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HSPF APPROACHES TO UNIQUE CONDITIONS IN THE ST. JOHNS RIVER WATERSHED HYDROLOGY MODELS FOR THE WATER SUPPLY IMPACT STUDY

Tom Jobes[1]

ABSTRACT

HSPF is a watershed model with a long history demonstrating its ability to model a wide variety of situations for a number of purposes. SJRWMD chose HSPF to construct a watershed model of the entire St. Johns River Watershed as part of its Water Supply Impact Study (WSIS). However, despite the software's flexibility, effective modeling of the St. Johns River Watershed using HSPF required some novel approaches to address processes that are uncommon outside of typical Florida conditions, with flat topography, shallow water tables, distributed wetlands, low stream gradients, and flood control structures. This paper summarizes several key innovations developed for this study.

1. INTRODUCTION

In 2006, the St. Johns River Water Management District (SJRWMD), South Florida Water Management District (SFWMD), and the Southwest Florida Water Management District (SWFWMD) recommended capping groundwater use at the 2013 demand level in order to prevent harm to ground water resources and natural systems of the region. The three districts agreed that alternative water supply (AWS) sources would need to be developed to meet water demands above the 2013 level. The SJRWMD's Water Supply Plan (St. Johns River Water Management District 2006) identified several potential AWS sources. Among these sources were surface water from the Ocklawaha River and surface water from the St. Johns River.

The Governing Board of the SJRWMD subsequently determined that a water supply impact analysis was necessary to ensure that the withdrawal of surface water from the Ocklawaha and St. Johns rivers would not cause unacceptable environmental effects in the St. Johns River. Consequently, the board called for the St. Johns River Water Supply Impact Study (WSIS). (St. Johns River Water Management District, 2012) The goal of the St. Johns River Water Supply Impact Study was to provide an analysis of the potential environmental effects to the St. Johns River of surface water withdrawals for consumptive use.

As part of this study, the District determined that the development of basin-scale framework computer models would best meet the current and future needs to assist the District in managing water resources in a cost and time efficient manner. A framework model is a large-scale computer model that simulates the hydrologic and water quality processes in a basin with adequate detail to be meaningful. The simulation environment must address relevant issues related to the computer simulation of hydrologic, hydrodynamic, and water quality processes in selected District watersheds

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and District receiving water bodies. For watershed modeling, the District chose the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) interface and the Hydrologic Simulation Program – Fortran (HSPF) as the framework model. The Environmental Protection Agency (EPA) has sponsored the BASINS and the HSPF projects for many years for hydrologic and water quality simulations. Combined they are used by the EPA and stakeholders across the country to assist in the development of Total Maximum Daily Loads (TMDL) and they are part of the EPA's TMDL Toolkit. (Bicknell, Imhoff, Kittle, Jobes, & Donigian, 2001)

While HSPF has been used for decades and been found applicable to broad variety of watershed conditions across the US and around the world, there are some conditions that exist in the St. Johns River Watershed, and in Florida in general, that were not easily representable with the algorithms used in the model. In order to achieve better model performance, several new or newly adapted approaches were developed for the WSIS application. These include:

- Expansion and contraction of reaches within floodplain (riparian) wetlands
- Interaction between lakes and groundwater
- Flows through water control structures
- Handling of storage of upland runoff within non-riparian wetlands

The first three of these were accomplished using an HSPF feature known as Special Actions (Jobes, Kittle, & Bicknell, 1998). A Special Action instruction specifies the following:

- The operation (e.g. a land segment or reach) on which the action is to be performed
- The date/time at which the action is to be taken and/or the logical conditions which must be satisfied
- The variable to be updated, normally either a parameter or a state variable such as a storage
- The action to be performed. The most common actions are to reset the variable to a specified value and to increment the variable by a specified value, but a variety of mathematical functions are available.

The special action facility is used to accommodate unique characteristics of a watershed, such as:

- Human intervention in a watershed. Events such as plowing, cultivation, fertilizer and pesticide application, and harvesting are simulated in this way.
- Changes to parameters. For example, a user may wish to alter the value of a parameter for which 12 monthly values cannot be supplied. This can be done by specifying a special action for that variable. The parameter could be reset to its original value by specifying another special action, to be taken later.

For instance, a simple use of Special Actions in the WSIS model was to alter a parameter which selects different rating curves at a single location to account for different conditions during the calibration period. This is an example of a more common usage of Special Actions, and will not be discussed here in detail.

2. VARIABLE FLOODPLAIN WETLAND AREA

The first type of new Special Actions were used to account for variable reach areas. Normally, the watershed areas are fixed, while the reach areas vary with stage. When the reach surface area increases during a large event, the effective total area of the watershed increases. If rainfall continues on a growing reach, the total volume of the rain on the watershed increases with it. In most watersheds, this constitutes only a slight change in the overall watershed area, and the mass-balance error in rainfall thus introduced is generally considered negligible. Figure 1 below shows this case for a stream (on the left) and a lake (on the right) in watersheds with relatively high gradients and small floodplains.

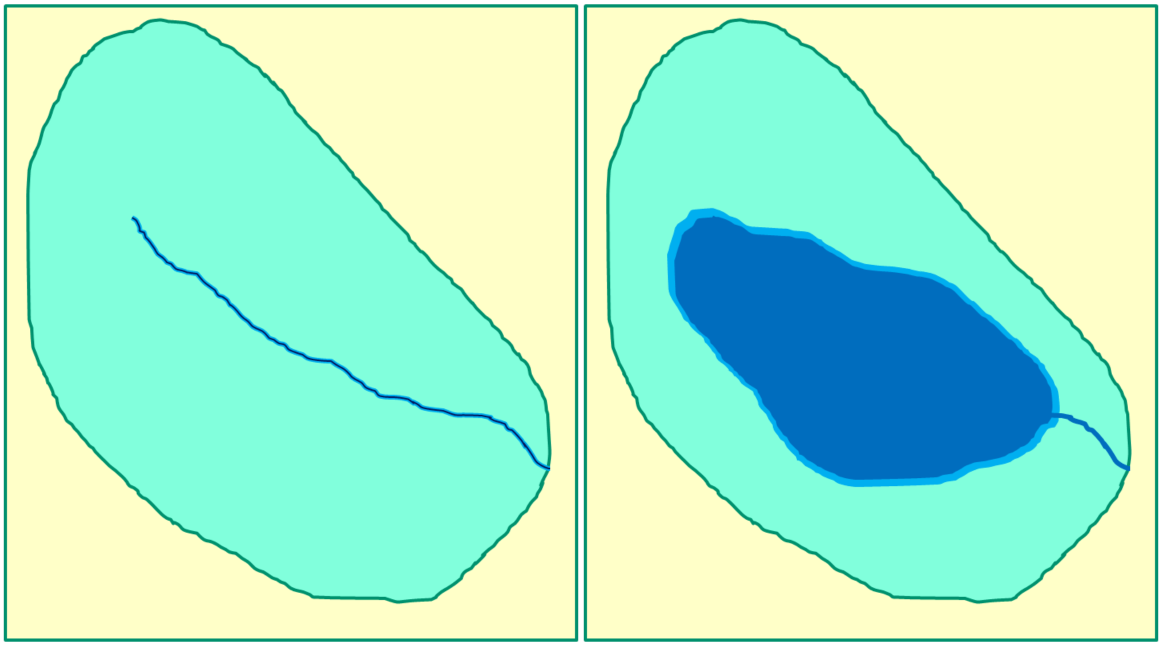

Figure 1 Typical high-gradient stream and lake with small areal variability.

However, in the St. Johns River, inundation of wide flat floodplains would result in a relatively large increase, which in essence would double count a significant area receiving rainfall, resulting in a mass balance error. Figure 2 shows satellite photos of the Upper St. Johns River Basin and surrounding areas immediately before and after Tropical Storm Fay in August of 2008. Such broad areas of inundation can result in changes in reach area that exceed 20 percent of the subwatershed area. If rainfall continues to fall, and is applied both to the full area of the stream reach (represented by an operation called RCHRES) and the full area of the floodplain (represented as one or more pervious land segments by operations called PERLND), then the mass-balance error can grow quite significant.

Figure 3 is a schematic representation of a more typical situation in the study area. On the left, the difference between minimum (shown in dark blue) and maximum (shown in light blue) surface area of the reach covers a large percentage of the subwatershed.

The approach used in this study is to make the area of the wetland floodplain variable instead of constant. Each hourly time step, the Special Actions examine the current RCHRES surface area and subtract it from the total of river reach and riparian wetland area for the basin. The per-acre runoff from the wetland is multiplied by this reduced area so that rainfall and runoff from the floodplain do not duplicate direct rainfall on the water surface. As large changes in area, both increasing and decreasing, generally happen during large storm events, the water stored in and above the soil in the wetland floodplain should be near full capacity during both rising and falling limbs of the flood. Therefore, any mass-balance error induced by assuming that the per-acre conditions on the non-inundated wetland are otherwise unaffected by the reach area should be very small. This modification was applied throughout the model domain.

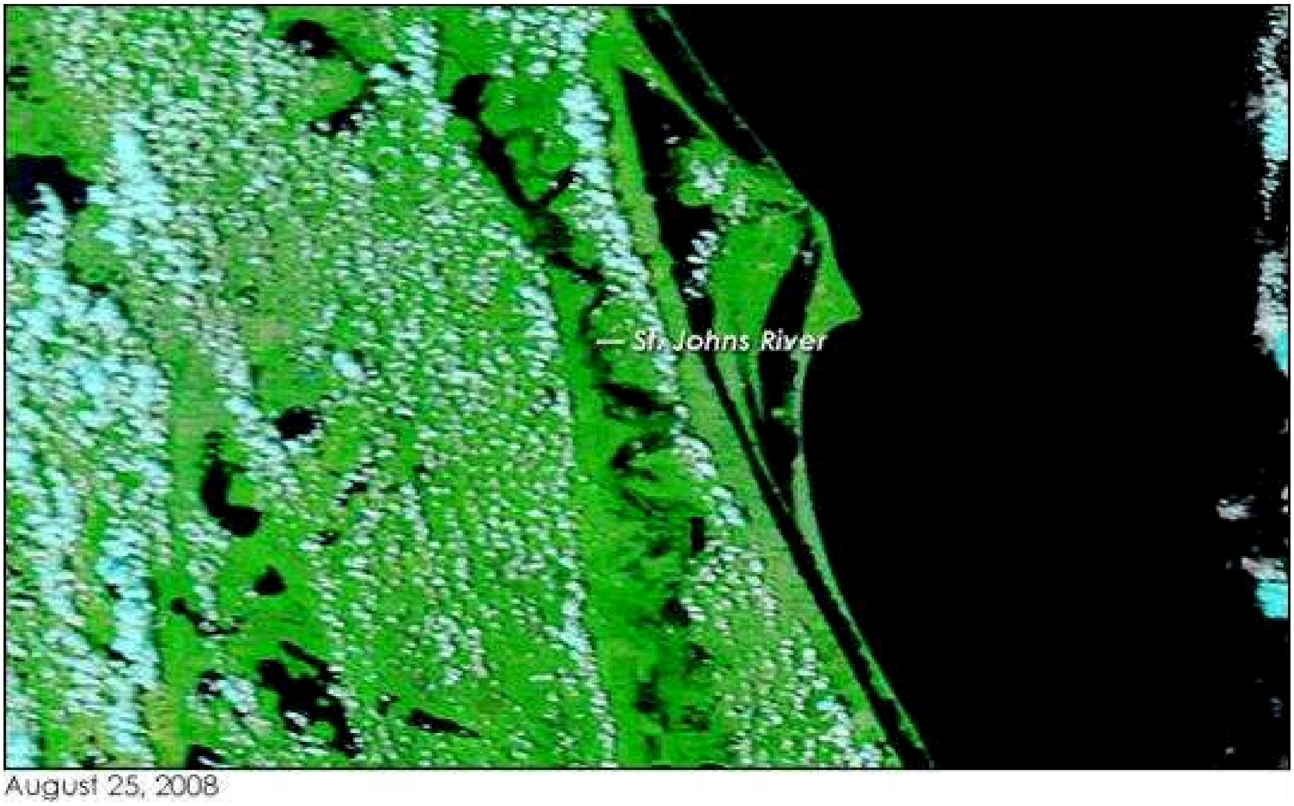

Figure 2 Satellite photos of Upper St. Johns River Basin before and after Tropical Storm Fay, August 2008.

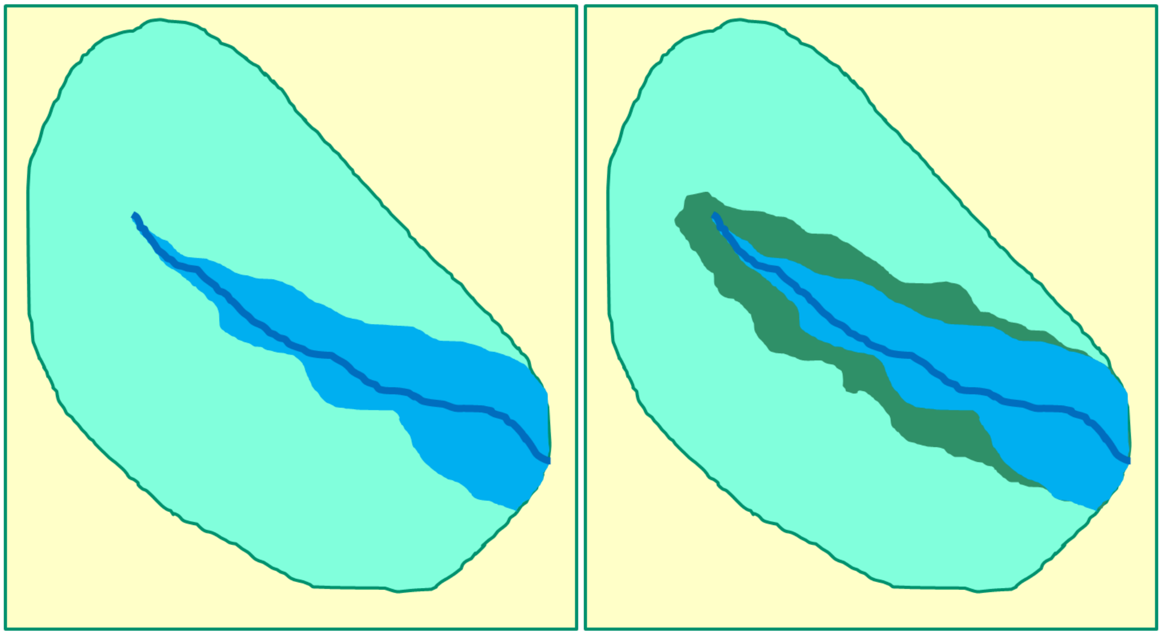

Figure 3 Typical SJRB subwatershed with large areal variability, showing minimum (dark blue) and maximum (light blue) reach area, and wetland floodplain extent (dark green)

3. GROUNDWATER CONNECTIONS TO LAKES

Another use of Special Actions was to make connections in certain lakes between groundwater and surface water to estimate recharge losses to the Upper Floridan Aquifer System or discharge from it through spring flow or seepage into the lake. Aquifer head was estimated using a local well hydrograph, and a simple application of Darcy's law computes the flux through the bottom of the lake. This occurs in both the Upper Ocklawaha and Orange Creek basins. This approach was originally developed for an immediate predecessor model of the upper parts of the Orange Creek basin, and adapted and expanded for the WSIS. (Lin, 2008)

Figure 4 shows a schematic of the system. Each hourly time step, Special Actions are used to compute the head difference between an input timeseries of head from a UFAS well near the lake and the lake stage itself. The transmissivity of the lake bed is calibrated as an additional hydrology parameter for the lake subwatershed as a whole, as part of the automated calibration effort using the PEST parameter estimation package. For Lake Apopka especially, local groundwater studies helped constrain the range of values that PEST was allowed to explore.

The direction of flow may be either upward or downward. For lakes that recharge the Upper Floridan aquifer, the hourly recharge is computed as a flow rate using Special Actions and then passed as the outflow demand timeseries for a separate groundwater "exit" from the reach (in addition to the usual downstream surface outflow "exit"). For lakes that receive Upper Floridan discharge, the lake inflow volume is computed using Special Actions and then simply added to the reach as point source. None of the lakes modeled had significant two-way interaction with the UFAS, but it would be possible to set up both directions on a single lake, so that water could flow in either direction over the course of a simulation.

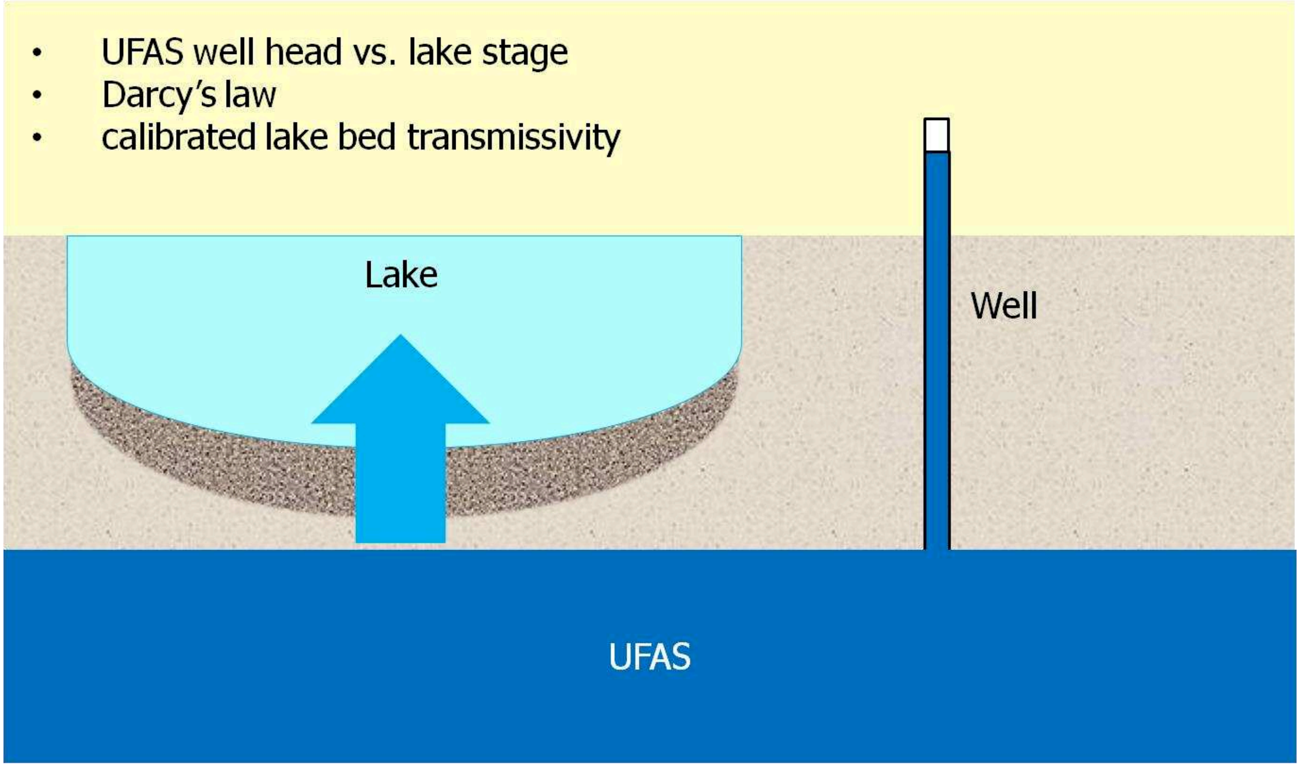

Figure 4 Lake-Groundwater Interaction

4. WATER CONTROL STRUCTURE FLOWS

Another common situation in the watershed is the control of discharge by downstream tailwater, which HSPF's simple hydraulics does not take into account. For free-flowing reaches, a simple static HEC-RAS model can often adequately represent the rating curve, which can then be transferred to HSPF. However, where there is poor correlation between headwater and tailwater stages, such as frequently occurs at structures and in short channels connecting two large lakes, more direct account of the headwater and tailwater must be used.

Special Actions were used to compute the flow based on the upstream and downstream stage and the appropriate structure equation (e.g. weir, culvert) to compute discharge, and the resulting amount passed to the reach as an outflow demand timeseries. These Special Actions were focused in the Upper St. Johns and the Upper Ocklawaha.

For flood gates controlling releases from large water bodies, Special Actions were used to compute the discharge based on a seasonal flood control regulation schedule, which sets a maximum stage, and a set of seasonal release curves, which specify how much water should be released, depending on how far above regulation the upstream water body. Examples of a regulation schedule and seasonal discharge curves are shown in Figure 5, respectively. For smaller structures, such as weirs or culverts, flows were computed in Special Actions directly from the appropriate hydraulic equations, accounting for headwater, tailwater, culvert losses, etc.

Figure 5 Regulation schedule and seasonal discharge curves

5. TAILWATER-CONTROLLED LAKE OUTFLOW

Lochloosa Lake and Orange Lake (see Figure 6) lie near Gainesville in the Orange Creek basin, and are connected by a short channel called Cross Creek, Low flows through Cross Creek can occur at both high and low stages for the lakes, as they can rise together during a large rainfall event that covers both subwatersheds, while at other times there are high flows when Lochloosa rises well above Orange Lake.

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Figure 6 Lochloosa and Orange Lake

Special Actions for Cross Creek were used to interpolate between multiple rating curves to compute flows from Lochloosa Lake to Orange Lake to account for backwater effects. Four curves for different tailwater elevations were constructed using HEC-RAS. The ratings curves are shown below in Figure 7. The first two are nearly identical, except that at a low enough tailwater stage, a small flow begins to pass through the channel at a lower headwater stage, whereas a higher tailwater cuts off flow completely.

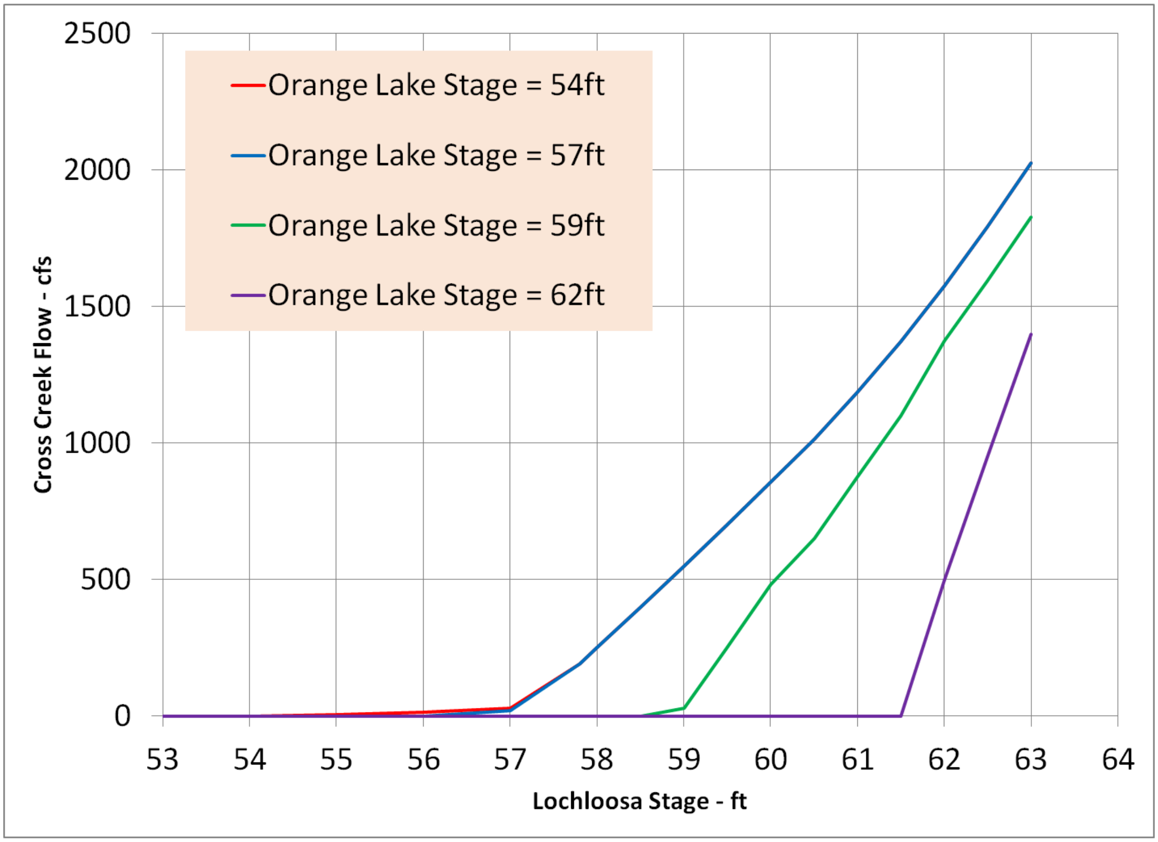

Figure 7 Lochloosa Lake Outflow Rating Curves

This level of detail is fairly coarse, but was deemed adequate for the large scale of the study. This approach was also tried for two paris of lakes in the Ocklawaha basin, but did not work as well as hoped, and was therefore replaced with traditional HSPF methods. However, current modeling efforts in the Upper Ocklawaha have involved a refinement of the method, giving superior performance.

6. WETLAND STORAGE AND NON-RIPARIAN WETLAND DRAINAGE

In the original model construction, thirteen land use types were modeled as pervious land segments (called PERLNDs), in combination with impervious land segments (called IMPLNDs) in the case of urban land uses. These land segments were routed directly to their associated streams or lake reaches (called RCHRESes). An external peer review suggested that routing some of the flow from upland surface areas to upland wetlands would provide a better representation of the watershed. (INTERA, 2009)

Wetlands tend to allow limited downward movement of water. Instead, water is stored at or near the surface, with reduced runoff and a larger potential for evapotranspiration. HSPF provides the option to use piecewise linear depth-discharge rating curves called FTABLES to define surface outflow as a function of surface detention depth. This feature allows improved representation of the surface storage and attenuated surface runoff typical of wetlands. This capability was originally added as part of the High Water Table package, developed in the mid-1990s as part of an effort to extend HSPF capabilities in Florida conditions. (Hydrocomp, Inc and AQUA TERRA Consultants, 1996) The full High Water Table package was not used in the WSIS because:

1. it requires significant additional data that was not readily available throughout the model domain;
2. it redefines some existing hydrology parameters in a way that their calibrated values may not be comparable to those for uplands, making calibration more complex; and
3. its additional fluxes and storages are not fully tied into the water quality sections in the model, making more difficult the anticipated future expansion of the framework model to examine nutrients in the watershed.

Another approach to addressing wetland storage is to use conceptual storage reaches. This was in fact the approach recommended in the peer review. A series of HSPF studies in the adjacent Southwest Florida Water Management District developed this approach, beginning in 2000 (Guerink, Nachabe, Ross, & Tara, 2000), (Tara, Trout, Ross, Vomacka, & Stewart, 2003). Separate reaches in each subwatershed for floodplain wetlands, which directly connect to the normal stream and lake reaches at high stages, and non-riparian wetlands such as pocket wetlands, which spill over into intermediate conveyances at high stage. Each subwatershed was then subdivided into land areas that drain into each of the three reaches: "connected wetland reach", "disconnected wetland reach", and "routing reach". The two wetland reaches then use piecewise-linear rating curves, developed using simple equations with calibrated parameters, to attempt to match the observed streamflow in the associated routing reach.

This method, however, requires a large amount of GIS processing, both to subdivide the subwatersheds into the three parts, which can be difficult in flat terrain, and to create a single disconnected wetland reach out of many pocket wetlands in such a way that their storage volumes, spill inverts, and spill characteristics align properly to give the correct flow to the routing reach. Finally, in some systems the lack of representation of vadose zone storage for non-inundated wetland areas may become a source of model error.

Therefore, the new approach used in the WSIS study preserved the idea of maintaining separate drainages for disconnected wetlands, while simplifying the necessary GIS processing and enabling the representation of soil moisture deficits in wetlands during dry conditions.

First, the watershed was divided into only two drainages – non-riparian and riparian – instead of three. Since Special Actions allow the expanding reach surface area to replace some (or in extreme cases all) of the riparian wetland, it was assumed that the storage characteristics of water flowing directly to the stream could be handled without using separate floodplain storage.

In the GIS processing, each wetland polygon was assigned a status as riparian if it was within 10m of the nearest model reach, while those further away were considered non-riparian. The District-wide DEM was then processed using ArcHydro watershed delineation tools to determine the drainage area for each non-riparian wetland. An example of the results of this processing is shown in Figure 8. The entire land-use coverage was then overlaid by both the original subwatershed boundaries and the riparian/non-riparian division to generate the full land segment drainage network.

The other principal difference was to use the pervious land segment (PERLND) module to simulate both the floodplain (riparian) and disconnected (non-riparian) wetlands instead of the reach (RCHRES) module. The HSPF code for PERLND was modified to allow use of the surface FTABLE with the normal HSPF subsurface hydrology. The changes were minor – essentially reworking the logic to allow the program to respond to the surface FTABLE option flag setting outside of the full High Water Table mode. The parameter set for such wetlands were then calibrated within different ranges to force them to hold and evaporate more water, while infiltrating and recharging much less.

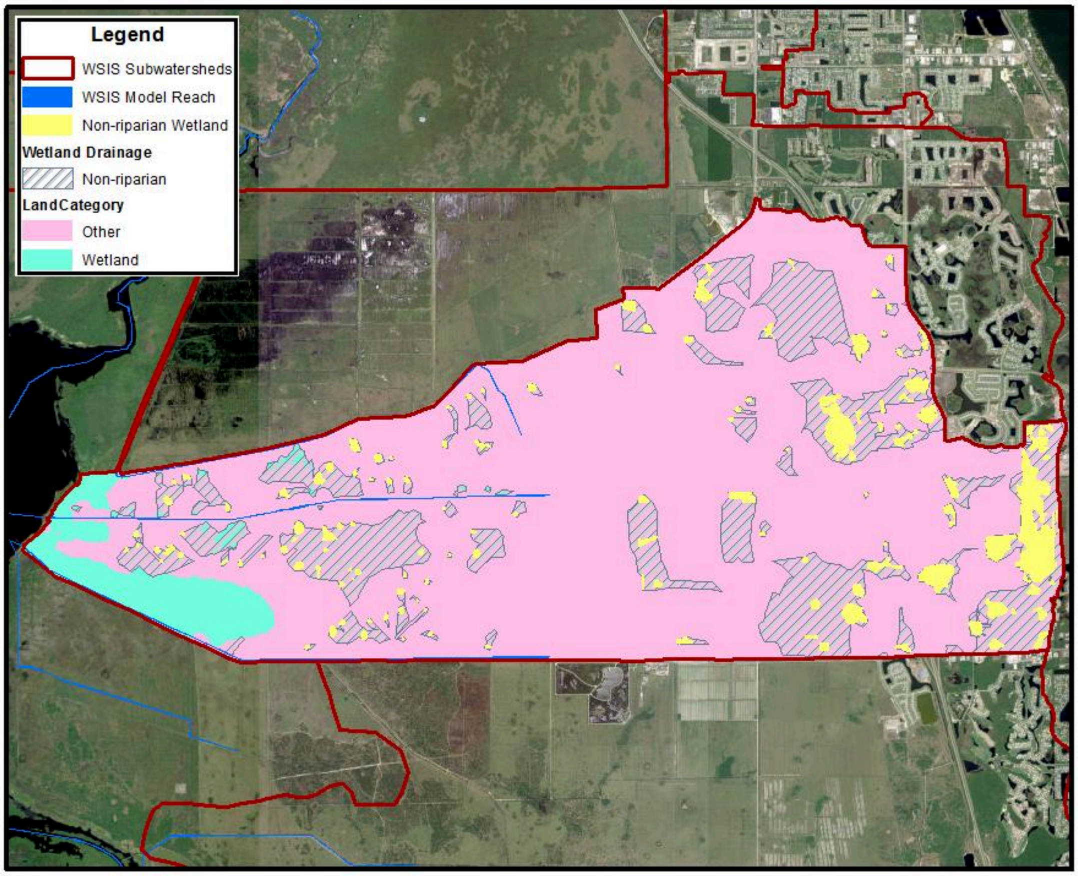

Figure 8 Example riparian/non-riparian drainage divide

A surface FTABLE was developed for each wetland PERLND. Since there was not enough data to separately calibrate them, the same FTABLE was used for both the riparian and non-riparian wetlands in each subwatershed. Development of the storage-outflow relationship begins with a simple power function:

$$Q = ay^{\mathrm{m}}$$

Where

Q = fraction of storage that runs off per hour
y = normalized depth above the invert
a, m = general coefficient and exponent

PEST was then used to optimize the wetland storage-outflow relation by adjusting the depth of incipient flow, and the coefficient and exponent.

Upland wetland distribution for the 2030 future land use scenario was calculated by reducing the non-urban land uses by the same percentage as its associated non-urban uplands were reduced. The difference between the 1995 and 2030 non-urban wetland drainage was added to the 1995 urban associated upland wetlands. This new urban associated wetland (2030 land use) was prorated between the four urban land uses based on its percentage to total urban lands. A sample of the change is shown in Table 1.

Table 1 Example division of 2030 land use between riparian and upland wetlands for Planning Unit 4E, subwatershed 18

Land Use	1995 LU to Riparian Wetlands	1995 LU to Upland Wetlands	1995 Total Acres	2030 LU to Riparian Wetlands	2030 LU to Upland Wetlands	2030 Total Acres
Low Density Residential	1,349.0	124.2	1,473.2	1,319.5	306.3	1,625.8
Medium Density Residential	203.0	108.3	311.3	2,693.4	625.2	3,318.6
High Density Residential	5.0	0.3	5.4	26.8	6.2	33.0
Industrial and Commercial	130.0	3.6	133.7	297.5	69.1	366.5
Mining	37.3	39.8	77.1	3.5	3.8	7.3
Open and Barren Land	160.9	14.5	175.4	19.6	1.8	21.4
Pasture	1,253.5	371.5	1,625.0	572.9	169.8	742.7
Agriculture General	582.5	173.4	755.8	239.9	71.4	311.3
Agriculture Tree Crops	663.1	112.5	775.6	160.5	27.2	187.7
Rangeland	999.7	343.5	1,343.2	398.7	137.0	535.6
Forest	529.3	189.8	719.1	177.3	63.6	240.9
Water	61.3	6.3	67.6	61.3	6.3	67.6
Wetlands	1.6	170.1	171.7	1.6	170.1	171.7
TOTALS	5,976.2	1,657.8	7,634.1	5,972.5	1,657.8	7,630.1

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SJRWMD Staff	Role
Timothy B. Cera, P.E. Florida Professional Engineer license: 52592	Editor, author, technical reviewer and manager; computer programming, lead for communication with National Academy of Sciences Review Committee, coordinated model development, and implemented training for HSPF, HSPF common logic, and PEST
Dale R. Smith, P.E. Florida Professional Engineer license: 32054	Working group leader, editor, author, technical reviewer and manager
Michael G. Cullum, P.E. Florida Professional Engineer license: 41869	Editor, project review and coordination
Marc Adkins, P.E. Florida Professional Engineer license: 42447	Author, hydrologic simulation of Black Creek, Deep Creek, Ortega, Trout, Little Wekiva; Helped to implement and use PEST with HSPF
Joseph Amoah, Ph.D., P.E. Florida Professional Engineer license: 73043	Author, hydrologic simulation of Crescent Lake and lower Orange Creek watersheds
David Clapp	Data management lead, author, hydrologic simulation of Orange Creek and Lake George watersheds
Robert Freeman, P.E. Florida Professional Engineer license: 17282	Author, hydrologic simulation of Etonia Creek watershed
Matt Hafner	Data management, author, hydrologic simulation of Lake George watersheds
Xiaoqing (Shaw) Huang, Ph.D.	Author, hydrologic simulation of Ocklawaha watersheds.
Yanbing Jia, Ph.D., P.E. Florida Professional Engineer license: 68422	Author, hydrologic simulation of Econlockatchee, Lake Monroe, and Lake Jesup watersheds; Water quality simulation of explicit modeling of BMP application to future land use
Tom Jobes	Author, computer programming, establishment of overall hydrologic framework, development of non-riparian/riparian methodology, hydrologic simulation of Upper Basin
Liang-Tsi (Maria) Mao, Ph.D., P.E. Florida Professional Engineer license: 46733	Author, hydrologic simulation of Six Mile, Big Davis, Pablo Creek watersheds and the north and south watersheds adjacent to the Lower St. Johns River

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