potential temporal change or reduction in the number of days of direct connection between the channel/floodplain at the floodplain/vegetation cross-sections on the Alafia, Myakka and Peace rivers was estimated through the alteration of the historic flow record and the HEC-RAS models. Target elevations corresponding to features of interest, such as the median elevation of cypress swamps or the top of the river banks, were identified during the vegetative surveys. The HEC-RAS model was then used to determine the flow necessary at the downstream gage to inundate the features with flow from the river. The HEC-RAS model thus allows the elevations, identified at different transects, to be compared as the flow required at the gage site, to reach the corresponding elevation at the upstream cross-section where the elevation was identified. The daily historic record from the gage site was then examined. All days during the flow period of interest were checked to determine if the flow of interest was exceeded. The total number of days during each year of the historic record that the flow of interest was reached or exceeded were then tallied. Because the HEC-RAS model estimates the water surface elevation at cross sections, based on flows at the down stream gage, the reduction in the total number of days a flow is exceeded is equivalent to the reduction in total number of days that the corresponding water surface elevation is exceeded, at any cross section. The flow record was then reduced incrementally, until the percent flow reduction required to reduce the number of days a flow was reached or exceeded was reduced by 15 percent.

A measure of spatial loss of habitat at each cross-section was also estimated using the HEC-RAS model output and historic flow records. For each flow profile calculated in the model, the top width (linear distance in a cross section of water's edge to water's edge) at each cross section is derived. The sum of top widths at all cross sections in the model is computed for each flow profile. This provides an estimate of the area inundated. Once top width was

calculated for each profile, the relationship between top width and flow was plotted. A 15% reduction was then made to the top width at each flow profile in each model. The generated relationships between top width and flow were then used to calculate the flow required at the downstream gage sites to achieve the reduced top widths. The flow needed to achieve the non-reduced top width and the flow required to maintain the top width minus 15% were then compared to determine the percent of flow reduction required to reduce the top width by 15 percent.

Results

The vegetative surveys on the Alafia, Myakka and Peace rivers resulted in the identification of different features of interest on each river. For the Alafia River, elevations of eight floodplain features were identified at each of the eight vegetative cross-sections where they occurred (Table 3-2). For the Alafia River, the downstream gage at which flow requirements were compared is the USGS Alafia gage at Lithia (USGS# 02301500). Flow requirements, for inundation of each feature ranged from 22.2 m^3s^{-1} to reach the floodplain wetted perimeter inflection point to 64.2 $m^3 s^{-1}$ to reach the low bank elevation for inundation of both sides of river floodplain. Relatively high standard deviations, for the required flows, indicate that the flow requirements for some features differed greatly among cross-sections. Flow reduction resulting in 15% fewer days of inundation for the floodplain features, ranged from 5% for the low-bank elevations and highest floodplain vegetation class to 9% for the highest swamp class and floodplain wetted perimeter inflection point. Comparison of percent-of-flow reductions, associated with the temporal loss of feature inundation between the two benchmark periods, indicate that the 1970 to 1999 benchmark period provided the more conservative flow reduction (Kelly et al. 2005a).

For the Myakka River, the median elevations of six vegetative zones (i.e., Oak-Palm Wet Hammock and Panicum Marsh) as well as six physical characteristics (i.e., Lowest Bank Elevation to inundation both sides of river floodplain and Median elevation of hydric soils) were identified at each of the 12 vegetative cross-sections, when they occurred. For the Myakka River the downstream gage at which flow requirements were compared is the USGS Myakka River near Sarasota gage (USGS# 02298830). The downstream flow requirements for each identified feature are summarized in Table 3-3 and range from 0.9 $m^3 s^{-1}$ to reach the median elevation of mixed marsh to 24.4 $m^3 s^{-1}$ to reach the median elevation of oak-palm wet hammock. Standard deviations are also presented and indicate that flow requirements of some features differ greatly among cross-sections, as noted in the Alafia River. The percentage by which reducing flow would result in 15% fewer days of the target flow being reached is also presented. Flow reduction resulting in 15% fewer days ranged from 8% for the median elevation of oak-palm wet hammock and the lowest bank elevation to inundate one side of the river floodplain to 68% for the median elevation of mixed marsh. This analysis was completed for each of the two benchmark periods and results were similar to those found for the Alafia River (Kelly et al. 2005b).

For the middle Peace River, 10 features, including both vegetative and physical, were utilized in characterizing the flood plain (Table 3-4). For the middle Peace River the downstream gage, at which flow requirements, are compared is the USGS Peace River at Arcadia gage (USGS# 02296750). The downstream flow requirements for each identified feature are summarized in Table 3-4 and range from 66.5 m^3/s to reach the mean elevation of mucky soils to 196.8 m^3/s to reach the 90^{th} percentile elevation of wet hardwood hammock. Standard deviations are also presented and indicate that some features' flow requirements differ

greatly among cross-sections, as was true for the Alafia and Myakka rivers. The percentage, by which reducing flow would result in 15% fewer days of the target flow being reached, is also presented. Flow reduction resulting in 15% fewer days ranged from 5% for lowest bank elevation to inundate both sides of the river floodplain to 10% for the mean elevation of mucky soils. This analysis was completed for each of the two benchmark periods and results were similar to both the Alafia River and Myakka River (Kelly et al. 2005c).

In establishing minimum flows for the high flow season on the Alafia, middle Peace, and Myakka rivers, Kelly et al. (2005a, b, c) did not select a single floodplain feature to protect. Rather, they noted that higher flows might require a slightly more restrictive standard than some of the indicators associated with low flows and that higher flows seem to consistently tend towards a reduction between 5% and 10% (Tables 3-2 to 3-4). To further investigate limiting factors associated with the river floodplains, plots of percent-of-flow reductions that would result in 15% losses in the number of days for which corresponding river flows were reached were produced for each river (Figure 3-2). The plots indicate that up to an 8%reduction in the flows necessary to inundate floodplain features of the Alafia and middle Peace rivers, including those features not identified, would result in no more than a 15% reduction in the number of days the features are inundated. Similarly, it was determined that a 7% reduction in flow in the Myakka River, during the high-season flows, would not reduce the number of days of floodplain-river connection by more than 15%. This measure of temporal loss of habitat is central to the approach taken by the District in establishing MFLs to protect the river-floodplain connection during the high flow part of the year.

In examining all three rivers it is evident that as flows increase, the percentage by which the flow can be reduced, without lowering the number of days that flow is reached, is reduced. It

is useful to normalize the flow by looking at flow per watershed area. Percent-of-flow reductions that would result in 15% losses of the number of days that river flows reached a given flow plotted against flow per watershed area, are presented in Figure 3-3. Power trends were fit to each curve. The trend lines and the data points for all three rivers are similar when plotted together (Figure 3-3).

Utilizing the HEC-RAS model, the spatial loss associated with decreased flows was determined. Specifically, the flow reductions, resulting in a 15% loss of top width, were calculated. Percent of flow reductions, required to achieve a 15% loss of spatial habitat, were plotted versus flow per square mile of watershed above the gage and again power trends were fit to the data (Figure 3-4). For each river, the relationship between spatial loss and flow resembles the relationship between temporal loss and flow, in so far as, at low flow, a high percentage of flow reduction is required to result in a 15% decrease in top width. The fraction of flow required to effect a 15% loss in top width, is reduced as flow increases until trending slightly upwards at the highest modeled flows.

However, plots of the percent of flow reduction required to effect a 15% loss of spatial habitat versus the percent of flow reduction required to effect a 15% loss of temporal habitat indicate that for the range of flows examined, temporal loss is a more restrictive measure of habitat loss on these three rivers than spatial loss (Figure 3-5). A 15% loss of temporal habitat is associated with less of a flow reduction than a 15% loss of spatial habitat, as estimated by top width.

Discussion

The goal of an MFL determination is to protect the aquatic resource from significant harm due to water withdrawals. An MFL was broadly defined in the enacting legislation as "the limit at which further withdrawals would be significantly harmful to the water resources or ecology of

the area." (F.S. Chapter 373.042, Munson et al. 2005). What constitutes "significant harm" was not defined. The District has identified loss of flows associated with fish passage and maximization of stream bottom habitat exposure as significantly harmful to river ecosystems. Significant harm can also be defined as quantifiable reductions in the amount of available habitat (Gore et al. 2002).

Determining the amount of habitat loss, or deviation from a benchmark, that a system is capable of withstanding is based on professional judgment. In establishing MFLs, the SWFWMD recognized that the Instream Flow Incremental Methodology (IFIM) involves a negotiated threshold to be used as an acceptable measure of habitat loss (Bovee et al. 1998). Gore et al. (2002) note that instream flow analysts often consider a loss of more than 15% habitat, as compared to undisturbed or current conditions, to be a significant impact on a population or assemblage when employing Physical Habitat Simulation (PHABSIM) analysis. With some exceptions (e.g., loss of fish passage or wetted perimeter inflection point), there are few clearly delineated break points which can be relied upon to judge when "significant harm" occurs. Hill and Cichra (2002) noted that loss of habitat in many cases occurs incrementally as flows decline, often without a clear inflection point or threshold.

The District employed a threshold of a 15% change in habitat availability as a measure of significant harm for the purpose of MFL development. Although the District utilized a 15% change in habitat availability as a measure of unacceptable loss, percentage changes employed for other instream flow determinations have ranged from 10% to 33%. For example, in reference to the use of PHABSIM, Dunbar et al. (1998) noted that an alternative approach is to select a flow that provides protection to 80% of the habitat, which is equivalent to a 20% loss. Jowett (1993) used a guideline of one-third loss of existing habitat at naturally occurring low flows, but

acknowledged that no methodology exists for the selection of a percentage loss of "natural" habitat, which could be considered acceptable. The state of Texas utilized a target decrease of less then 20% of the historic average of habitat area in establishing an inflow requirement for Matagorda Bay (Texas Parks and Wildlife 2005).

For establishment of minimum river flows, the District has proposed the use of a percent of flow approach, which identifies the percentage by which a flow may be reduced before the river system is significantly harmed. This approach preserves natural flow patterns by protecting the inherent variability of natural flow regimes. The approach accounts for flow seasonality, by identifying three distinct annual flow seasons and identifying different habitat measures to be protected during each season. Two distinct benchmark periods, with characteristically higher and lower flows were used to analyze all measures of habitat loss to assure protection during both phases of the climate cycle associated with the north Atlantic Ocean.

In examining the loss of temporal habitat on the three rivers, the comparison in Figure 3-3 suggests that these three rivers respond in a similar fashion to reduced flows. This could be interpreted as the three rivers having similar flow distribution patterns during the wet season and thus showing similar responses to declining flows. This is probable because rainfall drives wet-season flows and since these three rivers are all located in central Florida, it might be expected that some similarity in watershed-wide rainfall over the period of record exist (at least 60 years in all three cases). The use of spatial loss instead of temporal loss did not provide a similar response among rivers (Figures 3-3 and 3-4). Though somewhat similar, there is considerably more variation in the plots of spatial loss than those of temporal loss. This is likely due to the addition of morphology into the calculation, albeit implicitly. While rainfall drives the wet-season flow distribution, floodplain morphology also plays a direct role in calculating loss.

In comparing the flow reduction required to produce a 15% spatial loss with the flow reduction required to produce a 15% temporal loss, it was found that a 15% temporal loss occurred consistently at a smaller reduction in flow (Figure 3-5). This does not specify in an ecological sense how the two different measures relate though it does indicate that, on these three rivers, the temporal measure is more conservative with respect to protection of natural flows.

Summary

For determination of MFLs the District has chosen the measure of temporal loss as a measure of habitat change. This analysis requires that the relation between the target elevation at a specific point in the river corridor and the flow at a long-tem gage is reasonably well understood. It also requires long-term gage data. The spatial analysis requires the acquisition of cross-sections and the development of a model to calculate the habitat loss. The resolution of the cross-sections and the use of top-width as a proxy for inundated area limit the accuracy of the analysis. For rivers currently being studied for MFL development improved topographical data (i.e., LiDAR) is being collected. This will allow the development of digital elevation models and improved spatial analysis of floodplain inundation. Comparisons of these improved methods with the current methods should be performed. As instream flow professionals we are often asked to protect the environment from harm. However, ultimately what is measured is change and how much change constitutes harm must be determined. Therefore, we must know how different measures of change relate to each other.

Table 3-1. Beginning Julian days for the Wet and Dry periods (Blocks 1 and 3) and ending date for the Wet period at four different gage stations in the SWFWMD.

	Begin Block 1	Begin Block 3	End Block 3
Alafia at Lithia	106	175	296
Hillsborough at Zephyrhills	112	176	296
Myakka at Sarasota	115	181	306
Peace at Arcadia	110	174	299
Mean	110	176	300

Table 3-2 Mean flow requirement at the USGS Alafia River near Lithia gage needed to inundate floodplain features, and percent of flow reductions associated with no more than a 15% reduction in the number of days that the required flows are equaled or exceeded for two benchmark periods (1940 through 1969 and 1970 through 1999).

Floodplain Feature Identified for Development of Minimum Flows and Levels for the Alafia River	Mean (SD) Flow Requirements (m^3/s)	Percent-of-Flow Reduction from 1940 through 1969	Percent-of-Flow Reduction from 1970 through 1999
Low bank elevation	33 (17)	10	5
Low bank elevation for inundation of both sides of river floodplain	64 (18)	6	5
Highest floodplain vegetation class	101 (9)	9	5
Mean elevation of swamp classes	28 (12)	10	7
Highest swamp class	42 (22)	9	9
Floodplain wetted perimeter inflection point	22 (8)	12	9
Mean elevation of hydric soils	29 (11)	9	8
Highest elevation of hydric soils	58 (36)	5	7

Table 3-3. Mean flow requirements at the USGS Myakka River near Sarasota gage needed to inundate floodplain features, and percent of flow reductions associated with no more than a 15% reduction in the number of days that the required flows are equaled or exceeded for two benchmark periods (1940 through 1969 and 1970 through 1999).

Floodplain Feature Identified for Development of Minimum Flows and Levels for the Myakka River	Mean (SD) Flow Requirements (m^3/s)	Percent-of-Flow Reduction from 1940 through 1969	Percent-of-Flow Reduction from 1970 through 1999
Lowest bank elevation to inundate one side of the river floodplain	9 (8)	15	8
Lowest bank elevation to inundation both sides of river floodplain	16 (19)	16	11
Median elevation of oak-palm wet hammock	24 (12)	13	8
Median elevation of oak-popash wet hammock	13 (5)	16	9
Median elevation of popash swamp	10 (3)	20	15
Median elevation of paragrass marsh	9 (4)	21	15
Median elevation of mixed marsh	1 (1)	72	68
Median elevation of panicum marsh	18 (12)	16	11
Median elevation of mucky soils	20 (16)	15	10
Median elevation of hydric soils	18 (13)	16	11
First major low inflection point on wetted perimeter	13 (8)	17	11
First major high inflection point on wetted perimeter	23 (26)	15	9

Table 3-4. Mean flow requirements at the USGS Peace River at Arcadia gage needed to inundate floodplain features, and percent of flow reductions associated with no more than a 15% reduction in the number of days that the required flows are equaled or exceeded for two benchmark periods (1940 through 1969 and 1970 through 1999).

Floodplain Feature Identified for Development of Minimum Flows and Levels for the middle Peace River	Mean (SD) Flow Requirements (m^3/s)	Percent-of-Flow Reduction from 1940 through1969	Percent-of-Flow Reduction from 1970 through 1999
Lowest bank elevation to inundate one side of the river floodplain	115 (78)	7	8
Lowest bank elevation to inundate both sides of river floodplain	158 (57)	6	5
90^{th} Percentile elevation of river terrace vegetation	123 (47)	7	7
90^{th} Percentile elevation of wet hardwood hammock	197 (72)	7	6
Mean elevation of river terrace vegetation	112 (66)	8	8
Mean elevation of wet hardwood hammock	160 (61)	7	6
Mean elevation of cypress swamp	82 (25)	12	8
Mean elevation of hardwood swamp	83 (34)	12	7
Mean elevation of mucky soils	66 (31)	13	10

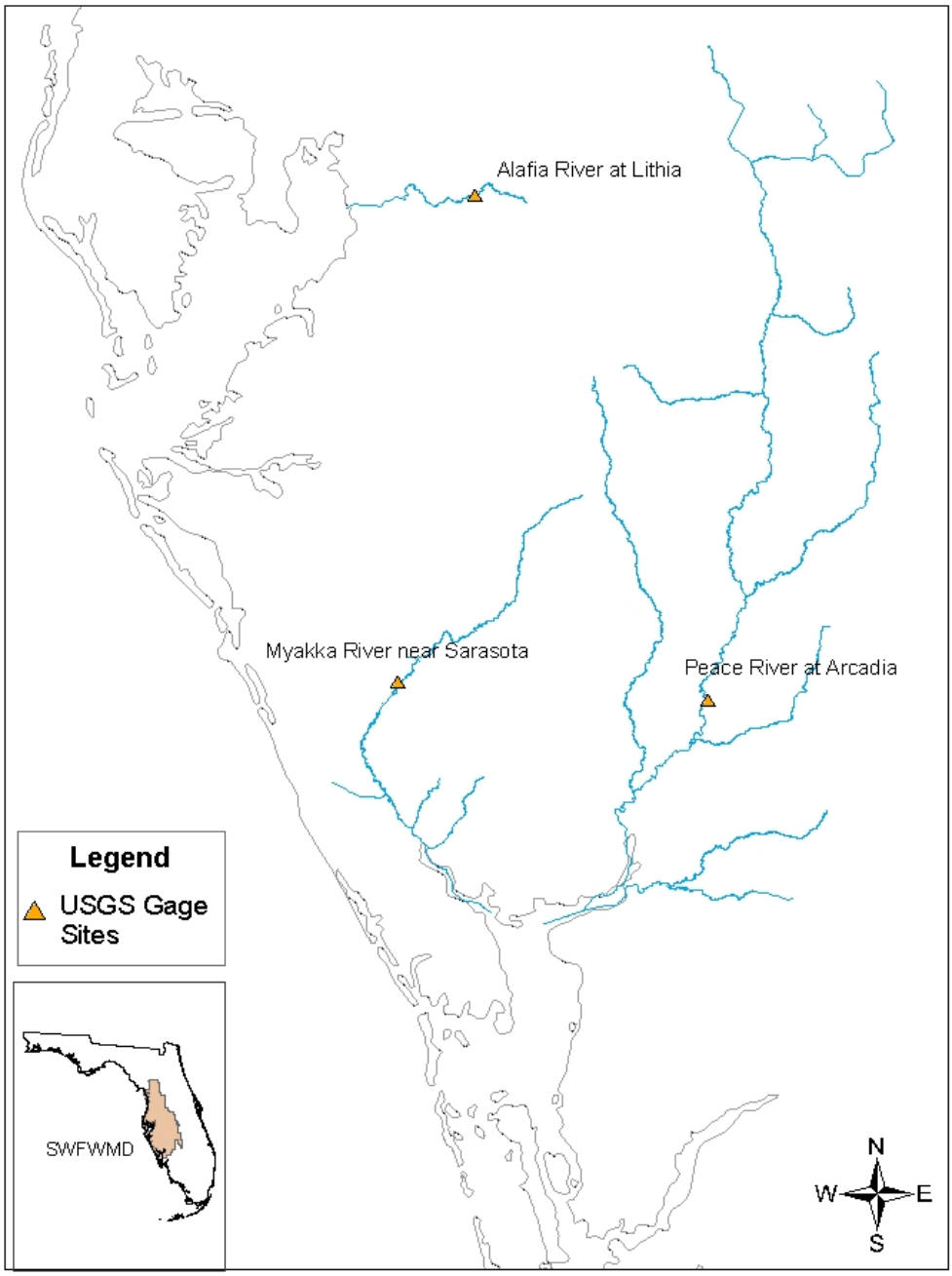

Figure 3-1. Map of the Southwest Florida Water Management District showing the Alafia, Peace and Myakka rivers and the USGS gage locations used in this study on each.

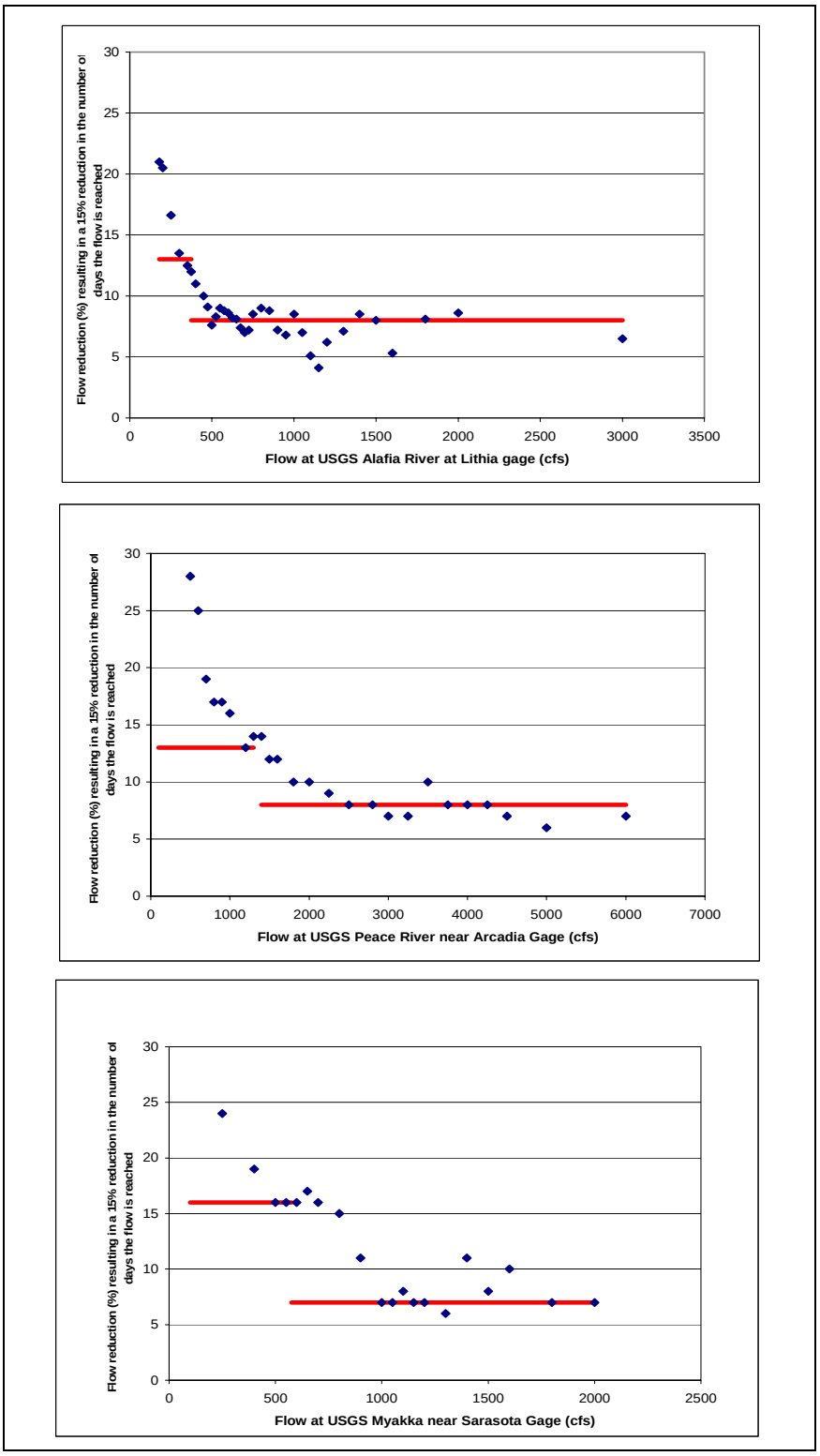

Figure 3-2. Percent-of-flow reductions that result in a 15% reduction in the number of days that flows on the Alafia, middle Peace, and Myakka rivers are reached. Horizontal lines represent the flow reduction standards chosen by the SWFWMD for each river. Graphs are adapted from Kelly et al. 2005a, b, and c.

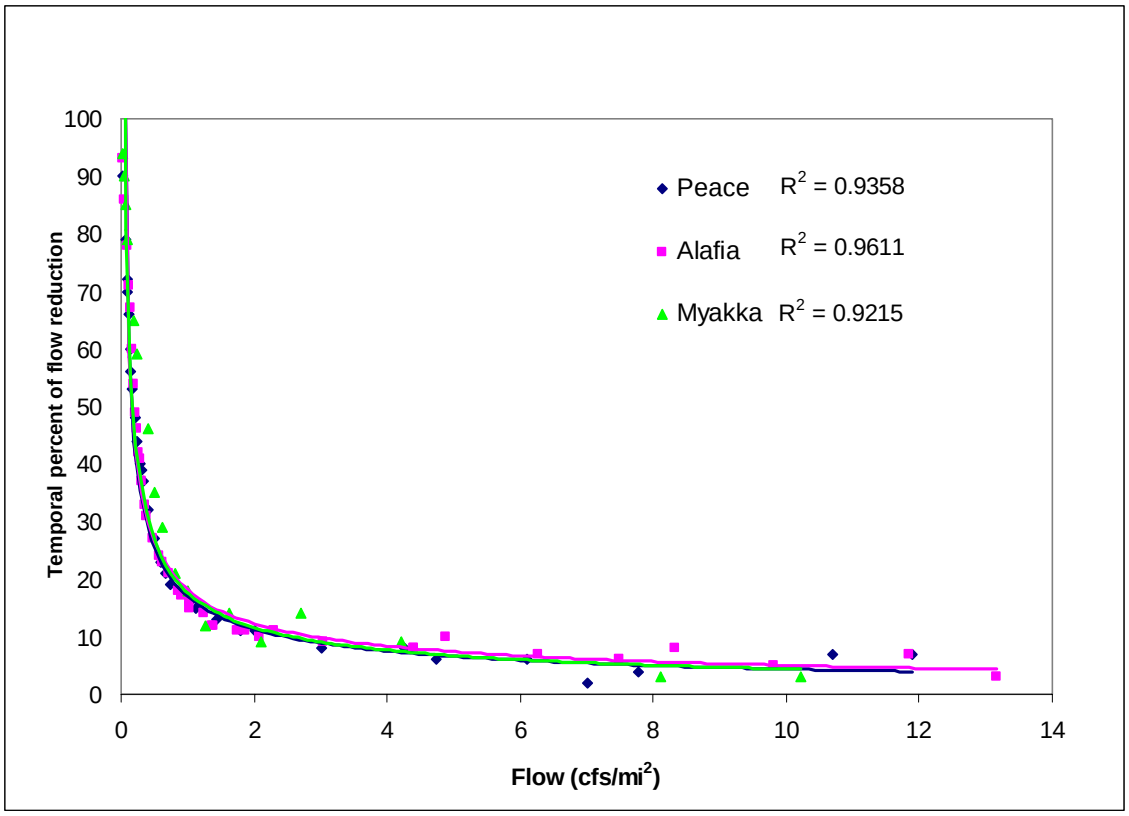

Figure 3-3. Percent-of-flow reductions that result in a 15% reduction in the number of days that flows on the Alafia, middle Peace, and Myakka rivers are reached. Gage flow has been divided by the area of the watershed above the gage and power curves fit to the data for each river.

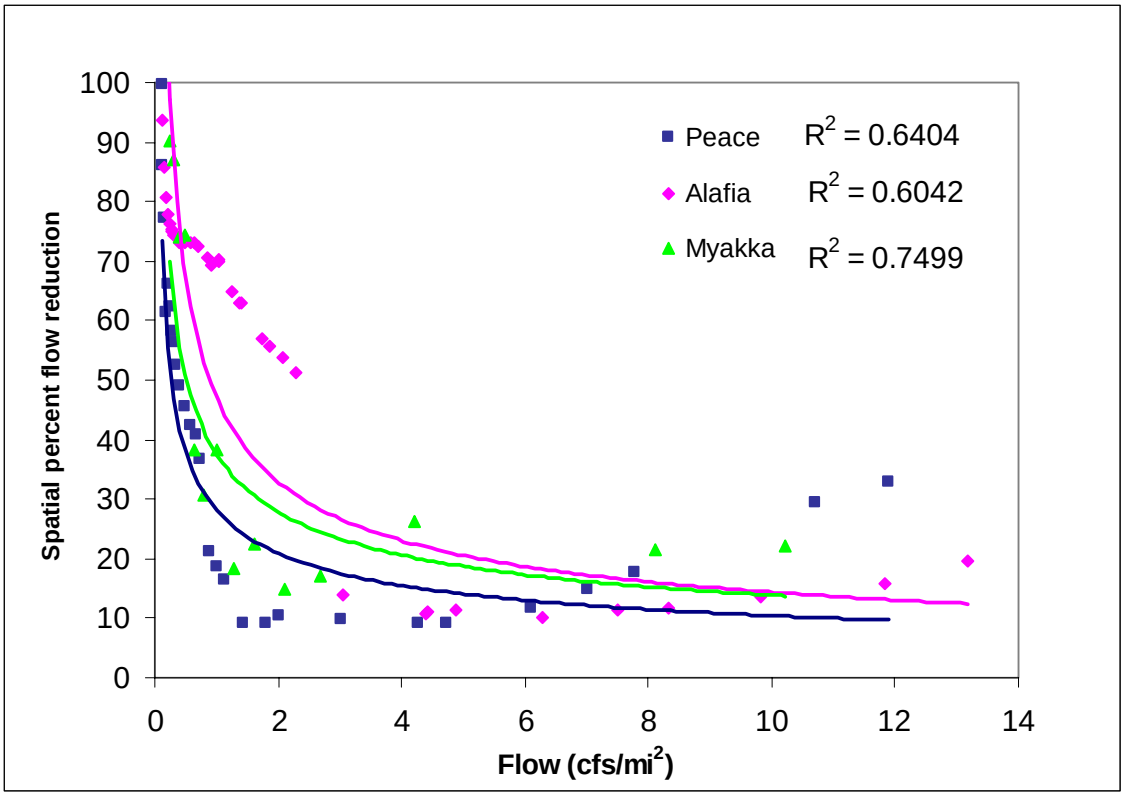

Figure 3-4. Percent flow reduction required to result in a 15% loss of top width plotted against flow for the Alafia, Myakka, and middle Peace rivers.

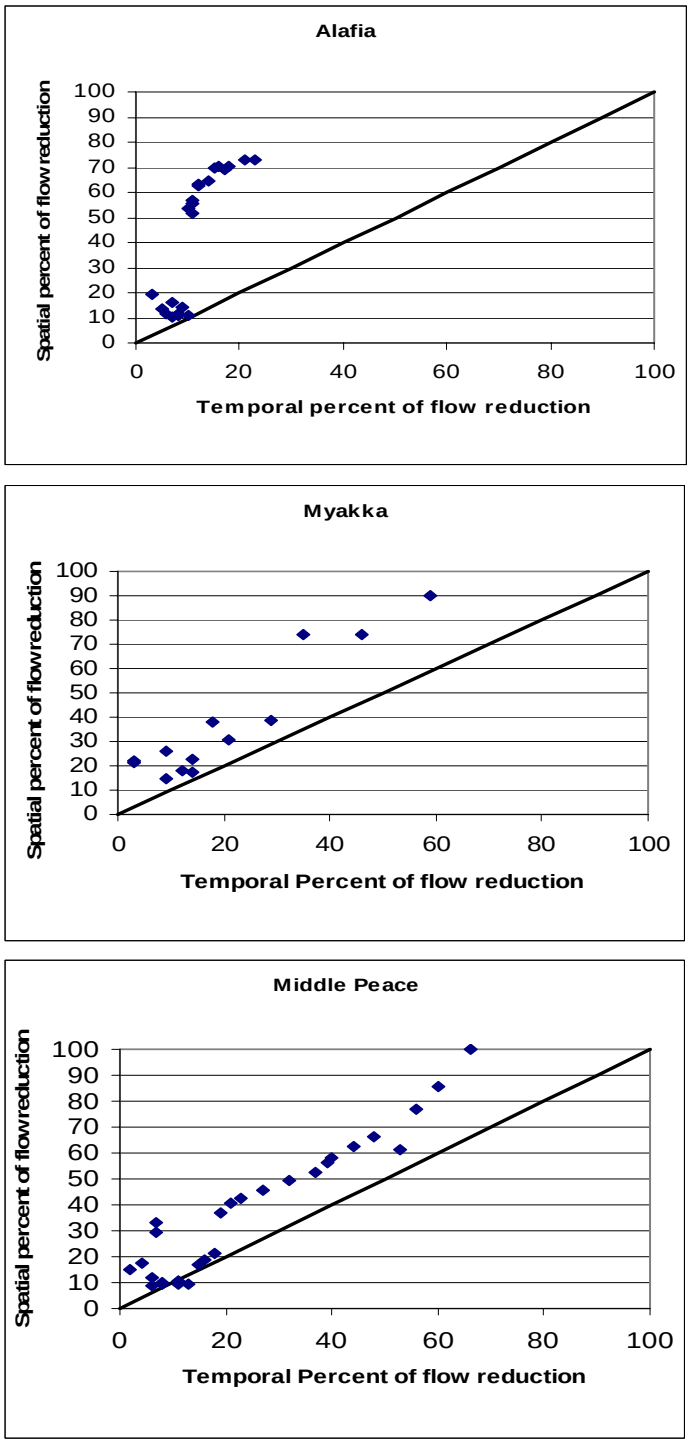

Figure 3-5. Percent of flow reduction, corresponding to a 15% spatial loss (measured as the summation of cross-section top width), plotted against the percent of flow reduction, corresponding to a 15% temporal loss (measured as a loss of days during which the river historically reached a specific flow), for the Alafia, Myakka, and middle Peace rivers.

CHAPTER 4
THE UTILIZATION OF GEOGRAPHIC INFORMATION SYSTEMS IN DETERMINING FLOODPLAIN INUNDATION FOR MFL DEVELOPMENT

Introduction

In its response to the 1997 law requiring the development of minimum flows and levels (MFLs) in the state of Florida, the Southwest Florida Water Management District (District) has developed minimum flows and levels for multiple freshwater rivers (Munson et al. 2005). As part of its MFL development, the District has acknowledged the importance of the natural flow regime and attempted to preserve it through the use of a seasonally specific percent of flow reduction approach (Flannery 2002). The use of seasonally specific criteria to identify acceptable percent of flow reductions to be applied to each of a low, middle, and high flow period, addresses both the cyclical nature of the annual flow pattern and the natural variation of this pattern. Further, the use of multiple benchmark periods has served to recognize that longer-term climatic cycles effect flow variation on a multidecadal basis (Kelly 2004).

By establishing a seasonally specific, block approach to the development of MFLs, the District required the development of criteria for each block that identified an appropriate percent of flow reduction to be used during each of the three seasonal blocks. Development of criteria to be applied during the low flow block and the medium flow block was aided by methods currently employed in the establishment of instream flow requirements in other areas of the state. Specifically, the use of wetted perimeter, PHABSIM, and availability of snag habitat were employed in the development of low and medium flow criteria (Kelly et al. a,b,c 2005). Methods suitable for developing criteria for high season flow protection were less well documented and few examples were available.

Floodplain wetlands associated with river systems have been recognized as an important component of the river corridors ecologic community (Hughes and Rood 2003, Likens and

Bormann 1974). However, for many years, the importance of out-of-bank flows to the riverine ecosystems was not recognized by instream methods used to assess flow requirements (Middleton 1999). Methods such as the Tennant method or the use of wetted perimeter can be serviceable in the protection of the lowest flows. However, they deal predominately with between bank analyses and offer little to no protection for high flows, though both methods have been widely applied (Gippel and Stewardson 1998, Jowett 1997, Postal and Ricther 2003). While these methods offer valuable information for regulating the low end of the flow regime, it is necessary to measure and assess the flows required at the high end of the flow regime as well.

Munson and Delfino (2007) state that quantification of potential differences in floodplain inundation associated with differences between minimum flow requirements and natural hydrologic regimes should be a critical component of regulatory programs that are intended to protect or restore riverine habitat. The District has employed a method for establishing MFLs that acknowledges the importance of seasonal flow regimes, including flows necessary for floodplain inundation. The method employs the historic flow records and a temporal measure of habitat loss based on the reduction in the number of days specified flows are reached under various flow reduction scenarios. An alternative approach, employing a measure of spatial loss that examined the change in top width at each cross section modeled under different flow conditions, was previously explored in this dissertation (Munson and Delfino 2007).

Both spatial and temporal measures of habitat loss can be related to percent flow reduction in a river channel. However, as previously discussed, both serve as proxies to evaluate the extent of the river-floodplain connection. This connection has not yet been fully described on any river studied by the District because complicated floodplain geometry is being represented by a limited number of historic floodplain cross-sections derived from earlier studies. Though these

cross-sections represented the best available data, their limitations were recognized, especially with regards to in-channel accuracy.

This chapter describes the role that Geographic Information Systems (GIS), coupled with hydraulic models, can play in MFL development by providing high quality data concerning floodplain inundation under different flow scenarios. As Overton (2005) points out, riverine ecosystems benefit from spatial analysis since it provides temporally dynamic data in three spatial dimensions. This coupling of a one-dimensional hydraulic model and spatial information from GIS results in a powerful tool for relating variations in floodplain inundation with variations (or reductions) in river flow.

Study Area

The Braden River is the largest tributary of the Manatee River located in Southwest Florida (Figure 4-1). It drains approximately 215 km^2 and is composed of three distinct segments. The most downstream segment is an approximately 10-km long estuarine reach, which joins with the Manatee River near its mouth. Immediately upstream of this is another approximately 10-km reach of river impounded by a broad-crested weir, creating the Ward Lake reservoir. Above this is a 13-km segment of naturally flowing incised channel (DelCharco and Lewelling 1997).

The Braden River was selected for this study by virtue of its listing on the MFL priority list and because its size made it an efficient option for the utilization of new technology. The river has three USGS gage locations within the study reach. These include, from upstream to downstream, the Braden River at Lorraine (USGS# 02300029), the Braden River near Lorraine (USGS# 02300032), and the Braden River at Linger Lodge (USGS# 023000358).

Flows in the Braden River are less substantial than other rivers in the area. In part, this is due to the watershed, though development and attenuation in the watershed may play a role.

Flows do not exceed 100 cfs until higher than the 10% exceedance flow. This, combined with the incised nature of the channel and well-drained sandy soils, results in the expectation that there is little floodplain inundation except under the highest flows.

Methods

For development of an accurate digital elevation model (DEM), three-dimensional topographic data are required. For the Braden River, these data were gathered through the use of Light detection and Ranging (LiDAR). In 2005, a qualified photogrammetric firm conducted the LiDAR and orthophotography acquisition for the Braden River project. The flights utilized an ALS40 LiDAR system flying at 5000 ft with a 30-degree field of view and 20% side overlap. Acquisition of LiDAR data used a 2-m post spacing interval, digital one-foot orthophotographs and 3D breakline features necessary to meet a one-foot contour interval product. The vertical accuracy of the data was specified at 10 cm in homogeneous, unambiguous terrain. All LiDAR data were collected using the North American Vertical Datum of 1988 (NAVD88).

For the Braden River, a Triangular Irregular Network (TIN) was used as the digital elevation model. The TIN was generated from a combination of LiDAR data, break lines, and a limited number of surveyed cross-sections (Figure 4-2). The TIN was then used to generate a series of cross sections for export into the Hydrologic Engineers Centers-River Analysis System (HEC-RAS; Figure 4-3). Known water surface elevations were used as downstream boundary conditions and a rating curve, supplied by USGS, was used to calibrate to the USGS near Lorraine gage (USGS# 02300032). All elevations, associated with USGS gages, were converted to a NAVD88 standard when necessary. The model was considered calibrated when calculated values of water surface elevation were within 0.5 ft of the rated value.

Once the model was complete, data from the model were imported back into the GIS environment. Essentially, these data consist of the cross-section locations and ground elevations

from the model and water surface elevations associated with different flow profiles. In the case of the Braden River, the model generated flow profiles for twenty-one evenly distributed percent exceedance flows. For each of these flow profiles, a water surface elevation was calculated at each cross-section and represented in GIS as a series of lines at each cross-section with different elevation. So, each specified flow corresponds in GIS to a series of lines with elevation from which a second DEM can be generated in the form of a TIN. This TIN becomes a TIN of calculated water surface elevation based on the model.

Once both terrain surface elevation and water surface elevation models are generated, analysis can be performed in a GIS environment, which clips the water surface elevation model to the terrain model. The use of an extension to the GIS software titled GEO-RAS automates this process, resulting in a raster surface. A raster surface is a form of digital elevation model which uses a matrix of same size squares with each one having an elevation based on the elevation of the data points within its bounds. Raster cells do not slope, and thus all the area falling within a cell is assigned the same elevation. The new DEM, generated by subtracting the land surface from the water surface, is a water surface model where each cell represents a depth of water over the land surface (Figure 4-4). This allows for the estimation floodplain inundation in a river corridor based on three dimensional floodplain topology rather than two-dimensional cross-sections and intervening channel length.

Results

This study utilized a combination of LiDAR data and survey data to generate a DEM of the freshwater portion of the Braden River. This DEM provides useful information for the development of cross-sections in the hydraulic model. Further, the output from the model is used to generate a water surface profile in GIS and to analyze inundation patterns.

The LiDAR points, used to generate the model, were numerous and dense in the upland area of the digital elevation model. However, points were sparser in the forested portion of the floodplain wetland and in the river corridor itself. A typical bend in the river and the lack of corresponding LiDAR data within the floodplain are shown in Figure 4-5. This trend continued for the length of the study corridor.

In the downstream half of the study area, break lines were added along each bank. This results in an approximation of the floodplain area by defining the upland portion with LiDAR and the river's edge with a hard break line. This is useful in the TIN because it keeps the river channel well defined, even in the absence of high-density LiDAR data near the river. However, the more upstream portion of the study lacked these break lines and the river channel is more poorly confined in this portion of the DEM. Survey data also provided localized improvement of the topography TIN and resulted in better development of the DEM in areas where survey data augmented the LiDAR data. However, these data resulted in only localized improvements in the topography TIN.

The hydraulic model estimates an inundated area by calculating the area of a trapezoid. The trapezoid is bound by the water surface extent at two adjacent cross-sections. The distance between cross-sections is defined in the model. In a GIS environment, it is possible to estimate the inundated area between cross-sections by calculating the area where the water surface DEM is higher then the topography DEM (Figure 4-6). The inundated area calculated by GIS and HEC-RAS between two cross-sections is presented in Table 4-2.

Discussion

GIS to HEC-RAS

The use of LiDAR to augment survey data was initially viewed as a device for supplementing partial floodplain survey work. The concept was that cross-sections could be

established manually across the river and then, subsequently, those cross sections could be lengthened, and potentially, additional cross-sections could be added, which are generated from the LiDAR data. This was not the case with the Braden River.

Cross-sectional data aligned well with LiDAR-derived data where overlap occurred. The generated DEM was used to create cross-section lines, which were imported into HEC-RAS. The DEM allowed surveyed cross-sections to be lengthened and extended beyond the floodplain. However, the quality of the DEM in areas where the LiDAR data were sparse and survey data did not exist, resulted in cross-sections which were too poorly defined within the floodplain and river channel to be useful in a hydraulic model.

It should be noted that this was due not to inaccuracy in the data but to a localized lack of data. Relatively few additional data points would be needed to significantly improve the accuracy of the DEM. The acquisition of a thalwag alone would add considerable accuracy to the DEM. It should also be noted that the LiDAR data for the Braden River corridor were among the first collected in the SWFWMD and that specifications were far less rigorous than more recently collected data. Preliminary results from the Withlacoochee River indicate that 4-foot post spacing and newer systems are penetrating the floodplain canopy and providing regularly spaced data. The data in the floodplain is less dense than the non-canopy areas flown, but significantly improved over the Braden River data.

HEC-RAS to GIS

The utilization of output from HEC-RAS to model floodplain inundation were useful but fell short of creating really meaningful results. The focus of future studies should be on the generation of a high quality DEM of the terrain. This can be accomplished by supplementing the LiDAR data with hydrographic survey data. Hydrographic surveys can be accomplished through both manual and electronic means. A combination of sonar, survey and global positioning

satellite (GPS) methods can be used to define a thalwag and provide credible sub-surface data to be used in conjunction with LiDAR. As noted above, LiDAR capabilities have increased significantly in the past few years as increased demand has resulted in increased precision. It should be noted that because the water surface elevation TIN is limited in geographic range by the extent of the cross-sections, and because the bounding polygon, generated by the GIS extension, is defined by the cross-sections, those cross-sections should be chosen carefully.

HEC-RAS offers approximations of inundation based on trapezoidal areas (Figure 4-6). It should be noted that Figure 4-6 is conceptual since HEC-RAS uses channel length and not geographic distance as the distance between cross-sections. However, inundation, in a broader, more complex floodplain than the Braden River, would not necessarily be well modeled in this manner without a significant number of cross-sections to capture variability in the floodplain. The GIS and HEC-RAS estimates, for inundated area in the section of the Braden River shown in Figure 4-6, are presented in Table 4-2.

GIS in MFL Development

It has already been noted that historically instream-flow requirements have been focused largely on the low-flow portion of the flow regime. This is probably due in part to the complexity of floodplain hydrology. As Mertes (1997) noted, floodplain inundation does not rely solely on overbank flows from the associated river. GIS provides the opportunity, when coupled with high quality data, to analyze floodplain inundation more accurately than was previously practical. Initially, this can improve MFL development by allowing more accurate assessment of habitat changes associated with changes in flow.

Future Work

The purpose of this research was to generate a hydraulic model to be used in the development of a MFL for the Braden River and also to determine the usefulness of LiDAR data

and the role they can play in MFL determinations. The Braden River LiDAR data represent approximately 26 km^2 of area. Generated as part of a larger flight plan, the data generally cost approximately \$700/ km^2 to collect and process, though it can vary depending on the size and shape of the area to be flown. Data collection has begun on the Withlacoochee River, which includes approximately 310 km^2 of necessary data. Prior to an investment of that size, it was prudent to determine to what extent the data was useful and what subsurface data are necessary to generate high quality results.

This project demonstrated that LiDAR, combined with ground surveys, can be used to generate cross-sections for the development of a hydraulic model. However, the LiDAR is best used to supplement floodplain portions of a cross section. LiDAR alone results in insufficient instream data to generate an accurate cross-section. This research also demonstrated that where LiDAR data are sufficiently augmented with high quality instream and below canopy data, GIS can be used to predict inundation patterns and depths under different flow conditions.

LiDAR data for the Withlacoochee River will be coupled with a hydrographic survey to produce a highly accurate DEM for the length of the study corridor. The hydrographic survey will include a combination of electronic data collected with sonar and manually surveyed data. A thalwag of the river will also be included. The Withlacoochee River study will be the first major river in Florida to have a highly accurate DEM generated which will be used in future studies of the river including MFL development.

Table 4-1. Percent exceedance flows for the Braden River near Lorraine gage (USGS# 02300032).

Percent Exceedance (%)	Exceedance flows (cfs)
99	0.67
95	1.02
90	1.40
85	1.73
80	2.04
75	2.47
70	2.87
65	3.35
60	4.09
55	5.12
50	6.22
45	7.45
40	10.25
35	13.59
30	17.95
25	25.16
20	36.36
15	54.41
10	89.53
5	188.82
1	647.47

Table 4-2. Estimated acres of inundated land at different exceedance flows between two Braden River cross-sections shown in Figure 4-6.

Percent Exceedance	GIS Results (acres)	HEC-RAS Results (acres)
90%Ex	1.12	1.26
50%Ex	1.14	1.26
25%Ex	1.33	1.30
10%Ex	1.95	1.49
1%Ex	5.49	7.10

Figure 4-1. Location map of the Braden River in southwest Florida.

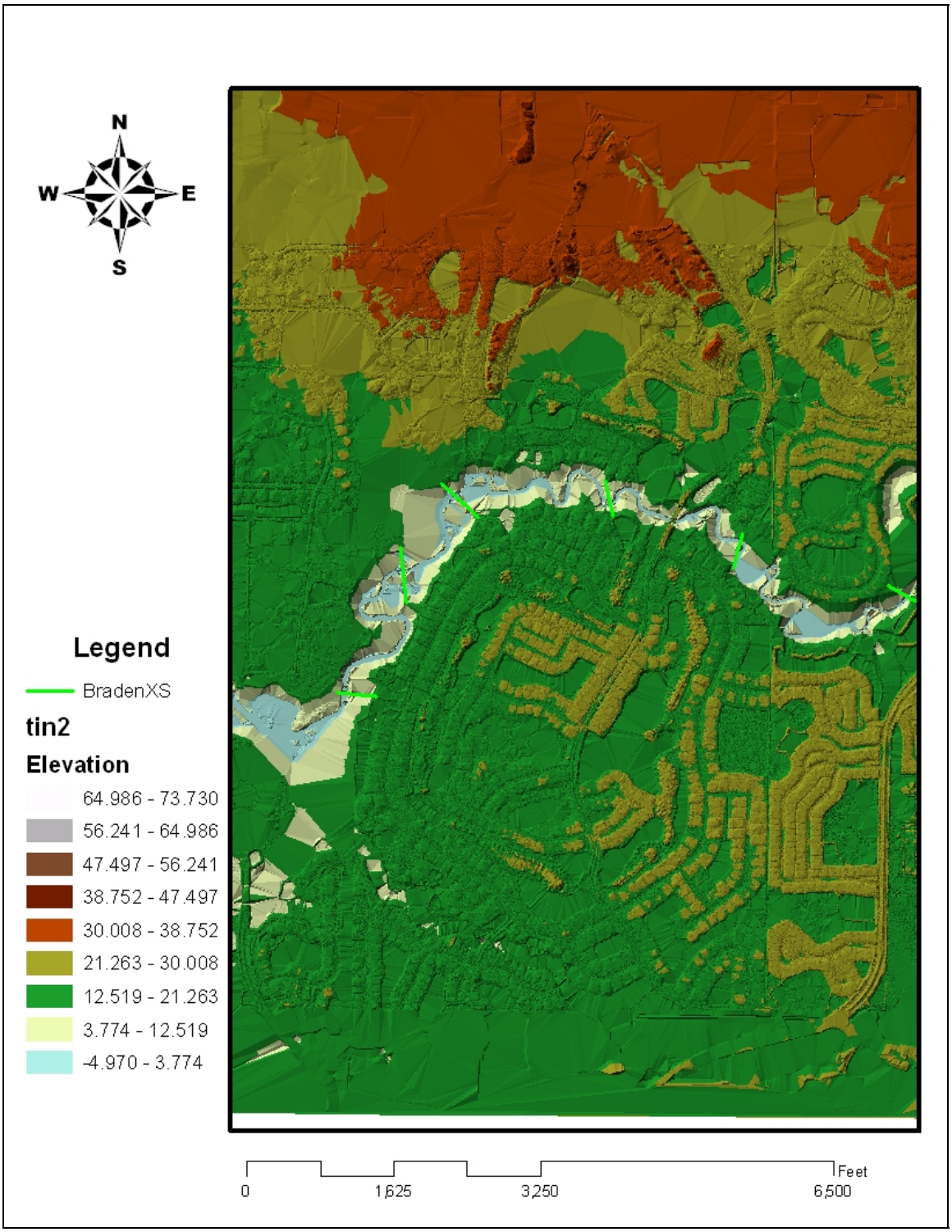

Figure 4-2. Portion of the digital elevation model generated of the Braden River, Florida.

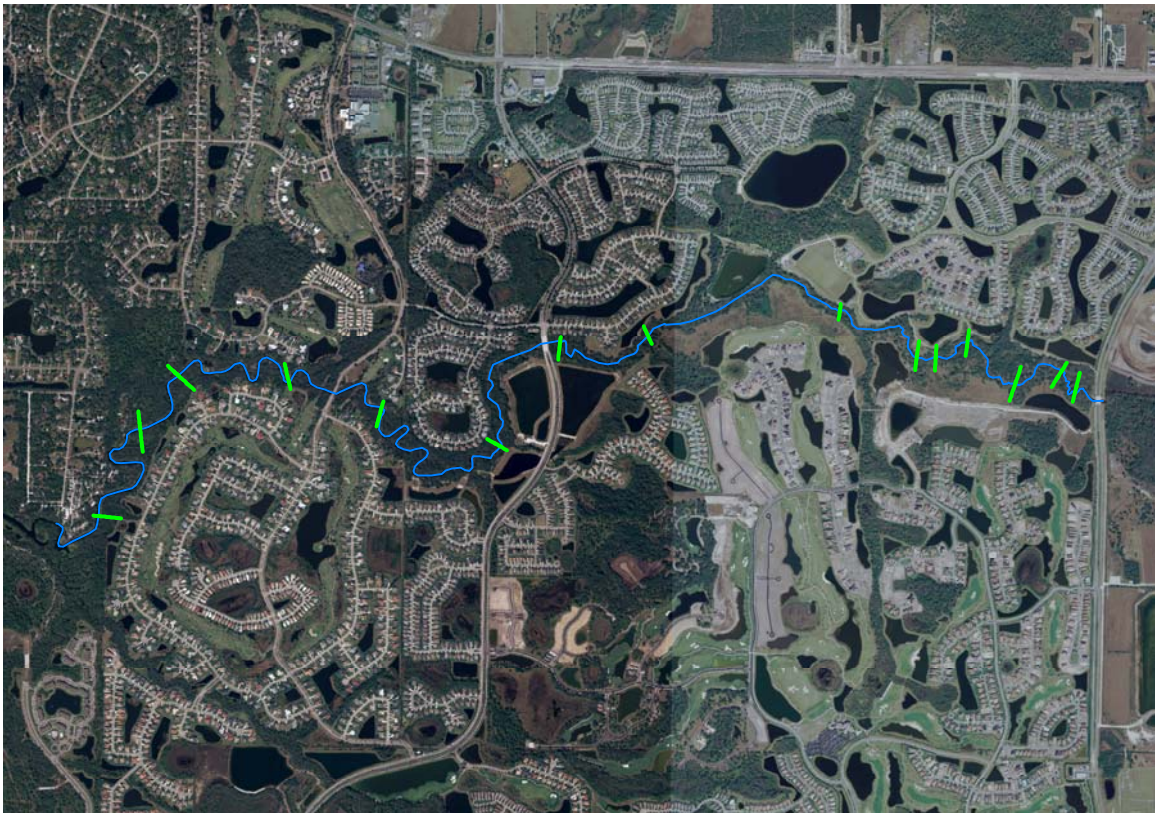

Figure 4-3. Location of surveyed cross-sections across the Braden River, Florida.

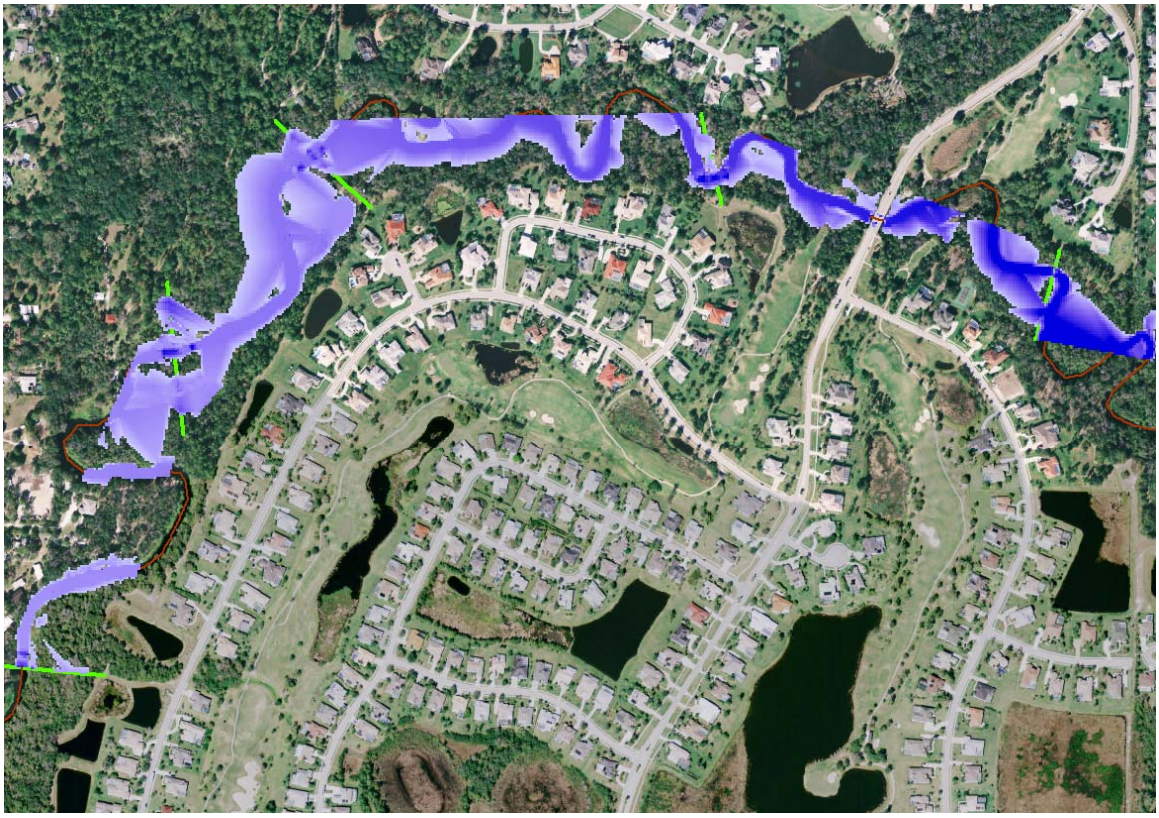

Figure 4-4. Portion of the Braden River, Florida with modeled inundation patterns from a 1% exceedance flow.

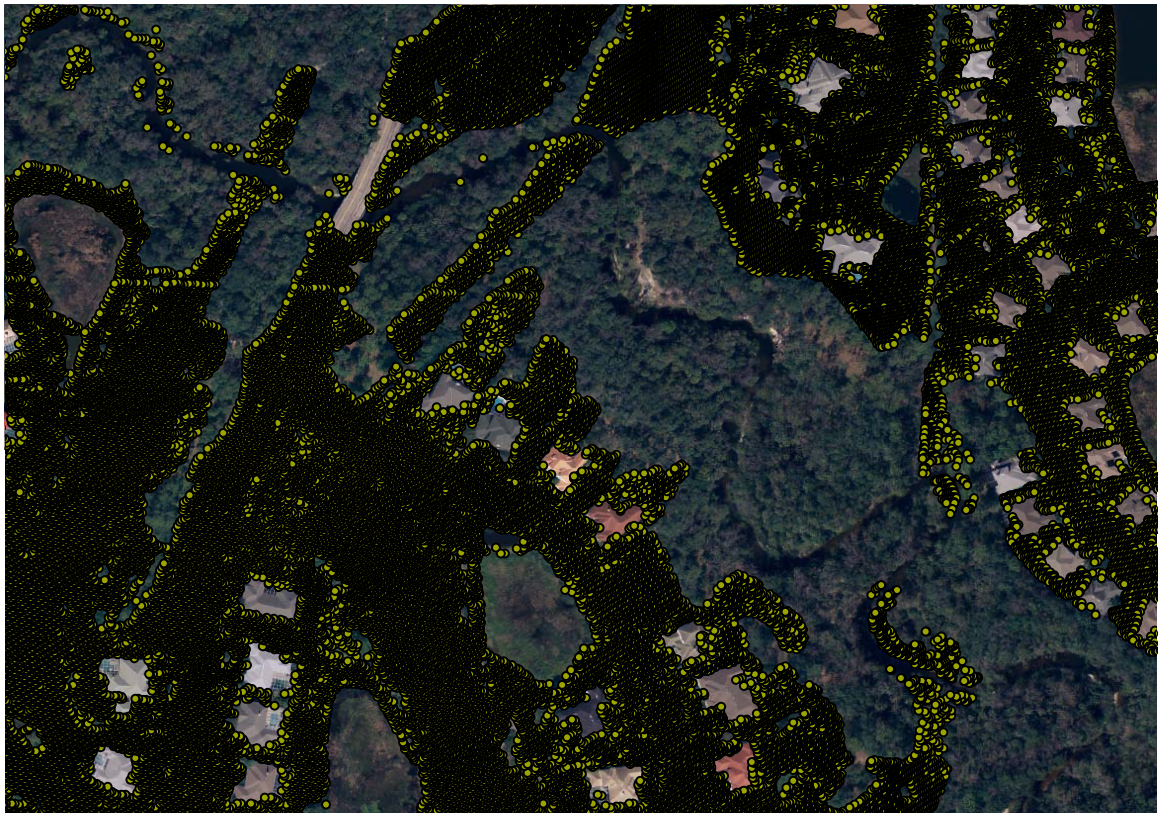

Figure 4-5. LiDAR points used in the DEM of the Braden River, Florida. LiDAR points are yellow dots, which are numerous enough to show as dark areas on the map. Empty areas are where data was determined not to represent the ground elevation (i.e., Houses and canopied areas where the LiDAR did not penetrate to the ground.

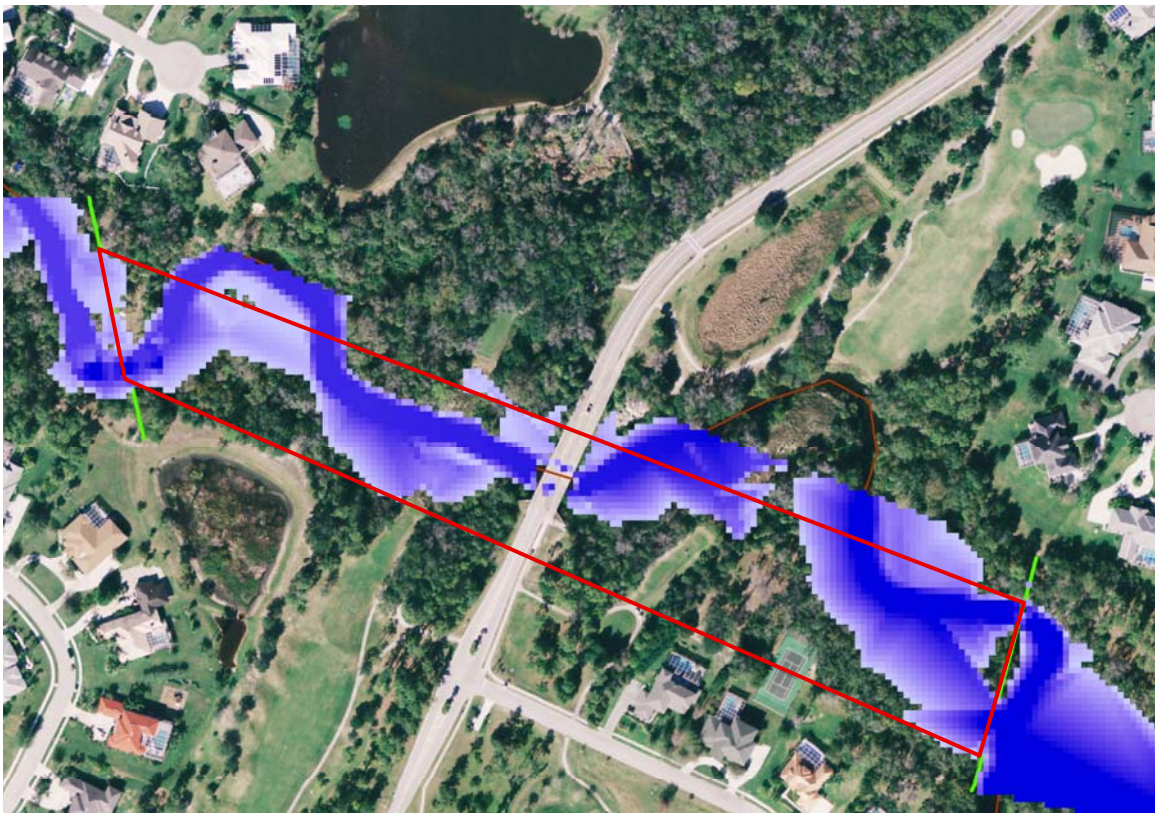

Figure 4-6. Conceptual view of inundated area calculated by HEC-RAS and in a GIS environment. The shaded blue area represents inundation patterns modeled in GIS. The red trapezoid is a depiction of how HEC-RAS would estimate the inundated area.

CHAPTER 5
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Summary

This dissertation reviewed the water management policies in Florida, which eventually led to a legislative mandate for MFL (minimum flows and levels) development. The five water management districts, tasked with MFL development, have responded using a variety of methods. These methods include utilization of multi-parameter approaches, including both hydrologic and biological components, as well as recognition of public water supply needs. As of the publication of the 2005 MFL priority list, minimum flows or levels had been established for 242 water bodies in four of the five water management districts. The fifth had an established priority list identifying water bodies within its boundaries for which MFLs were in the process of being established.

The development of the minimum flow standards used to protect riverine ecosystems from reductions in the highest part of the flow regime was the focus of this dissertation, because it is the least understood. Water managers frequently utilize methods described in the literature for the protection of in-channel flows. These included the use of physical habitat simulation analysis, fish passage, and lowest wetted perimeter inflection point in determining appropriate flow standards. River/floodplain interaction is less well understood in terms of establishing flow requirements for protection of the riverine floodplain ecosystem.

Two methods of measuring habitat loss in floodplain wetlands were evaluated. The use of a temporal measure of habitat loss as a criterion to develop minimum flows for protection of riverine floodplains was examined for three rivers in Florida. The appropriateness of the temporal measure was compared to a spatial measure of habitat loss, and an alternative method

using GIS for measuring floodplain losses, associated with water withdrawals, was presented and discussed.

The temporal loss of habitat measure is intended to provide protection of the riverine ecosystems by limiting the reduction in the number of days of connection between the river and the floodplain. Research showed that the relationship between the flow and the percent-of-flow reductions required to generate a 15% decrease in the number of days a certain flow is reached annually is similar for all three rivers studied. The similarity among rivers is highlighted when flows are plotted in terms of flow per watershed area.

This research also utilized an alternative approach to determining habitat loss by employing a spatial measure of habitat, derived from the HEC-RAS model. This method summed the lengths of inundation along each cross-section in the hydraulic model as a proxy of area of inundation. This was done because it was important to examine if different measures of habitat relate differently to changes in flow. Further, if they did respond differently to changes in flow, it was necessary to characterize which measure would be limiting in terms of flow reduction if a 15% loss of habitat criteria was applied. The reductions in flow required to generate a 15% loss of inundated width were calculated and the results for different flows per watershed area for all three rivers were plotted.

Calculations were preformed to relate habitat types to specific periods of inundation. Wetland characteristics were examined and the amount of flow reduction that would result in a 15% loss of inundation was determined. The results for each wetland characteristic among the cross-sections of a specific river varied widely. Vegetative cross-sections were selected based on location of shoals within the river and vegetation communities. Cross-sections were selected which were characteristic of the river corridor. However, as it became evident that it was

difficult to characterize a riverine floodplain with a limited number of cross-sections, alternatives to linear measures of spatial habitat were sought.

Utilizing LiDAR data, gathered in the Braden River basin, a digital terrain model of the Braden River corridor was generated. This was done to examine how useful digital terrain models might be in examining floodplain wetland inundation in a GIS environment, rather then simply along linear cross-sections. The accuracy of the digital terrain model was limited by the quality of the LiDAR data, which were among the earliest such data collected in southwest Florida. Inaccuracies were due mainly to the lack of bare earth data, collected in the canopied floodplain.

Cross-sections from the digital terrain model were imported into the HER-RAS hydraulic model and water surface profiles were calculated. These profiles were then exported into GIS where a digital elevation model of the water surface was created. The water surface map was then layered with the terrain map and the extent of inundation at different flows was assessed. This was done to develop a better measure of spatial habitat loss, which could ultimately lead to a better understanding of the inundation requirements of riverine floodplains.

Conclusions

- The 1997 legislative mandate to develop minimum flows and levels in Florida has placed the state among the leaders of forward-looking water resources protection in the United States.
- Minimum flow requirements, for protection of riverine wetland protection, are conceptually understood but poorly quantified.
- The measure of temporal loss among rivers in this study are highly similar due to similarities in flow characteristics of the rivers and do not account, directly, for differences in floodplain morphology.
- Abrupt changes in slope, when plotting spatial measures of habitat loss, are likely associated with variations in channel and floodplain morphology, and not accounted for with the temporal measure of habitat loss.

- The use of a temporal measure to assess habitat loss is appropriate since floodplain characteristics, at least in part, are derived from fluvial processes.
- LiDAR is a useful tool in the development of digital terrain models.
- Digital terrain models should be used, in conjunction with hydraulic models, to estimate a spatial measure of habitat loss.
- GIS offers the opportunity to better estimate inundation in the floodplain as a result of over-bank flow, and thus spatial habitat loss, as a result of changes in river flow.
- The use of GIS in determining spatial loss is preferable to the use of cross-sectional data because the three dimensional nature of the spatial data resolves some issues of characterizing the river corridor with a limited number of cross-sections.
- Hydrology is currently the dominant factor in establishing high-flow MFLs.
- MFLs are intended to protect the aquatic biology and ecology of the river system, though to date, biology and ecology have only been minor components in the development of high-flow protection standards.
- Current methods of MFL development do not differentiate flow needs based on wetland habitat type.
- Better modeling ability, derived from GIS, should allow improved understanding of floodplain community structure relative to flow.

Future Work

This dissertation has shown that the MFL requirements for riverine floodplains wetlands are poorly understood. The conceptual importance of over-bank flows has been well documented but not well quantified. This research pointed out that habitat and change in habitat can be measured in multiple ways and it explored the use of new technology in measuring habitat extent. These measures suggest future studies that should be conducted, given the information presented in this dissertation.

Spatial loss in river floodplains is inconsistent from river to river while temporal loss is similar among the three rivers studied and both should be considered in MFL development. Thus, both spatial and temporal measures should be examined in future MFL determinations.

Flow reductions, on rivers studied in this dissertation, consistently resulted in higher habitat loss when measured by the temporal measure of habitat loss rather than the spatial measure of habitat loss. It will be important to determine if this is a consistent finding for other rivers in the area.

If this relationship proves to be inconsistent, then both the spatial and temporal methods should be applied to each river and the more restrictive one utilized. This will assure that no more than a 15% loss of habitat would be allowed due to water withdrawals, whether habitat is measured spatially or temporally. It is recommended that in the future, the flow reductions from the temporal analysis be evaluated in GIS to determine the corresponding spatial loss of habitat. If the resulting spatial loss is calculated to exceed the temporal loss, consideration should be given to this loss when determining the MFL.

Use of GIS as a spatial modeling tool provides the means for better understanding of the river floodplain interaction. Inundation maps combined with vegetation maps (i.e., National Wetlands Inventory Maps) may provide a better understanding of the inundation requirements of various wetland types and these relations should be investigated.

It is necessary to measure not only the accuracy of the MFL, but also to evaluate the accuracy of some of the underlying assumptions, and thus the effectiveness of the MFLs. This requires the implementation of biological monitoring and a long-term commitment to evaluate the effectiveness of MFLs. This should begin with the monitoring of the wetland extent at various locations in each river system. This could be spatially mapped. Changes over time could be noted and correlated to changes in inundation as a result of changes in flow.

The LiDAR data, used to generate the Braden River digital elevation model, had gaps in the canopied area. Current LiDAR technology has improved and these improved data should be

coupled with ground surveys to supplement areas of sparse LiDAR data. This combination of remote and ground surveys can result in a dense enough network of points to generate an accurate and detailed digital elevation model of the river/floodplain system. These techniques should be pursued and incorporated into future MFL determinations.

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BIOGRAPHICAL SKETCH

Born and raised in southwest Florida, Adam Munson has spent his academic and professional career working to protect local water bodies. A graduate of Vivian Gaither High School in north Tampa, Adam attended the University of Florida as an undergraduate majoring in mechanical engineering. Graduating with a B.S.M.E. in 1994, Adam's interest in natural systems and science led him to the Department of Fisheries and Aquatic Sciences at the University of Florida, from which he graduated in May of 1999 with a M.S. specializing in limnology. After a brief period as ecosystem manager for the St. Marks and Ochlockonee River basins in North Florida, Adam returned to the southwest Florida area where he evaluates instream flow requirements for the development of minimum flows and levels.