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Subject:

Review of SJRWMD Wekiva Basin hydrology and hydraulic modeling for minimum flow and level evaluations

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Introduction

This technical memorandum documents Arcadis' review comments on Wekiva River Basin HSPF (Hydrological Simulation Program-Fortran) and HEC-RAS (HEC River Analysis System) models developed by the St. John's River Water Management District (the District) for evaluation of Minimum Flows and Levels (MFLs) mandated by Florida statute.

Our comments range from general to specific, focusing on modeling assumptions, setup and inputs, model limitations, appropriateness of the modeling approach, and interpretation of model results relative to MFL evaluation. We address the following aspects of the District's models:

- HSPF models
  - Calibration and verification
  - Simulation period
  - Model inputs
  - Model processes
  - Anomalous simulation results
  - Analysis and interpretation of model results
- HEC-RAS models
  - General comments
  - Steady flow model
  - Unsteady flow model
  - Anomalous model results
  - Model results and interpretation

To facilitate comparison, graphical display, mathematical and statistical analysis of model simulation results, we modified the District's HSPF models to write specific simulation results directly to HEC-DSS (HEC Data Storage System), as the HEC-RAS unsteady-flow model currently does. Time-series data exported to HEC-DSS include:

- RO – reach outflow (cfs)
- ROVOL – cumulative RO (acre-feet)
- IVOL – cumulative reach inflow (acre-feet)
- LZS – lower zone storage (inches)
- AGWS – active groundwater storage (inches)
- SURS – surface storage (inches)
- UZS – upper zone storage (inches)
- IFWS – interflow storage (inches)

Our review of the HSPF and HEC-RAS models considers relevant information provided in the District's Draft Report[1] and the independent technical peer review comments provided by Dynamic Solutions[2] and Intera[3]. Among other documents informing this review is the HSPF User's Manual.[4]

HSPF models

Calibration and verification: The calibration period for the Blackwater Creek, Little Wekiva River, and Wekiva River HSPF models was 2003-2012, but the model was not verified – as is normally the case – using a different (non-overlapping) period of analysis. The model simulation period was 2001-2016, 60 percent of which comprised the calibration period. Consequently, the model's accuracy over a longer period of record and a full range of hydrologic conditions period has not been fully established.

To offset potential effects of long-term wet and dry climate cycles, the model should be verified over a range of hydrologic conditions that include droughts and floods experienced over a multi-decadal historical record. The District draft modeling report does not document effort, if any, to characterize the 2001-2016 simulation period as relatively wet or dry on average, or to estimate recurrence intervals of droughts and floods occurring during the simulation period.

More information is needed on procedures used for record filling of the eight stream gages on Blackwater Creek, Little Wekiva River, and Wekiva River used for model calibration, including assumptions and procedures for updating of gage rating curves, if applicable. The location of the Debary Gage on the Lower Wekiva River is missing from Figure 7 of the draft modeling report.

Model calibration parameters including LZSN, INFIL, LSUR, SLSUR, KVARY should be identified in the draft modeling report, with calibrated values presented and discussed relative to typical values for the region. Sensitivity analysis is recommended to identify the most sensitive parameters and their impacts on overall model calibration.

Simulation period: Statistical analysis of long-term mean aerial precipitation (MAP) data over the Wekiva Basin would be useful to identify where the simulation and calibration periods (2001-2016 and 2003-2012, respectively) rank in terms of long-term climate cycles and hydrologic extremes. Figure 1 below, for example, shows approximately 13% wetter summers (June – September) on average during the 2001-2016 model simulation period (red line) than over the full 1914-2016 precipitation record (blue line). Overall, average annual precipitation during the simulation period is also slightly higher (about 1.5%) than over the full period of record.

Sixteen years is not a long period of analysis for derivation of streamflow frequency and duration relationships representative of historical hydrology. However, daily precipitation records at the rainfall gages applied in the model date back to 1914, potently allowing for simulation of several decades of daily flows and stages for evaluation of MFLs, contingent on availability of other hydrologic and physical data input to the HSPF models.

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[1] Seong, C-H, Wester, A.E. (2018). *Wekiva River Hydrology and Hydraulic Modeling for Minimum Flow and Level Evaluations*. St. Johns River Water Management District.
[2] Lu, Silong (November 14, 2018). Memorandum, re: *Review of HSPF and HEC-RAS Models Development and Documentation for Wekiva Basin, Florida*. Dynamic Solutions, LLC.
[3] Intera (November 14, 2018). Memorandum, re: *Review of Wekiva River Hydrology and Hydraulic Modeling*.
[4] Bicknell, B.R. et. al., Aqua Terra, USGS, USEPA (December 2016). *HSPF Version 12.5 User's Manual*.

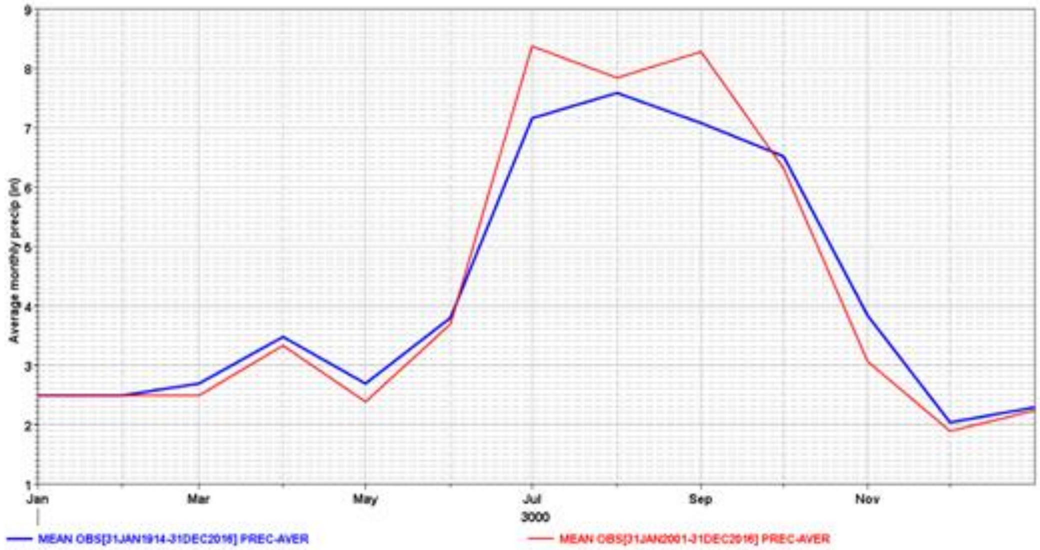

Figure 1: Mean monthly precipitation for the 1914-2016 period of record (blue line) and the 2001-2016 HSPF model simulation period (red line)

<u>Model inputs – Wekiva Basin spring flows</u>: Appendix A of the District draft modeling report describes procedures used for gap-filling and extension of spring flow data based on available historically observed flow data for the springs. Gap-filling procedures applied were based on length and quality of historical data records, characterized as long, short, or intermittent, specifically as follows:

- Springs with relatively long records – maintenance of variance extension (MOVE)
- Springs with relatively short records – linear regression
- Other (intermittent springs – mean flow ratio (spring observations to nearby reference spring observations)

Springs constitute a major source of Wekiva River inflows – from 40 to 90 percent during periods of low flow. However, spring flows are provided as inputs to rather than simulated by the HSPF model. Uncertainty in estimated and filled spring flows creates uncertainty in model results and determination and evaluation of MFLs based on model simulation results. Table 10 in Section 3.2 classifies coefficients of determination (R^2) for model-simulated daily flows as follows:

- Very good – $0.80 \leq R^2 \leq 1$
- Good – $0.70 \leq R^2 \leq 0.80$
- Satisfactory (fair) – $0.60 \leq R^2 \leq 0.70$
- Unsatisfactory (poor) – $R^2 \leq 0.60$

By these measures, coefficients of determination for three of the springs filled by MOVE regression would be characterized as poor (0.12 – 0.58), two as fair (0.63, 0.67). and only one as good (0.79). Two of the springs filled by linear regression would be classified as poor (0.40, 0.52), and the third very good (0.83). In total, five of the nine springs with filled records had coefficients of determination that would be considered unsatisfactory. While methods applied by the District for filling of spring flows may be appropriate from a statistical perspective, the large influence of weakly correlated, filled spring flows on simulated surface water flows calls into question the overall reliability of the HSPF model for simulation of flows and levels – especially during low-flow periods – throughout the Wekiva Basin. Given the poor correlations, the District should consider development and calibration of deterministic groundwater models as an alternative approach to simulation of spring flows input to the HSPF models. The case for deterministic modeling of surface-groundwater interactions is strengthened by the fact that spring flows are the principal means of conveyance of infiltration from closed sub-basins to surface streams.

Model inputs – municipal water withdrawals: Municipal water withdrawals from groundwater and return flows to surface or groundwater do not appear to have been accommodated in the HSPF model input, nor are they addressed in the draft modeling report. The HSPF does allow for time-varying municipal, industrial, or agricultural withdrawals from surface stream reaches and reservoirs, but not from groundwater. Under low flow conditions, well withdrawals by municipalities including OUC, Orange County, Seminole County, and Winter Springs can be large and could significantly draw down groundwater levels and consequently reduce surface water flows. Failure to account for large municipal withdrawals in model input could cause over-simulation of flows and levels, and lead to prescription of unrealistically high MFLs that could become increasingly difficult to achieve with growing water demands and non-stationary climate.

Model inputs – point discharges: The draft modeling report identified 60 permitted point discharge sites were identified in the Wekiva River basin, only two of which however appeared to have been input to the model. All available point-source discharge data should be input because they directly affect surface water flows. Discharge data can be highly variable on a seasonal basis and during low-flow periods, and consequently magnitude and timing of discharges should be specified in model input for purposes of verification and accuracy of simulation results.

Model inputs – rainfall data: Because rainfall is the principal driver of hydrologic response, more information is needed in the District modeling report showing periods of missing data for reference and filled gages, and describing in detail procedures used for record filling and disaggregation of daily data to produce hourly time series. Annual rainfall data for the Sanford Gage are missing from Figure 6 of the draft modeling report.

Model processes – streamflow routing: Dynamic wave flow routing capabilities of the USEPA SWMM (Storm Water Management Model) are available in HSPF v12.4 and v12.5 (the version applied by the District). Nonetheless, the District elected to use storage routing – the only hydrologic or lumped routing method available in HSPF – in its Wekiva Basin HSPF models. Storage routing attenuates but does not lag flow moving downstream, whereas other commonly-used hydrologic routing methods (e.g. Muskingum, Muskingum-Cunge, Lag and K, and variable Lag and K) both lag and attenuate flow from upstream to downstream. Because there are no reservoirs in the Wekiva basin and channel storage is small, cumulative flows simulated by the District's HSPF model are effectively summed rather than lagged or attenuated to any significant degree. Consequently, simulated hydrograph shapes are identical, and simulated peak and low flows occur simultaneously in all rivers and along the full length of each river. These results are shown in Figure 2 for Blackwater Creek, in Figure 3 for the Little Wekiva River, and in Figure 4 for the Wekiva River. Application of simulated flows to rating curves derived using HEC-RAS causes computed stages to rise and fall simultaneously along the length of river, as shown for Blackwater Creek in Figure 5 over the entire 2001-2016 simulation period. This result is unrealistic, and unless both lag and storage effects are properly accounted for in channel routing, variability in simulated flows and stages will be exaggerated. As a result, frequency and duration relationships derived using these simulation results will be distorted for purposes of MFL evaluation.

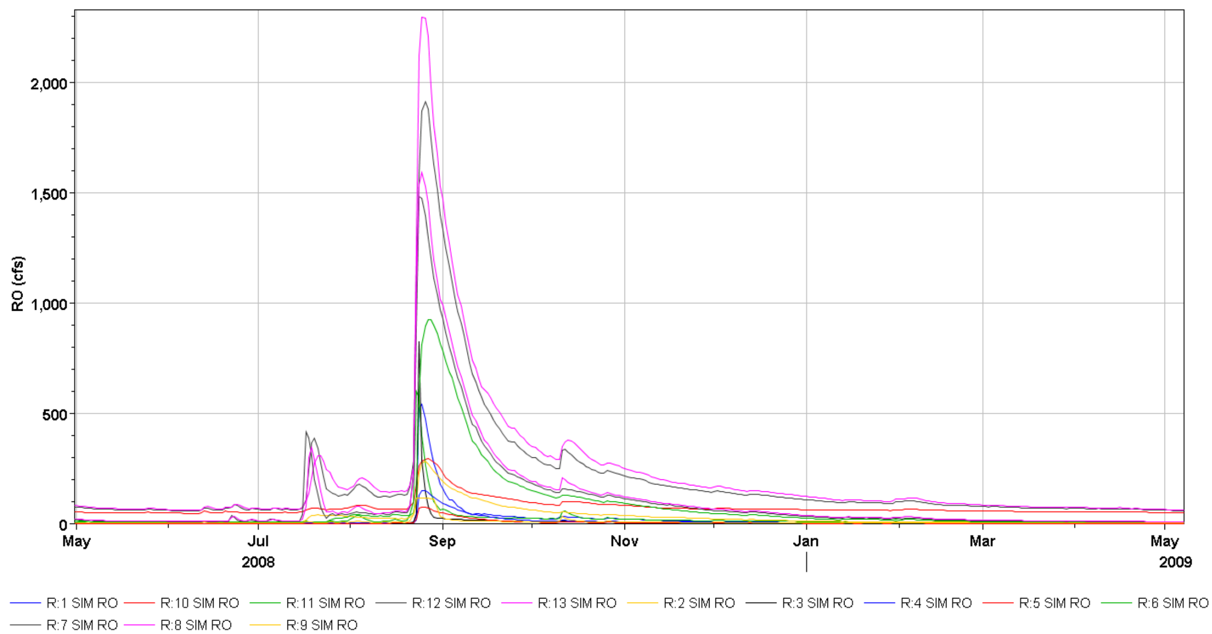

Figure 2: HSPF-simulated cumulative flows in Blackwater Creek, 2008-2009

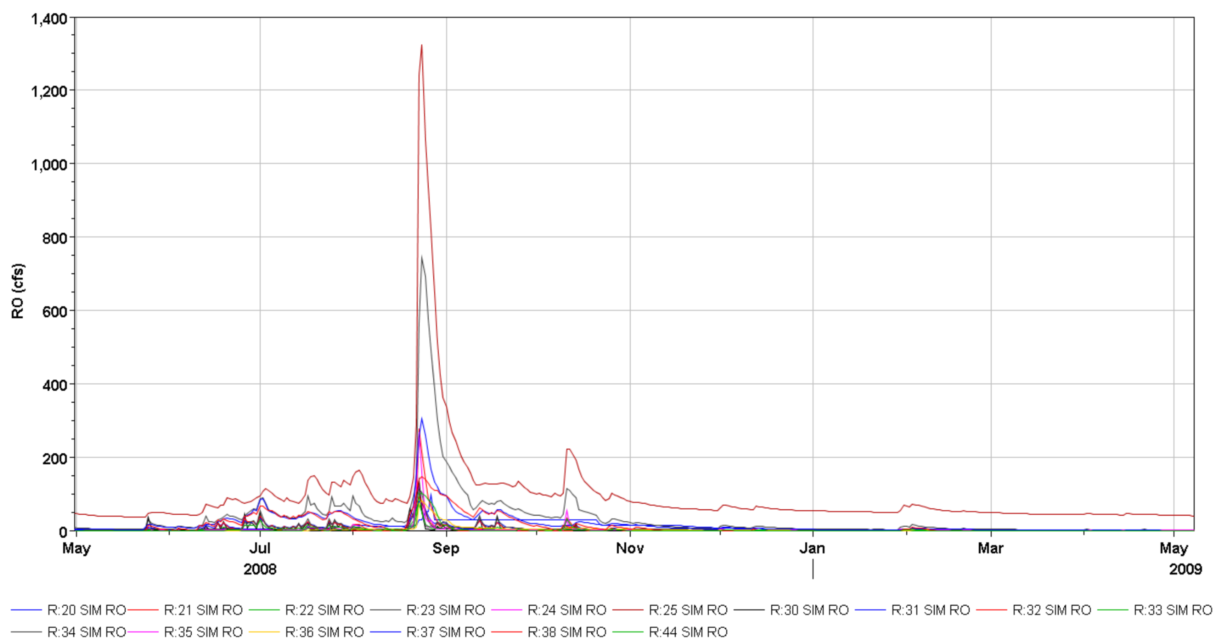

Figure 3: HSPF-simulated cumulative flows in Little Wekiva River, 2008-2009

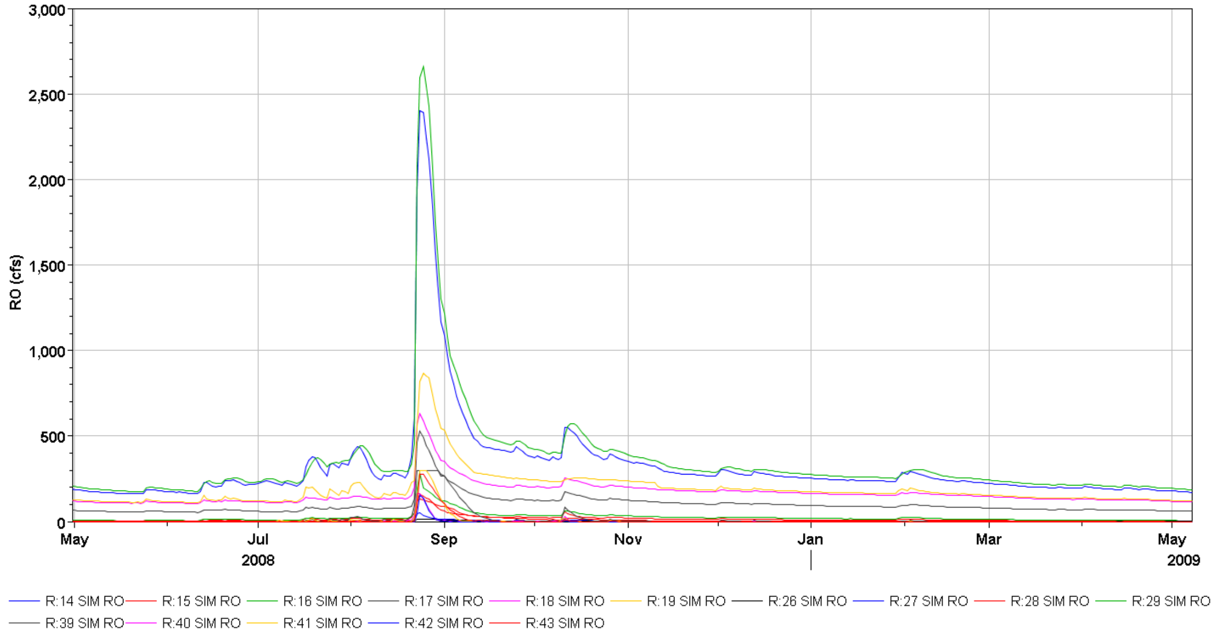

Figure 4: HSPF-simulated cumulative flows in Wekiva River, 2008-2009

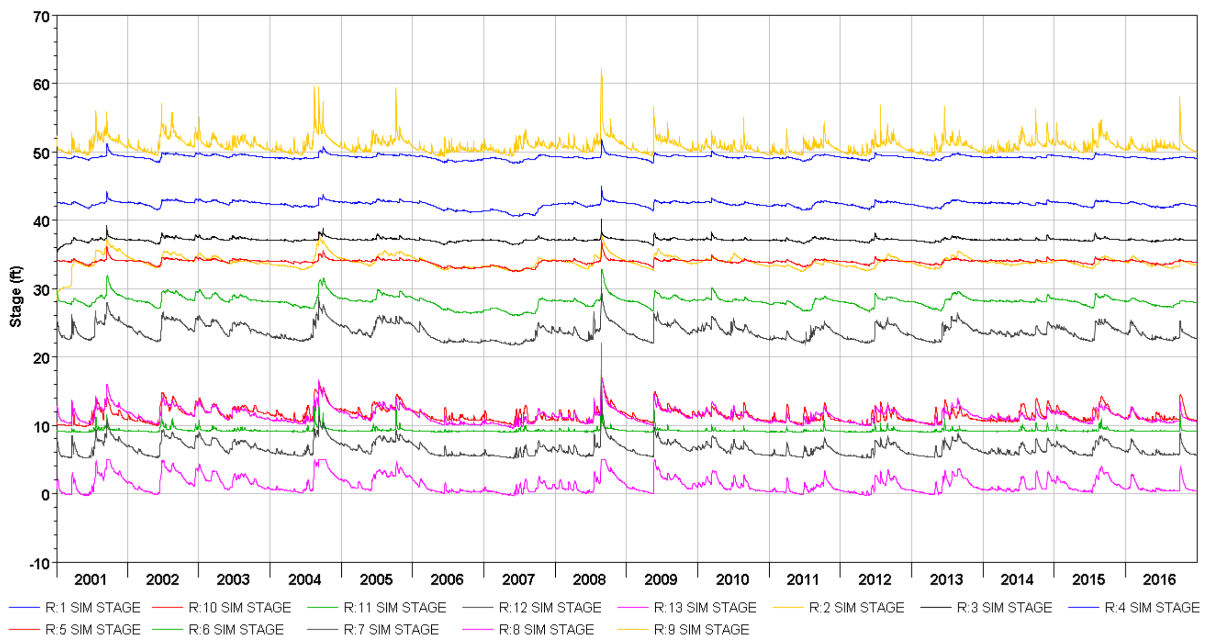

Figure 5: HSPF-simulated Blackwater Creek stages, 2001-2016

<u>Model processes – groundwater-surface water interaction</u>: Groundwater effects on streamflows were not discussed in the draft modeling report, nor did groundwater parameters other than deep percolation

appear to be considered in the model calibration process. Upper and lower zone storage interaction with surface water can be significant during low-flow periods and can affect MFL evaluation as a result. Spring flows, an important component of surface water flows, were estimated statistically rather than simulated deterministically for input to the model. Only surface water parameters (principally flows and stages) were presented in the District draft modeling report.

Anomalous simulation results: As will be subsequently discussed, HEC-RAS model cross section locations and spacing may not support derivation of accurate rating curves for conversion of HSPF simulated flows to river stages. This may be a factor in HSPF model predictions of negative stages at some locations along Blackwater Creek, the Little Wekiva River, and the Wekiva River (lower reaches and upper reaches to the east of Lake Apopka). Some of the negative values appear to be limited by the invert elevations of the applicable cross section for which the rating curve was applied, signifying zero depth of flow. Examples of invert-limited negative simulated stages to the east of Lake Apopka are shown in Figure 6. Inaccurate rating curves and false negative stages would improperly bias stage-frequency and stage-duration relationships used for MFL evaluation.

Analysis and interpretation of model results: Based on guidelines shown in Table 10 of the District's draft modeling report, computed vs. observed performance measures shown in Table 11 predominantly fall in the 'satisfactory' category, with very few falling in the 'good' or 'very good' categories, and with the 'Near Apopka' location showing unsatisfactory results for daily and monthly flows. The subsequent conclusion of the draft modeling report (p. 37) that the model "performed well' is therefore debatable. More importantly, the report does not elaborate on potential sources of error other than for the Apopka location. It seems plausible that uncertainties in estimation of spring flows, omission of municipal water withdrawals and point discharges, and simplified flow routing could be sources of systemic error or bias. Coupled with the short simulation period relative to the historical precipitation record, there appears to be significant uncertainty in model simulation results and resulting MFLs, the major sources of which should be investigated.

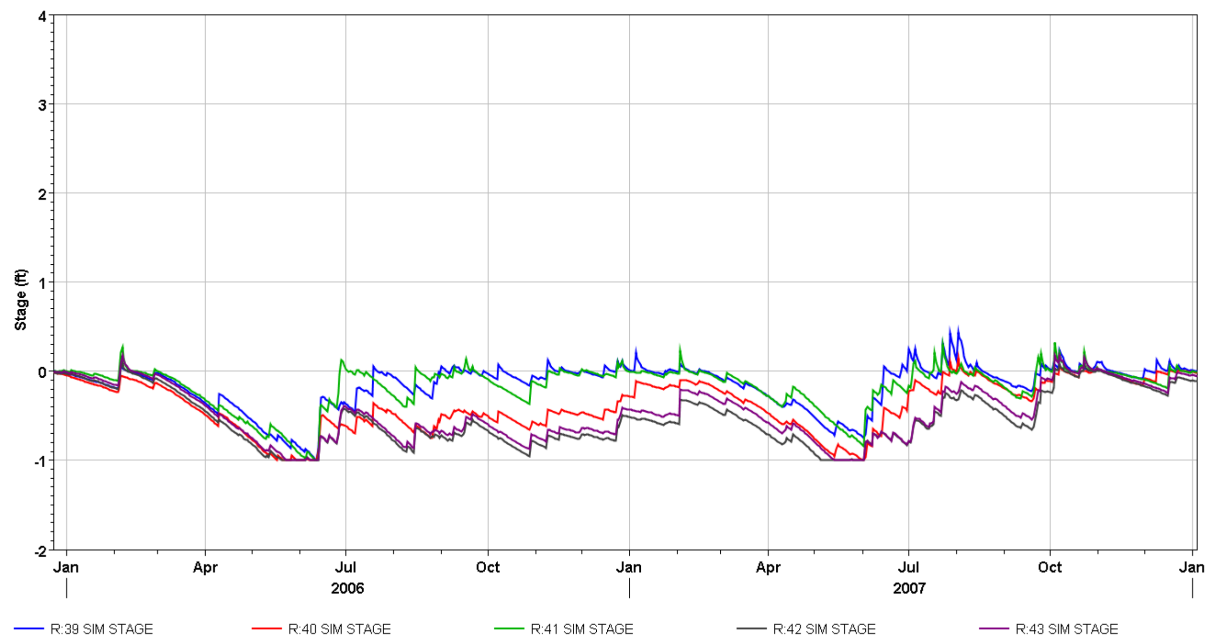

Figure 6: HSPF-simulated upper Wekiva River stages east of Lake Apopka, 2006-2007

HEC-RAS models

General comments: Cross sections along the Wekiva river and tributaries are not sufficiently closely-spaced to reflect incremental changes in cross section shape or changes in flow in the case of the unsteady flow model. Many reach lengths exceed 2,000 feet and range up to 13,300 feet in the Little Wekiva River and Rock Springs Run. Excessive reach lengths between cross section can cause non-convergence or inaccuracies in simulated flows and stages. To avoid non-convergence, interpolated sections were created between widely-spaced cross sections, but linearly interpolated sections would not necessarily capture abrupt changes in channel or overbank shapes or flow changes at junctions. A better alternative to interpolation would be development of a digital elevation model (DEM) from which more closely-spaced and vertically-extended cross sections could be created.

Some of the cross sections were surveyed in the 1990s and are more than 20 years old, and some exhibit significant differences in floodplain areas between 1990 and 2013 surveys. In general, 20+ year-old surveys are normally considered inaccurate for unsteady-flow modeling purposes. Development of a new DEM would bridge differences between the older and more recent surveys.

Steady flow model: Steady flow profile data shown in Table 13 of the District draft modeling report show decreasing flows at some locations in the Little Wekiva, Rock Springs, and Wekiva runs with increasing percentages of flow for PF 8 and PF 12 at SR46. In addition, Table 14 of the report shows computed elevations in the downstream reaches of the Wekiva River decreasing for PF 11, as shown in Figure 7, and for PF 7, shown in Figure 8. Some explanation is warranted in the District modeling report.

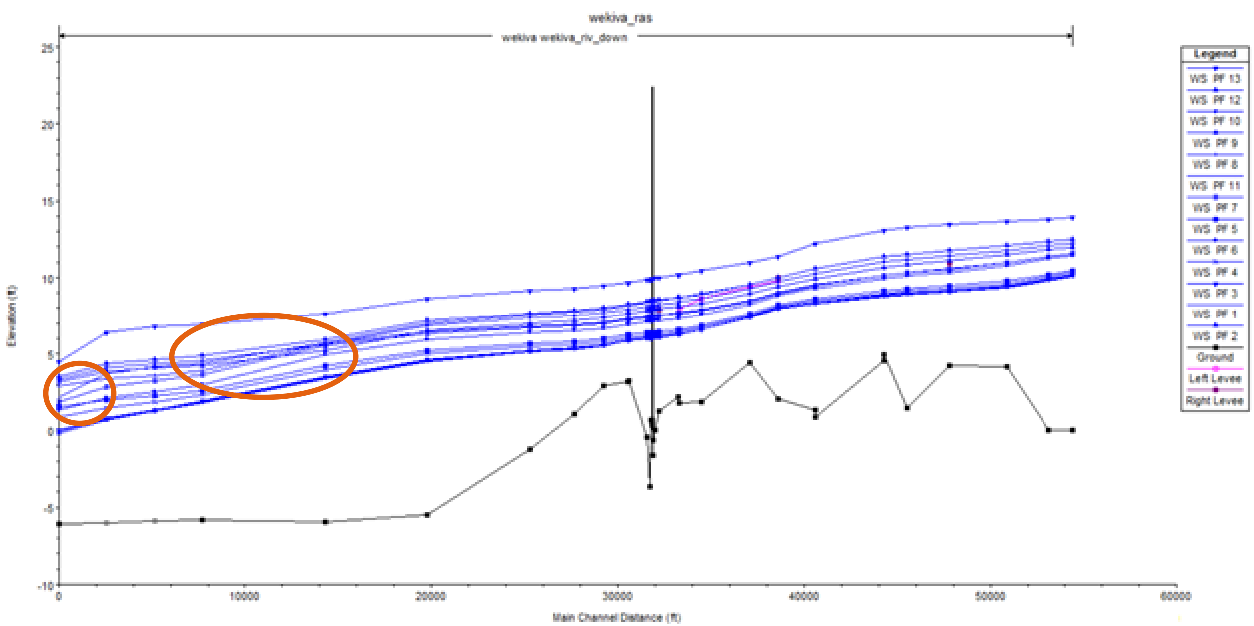

Figure 7: HEC-RAS PF 1 – PF 13 Wekiva River steady flow profiles, showing comparative reduction in PF 11 stage with increasing flow

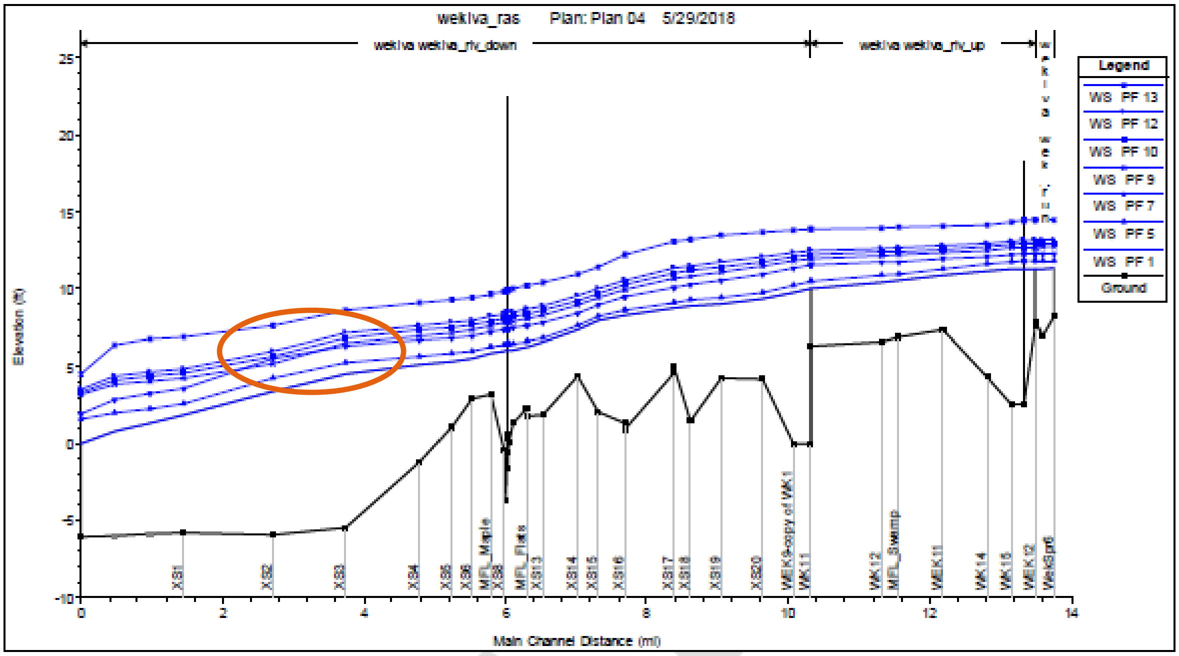

Figure 39 Simulated water surface profiles along Wekiwa Run and the Wekiva River

Figure 7: HEC-RAS PF 1 – PF 13 Wekiva River steady flow profiles for Plan 04, showing comparative reduction in PF 7 stage with increasing flow (Figure 39 in District draft modeling report)

Unsteady flow model – calibration: As previously recommended for the HSPF model, the HEC-RAS model should be validated for high and low flow events outside of the 2003-2012 calibration period.

At some sections, simulated stages exceed cross section boundaries, necessitating extension of cross sections horizontally and vertically at these locations for accurate simulation of reach conveyance and storage.

Unsteady flow HEC-RAS model simulation results displayed in Figures 42 – 47 of the draft modeling report show a high-flow bias, i.e. simulated stages are higher than observed on average. This could suggest the HEC-RAS model calibration is not satisfactory. Additional model testing should be performed to determine whether reduction in Manning's n value is sufficient, provided adjusted n values are within reasonable limits. Another source of high stage bias, however, might be over-simulation of streamflows by the HSPF models due to (1) omission of large municipal well withdrawals and subsequent surface-groundwater interactions effecting streamflow depletions, (2) over-estimation of spring flows input to the models, (3) magnification of streamflow variability due to unlagged and under-attenuated flows produced by storage routing, or (4) some combination of these factors.

Anomalous model results: Anomalies shown for the steady-flow HEC-RAS model in Figures 6 and 7 should be examined and either explained or corrected in the District modeling report. Potential anomalies and non-convergence events were also observed in the unsteady flow HEC-RAS model results, most likely associated with excessive spacing and insufficient resolution in model geometry as previously described. Examples, some of which are fairly drastic, are shown in Figures 8-10

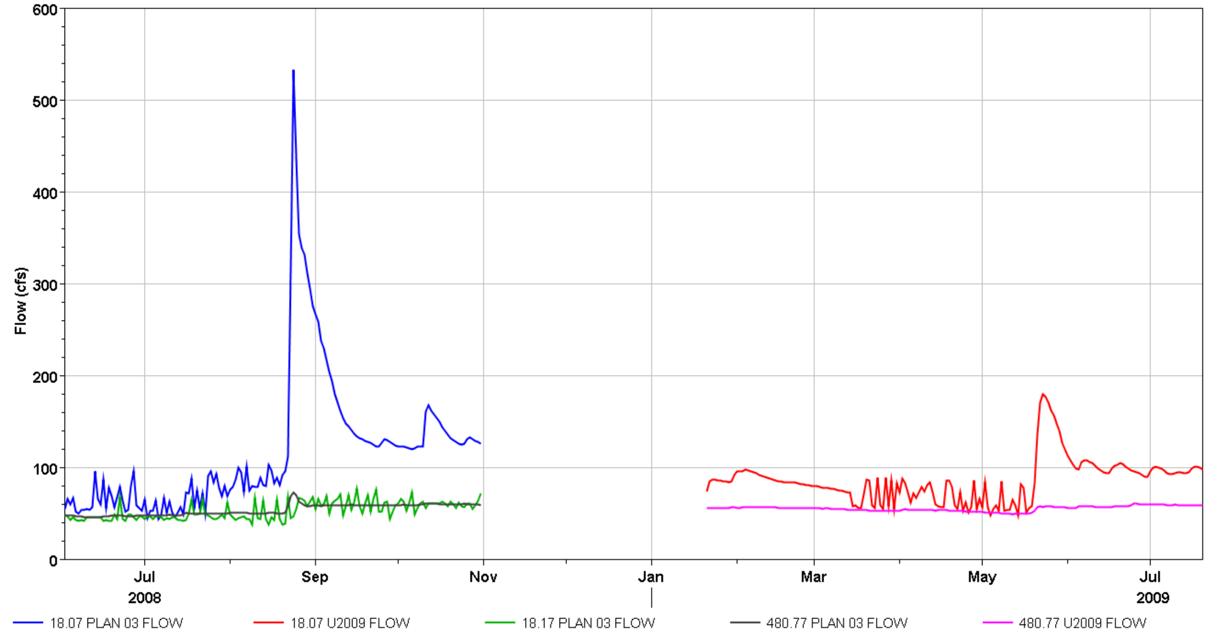

Figure 8: Potential non-convergence of simulated flows, HEC-RAS unsteady-flow Rock Springs run

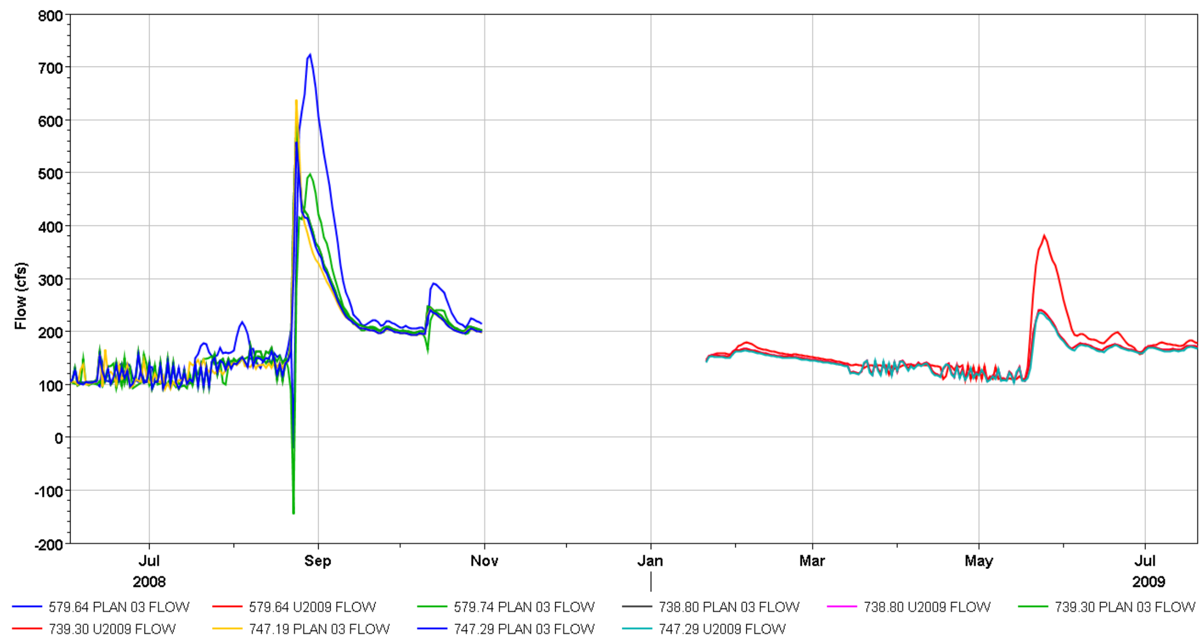

Figure 9: Potential non-convergence of simulated flows, HEC-RAS unsteady-flow Upper Wekiva River run

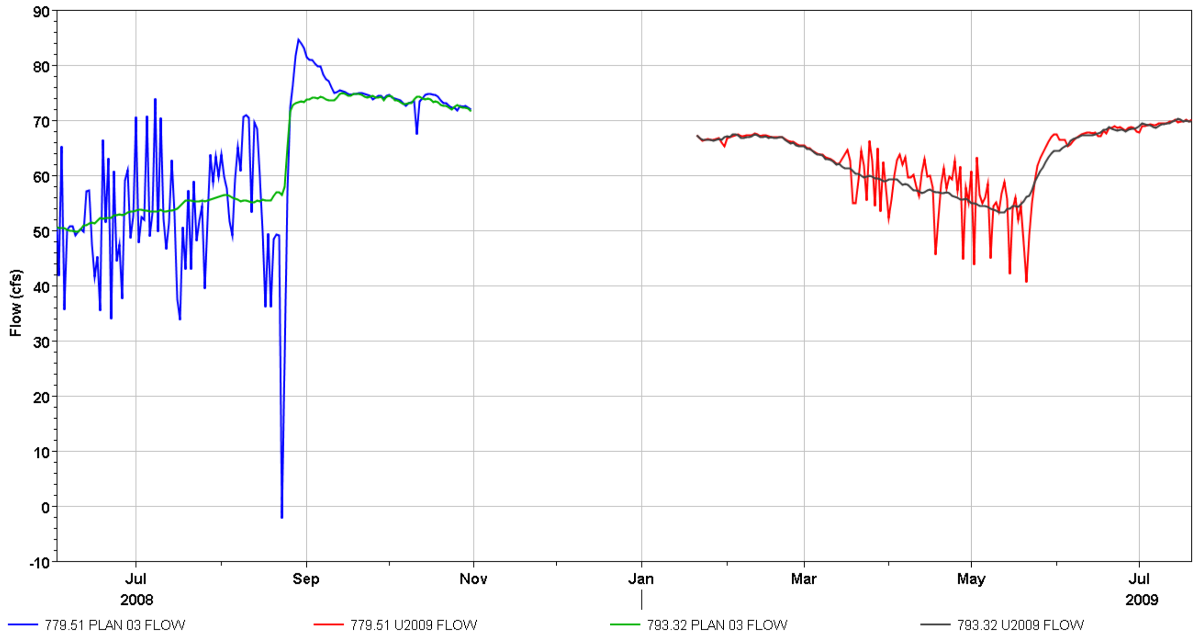

Figure 10: Potential non-convergence of simulated flows, HEC-RAS unsteady-flow Wekiva River run

Analysis and interpretation of model results: The relative coarseness of geometric data and resulting biases, anomalies, and non-convergence issues evident in HEC-RAS model simulation results appear to be serious, calling into question the accuracy of rating curves defined in HSPF model FTABLE input.

Independent peer reviews

Dynamic Solutions LLC (DSLLC): While our comments on the District's HSPF and HEC-RAS modeling are generally consistent with DSLLC's observations in areas where our and DSLLC's comments overlapped, we have addressed some of the broader questions not raised in DSLLC's comments. In contrast, DSLLC examined several aspects of the modeling in detail that we did not. We differ to some extent in our assessment of (1) appropriateness and validity of model development and calibration, (2) model instabilities, and (3) overall utility of the models for evaluation of MFLs.

Intera: As with DSLLC, our comments do not address many of the details covered in Intera's review comments. We differ to a greater extent with Intera's assessments than DSLLC's of (1) appropriateness and validity of model development and calibration, (2) cross section spacing and adequacy of HEC-RAS geometric data, (3) appropriateness and validity of methods used to derive spring flow boundary conditions, (4) model instabilities, and (5) overall utility of the models for evaluation of MFLs.

Conclusions

The District's approach to MFL evaluation involves partial integration of HSPF and HEC-RAS models, an approach which requires both models to be carefully calibrated and synchronized for robust application across a range of historical and potential future climate-adjusted hydrologic conditions. In our opinion, improvements to and more complete integration of these models (data and code), and possibly introduction of other tools, may be needed for accurate and defensible MFL determination in the Wekiva Basin and in other basins in the future. Some specific areas of improvement that we have identified are briefly described as follows:

- The District's HSPF models should be configured, as we have done in this case, for output of time-series data to HEC-DSS (in addition to .wdm files) for greater accessibility and capabilities for graphical display, mathematical and statistical analysis of time-series data than available in the WDMUtil or SARA time-series utilities traditionally applied to HSPF-generated .wdm and .hbn files. Access to HEC-DSS databases containing HSPF and HEC-RAS output greatly facilitated identification and assessment of anomalies and inconsistencies in model outputs, some of which appear to have been missed in the independent peer reviews. Examples include:
    - Comparison of mean monthly precipitation for period of gage records and simulation period
    - Effects of storage routing on HSPF-simulated daily flows
    - Identification of anomalous HSPF and HEC-RAS model simulation results
    - Identification of potential non-convergence issues in unsteady-flow HEC-RAS model simulation results
- Given the problem of sparse spring flow data observations and the importance of spring flows to the overall water balance and surface-groundwater interactions, statistical gap-filling methods may not be sufficiently reliable for modeling in support of MFL evaluations. Consideration should be given to development of external regional groundwater models, or application of HSPF to track direct inflow to surface streams from groundwater and direct discharge of surface streams to groundwater storage. The HSPF code may require modifications for this purpose.
- Storage routing of reach outflows is not adequate for realistic simulation of magnitude and timing of streamflows. Alternative approaches include application of the SWMM dynamic wave flow routing capabilities of HSPF v12.5, use of HEC-RAS for dynamic flow routing, or application of HEC-HMS for continuous rainfall-runoff simulation and lumped hydrologic routing. Because accurate long-term continuous dynamic routing is data- and resource-intensive, and HEC-HMS may not track all of the parameters of interest for MFL determination, the simplest approach may be to modify the HSPF code to incorporate widely accepted parametric hydrologic routing techniques, e.g. Muskingum, Muskingum-Cunge, Lag and K, and variable Lag and K.

The questions directed by the District to the independent peer reviewers were generally appropriate for detailed assessment of model inputs, but less well suited to broader assessment of the overall modeling approach, limitations of the models themselves, and availability of data for calibration, verification, and long-term continuous simulation. We chose to address some of these broader issues rather than duplicate the efforts of the independent peer reviewers.