Comparison of Flow Estimation Methods

UNRBA Monitoring Program Development and Implementation

E213006400

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Document Information

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1 Executive Summary

This technical memorandum (TM) describes a number of approaches that the Upper Neuse River Basin Association (UNRBA) can use to estimate tributary flows. These approaches, if sufficiently accurate, may be used as an alternative to installing additional flow gages at locations where the UNRBA may want to estimate nutrient loading throughout the Falls Lake watershed. The use of flow estimation methods provides the opportunity to secure flow information that is acceptable for load determination from un-gaged watersheds and allow the UNRBA to reduce costs as compared to the installation and maintenance of USGS flow gages. Confidence in these approaches can be increased through data collection in catchments with traits that are currently under-represented in available data sources. This will provide the UNRBA with the flexibility to use multiple methods to predict flows and minimize the number of new USGS gages that need to be installed and maintained.

Of the existing models and methods available, Cardno ENTRIX recommends that the UNRBA use the basin proration and United States Geologic Survey (USGS) Streamflow Regionalization methods for estimating flow at ungaged tributary loading and jurisdictional boundary locations throughout the watershed. These methods provide daily flow predictions whose accuracy is generally within about plus or minus 10% at most locations. When compared to the accuracy of flow data from USGS gages which ranges from between 5% to more than 15%, these estimation methods provide almost equivalent accuracy and certainly allow for the development of acceptable loading values.

The existing USGS gages on the five largest tributaries to Falls Lake (Ellerbe Creek, Eno River, Little River, Flat River, and Knap of Reeds Creek) should continue to be maintained throughout the re-examination process. It is possible that a very limited number of these could potentially be removed without impacting the UNRBA Stage II re-examination process, but most are essential as donor gages for estimating flow at upper watershed jurisdictional boundaries. Many of the upper watershed gages are needed to support existing agreements or water management activities that impact UNRBA members such as the Eno River Voluntary Capacity Use Area. In any event, it is recommended that a careful evaluation of the relationship between the existing gages and the estimation methods and the use of this data by local jurisdictions should be done before making any final decisions.

It is recommended that the UNRBA and Cardno ENTRIX work with the USGS to identify two locations for installation of new flow monitoring gages that can be used to provide further confidence in the flow predictions generated for middle and lower Falls Lake jurisdictional boundaries and tributaries. If suitable flow conditions are present and appropriate gage locations can be identified then it is our recommendation that one gage is located on a stream that is primarily in the Triassic Basin (middle lake tributaries) and one is located on a stream that is primarily in the Raleigh Belt (lower lake tributaries).

2 Flow Estimation Methods

In 2010 the Environmental Management Commission (EMC) passed the Falls Lake Nutrient Management Strategy, requiring two stages of nutrient reductions (N.C. Rules Review Commission 2010). The basis used by the NC Division of Water Quality (NC DWQ)—now the Division of Water Resources (NCDWR) for setting the nutrient loading targets in the Falls Lake Nutrient Management Strategy is the Falls Lake Nutrient Response Model developed with the Environmental Fluid Dynamics Code (EFDC) model (NCDENR 2009). In 2011, the Upper Neuse River Basin Association (UNRBA) began a project to re-examine, under the adaptive management provisions of the Falls Lake Rules, the Falls Lake Nutrient Management Strategy. Cardno ENTRIX has developed and is evaluating additional tools and models for the UNRBA to support the re-examination process.

Cardno ENTRIX is currently assisting the UNRBA with the development of a monitoring design plan to support the re-examination process. In order to address some of the key questions regarding the design of the monitoring program, this technical memorandum presents the results of an evaluation of different methods that can be used to estimate flows at tributary inputs to Falls Lake and at jurisdictional boundaries throughout the watershed.

The State of North Carolina's existing Falls Lake Nutrient Response Model requires estimates of daily flow and nutrient inputs from 17 tributaries around Falls Lake. Because the re-examination of the Falls Lake Nutrient Management Strategy includes revisions to the Falls Lake Nutrient Response Model, tributary flow estimates from all 17 tributaries are needed to provide inputs to the model. Flow data is also needed to estimate pollutant loading at a minimum of 21 jurisdictional boundaries (loading =water quality * flow). The distribution of the underlying geology in the Falls Lake Watershed is provided in Figure 2-1 as is a description of "Upper", "Middle" and "Lower" Falls Lake Watersheds.

The Upper Neuse River Basin Association's (UNRBA) monitoring program is being designed to cost-effectively provide the data needed to support the Stage II re-examination and estimation of loads at jurisdictional boundaries. The most accurate way to estimate flow in streams is to install a United States Geological Survey (USGS) supported flow gage that measures flow every 15 minutes. A single USGS gage costs approximately $25,000 for equipment installation and $15,000 for yearly maintenance. The purpose of this technical memorandum (TM) is to explore a range of models and flow estimation approaches that can effectively be used to provide some of the UNRBA's flow data needs using a less expensive approach than adding a new USGS gage. Another key consideration in this evaluation is to identify less expensive methods that generate flow information with acceptable accuracy. Based on sensitivity analyses and other factors, there are some locations where flow estimates may not need to be as accurate as what is provided by a USGS gage. Implementing flow estimation methods at these locations may provide an opportunity to reduce the overall cost of the monitoring program without any significant impact to the quality of the data required for the re-examination.

The Falls Lake Nutrient Response Model's predictions of chlorophyll *a* in the lake are most sensitive to tributary flows and nutrient contributions from the five upper most tributaries that enter the system above Interstate 85 (Ellerbe Creek, Eno River, Flat River, Little River, and Knap of Reeds Creek). The USGS maintains several gages that provide daily, as well as 15-minute, flow data for these uppermost tributaries. The monitoring program will likely include the continued support of many of the existing USGS gages on these tributaries in the Upper Falls Lake Basin. It is important for this data to have the highest degree of accuracy (gage based) since flows from these five main tributaries have a significant influence on Falls Lake water quality predictions (Cardno ENTRIX Draft Model Sensitivity Memo, March 7, 2014).

As currently configured the NCDWR Falls Lake Nutrient Response Model's predictions are much less sensitive to flows and nutrient inputs from the other 12 tributaries that enter the middle and lower sections of Falls Lake (Cardno ENTRIX Draft Model Sensitivity Memo, March, 2014). There are no active USGS flow gages in the middle and lower part of the Falls Lake watershed, other than a stage only gage in the upper portion of the Little Lick Creek watershed. Due to these considerations, some additional uncertainty in flow estimates may be tolerable for these middle and lower Lake tributaries. However, the flow estimation methods identified in this TM will still allow effective flow estimation at jurisdictional boundaries. As a result, the flow estimation methods investigated in this document could be used to provide the flow data needed for specific tributaries instead of installation of a new USGS gage.

Understanding daily streamflow is critical for a wide range of hydrologic and management issues, and the development of methods for predicting flow time series at ungaged locations is an active focus of hydrologic research. The recent development of models and estimation techniques by NCDENR (WARMF, Cape Fear and Neuse River Hydrologic Model), USGS (Archfield et al. 2013), along with other new models and existing techniques highlights the need for assessing the capability of these approaches for estimating streamflow in the Falls Lake watershed. Methods for predicting streamflow range from highly parameterized, process-based watershed models to straight-forward, ratio-based calculations stemming from simple assumptions about how drainage area affects flow.

Cardno ENTRIX has completed an evaluation of several flow estimation approaches with respect to their utility and cost-effectiveness for predicting streamflows in ungaged areas of the Falls Lake watershed. This TM briefly describes each approach in terms of methodology, utility, limitations, and level of effort necessary for implementation. The following sections describe each of the flow estimation methods considered for this project. A brief description of each method is provided with its limitations, assessment of accuracy of flow predictions if applicable, history of use, level of effort, and cost of using the method (license fees, etc.), and potential best use by the UNRBA.

The flow estimation approaches are discussed in two groupings.

- Group 1: This group includes existing hydrologic and watershed models.
- Group 2: This group includes alternative statistically based techniques for predicting flow.

A number of existing models and approaches were evaluated for their potential use to predict daily stream flows:

- The State of North Carolina's Neuse River Basin Hydrologic Model or combined Cape Fear and Neuse River Hydrologic Model. These models were developed using HydroLogic's OASIS software. (Group 1)
- The Research Triangle Institute's Watershed Flow and ALLocation (WaterFALLTM) Watershed Modeling Tool. (Group 1)
- The State of North Carolina's existing Falls Lake Watershed Model. This model was developed using the Watershed Analysis Risk Management Framework (WARMF). (Group 1)
- The Basin Proration Approach (Group 2)
- USGS's Flow Regionalization Method (Group 2)

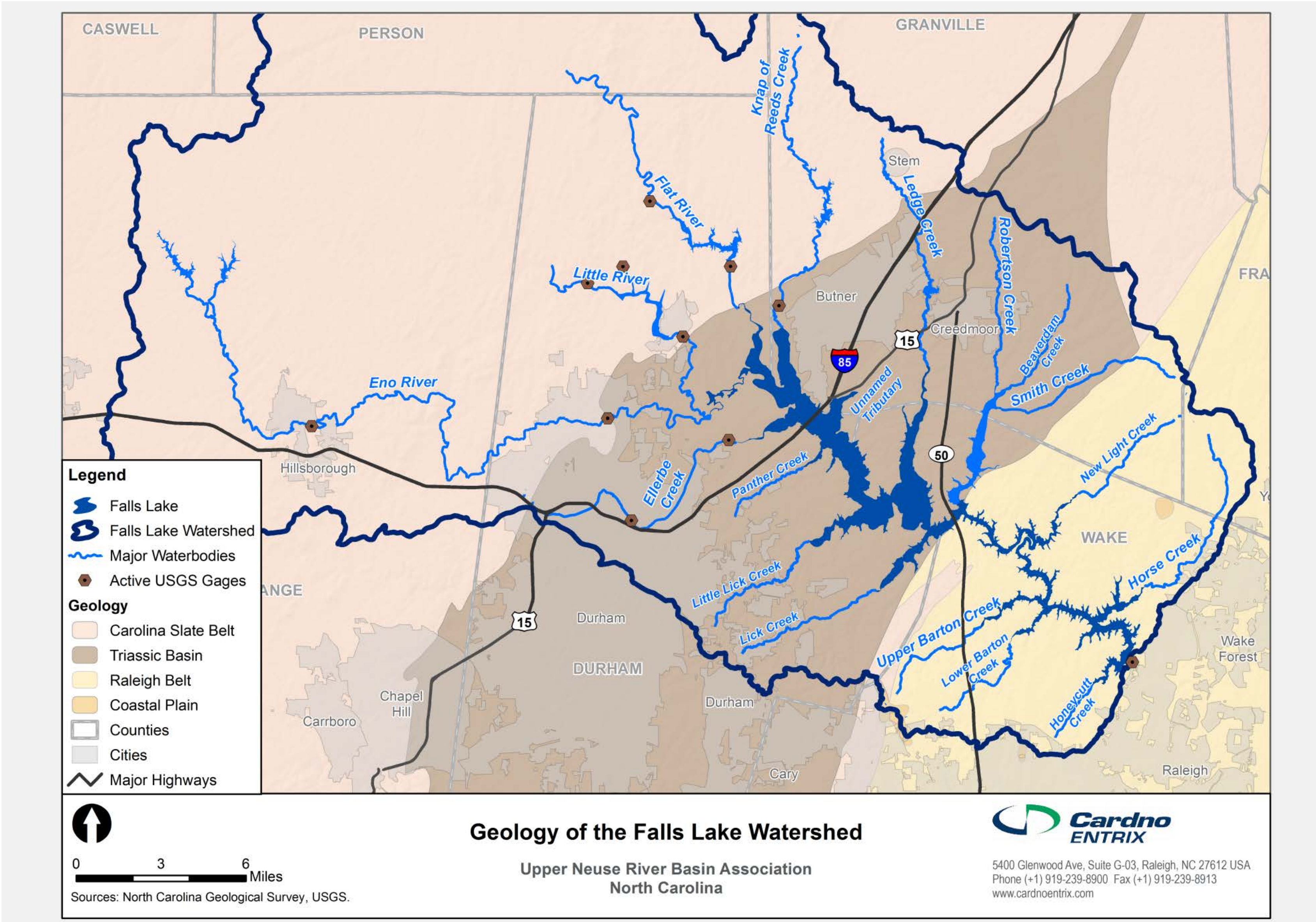

Figure 2-1 Distribution of geologic conditions across the Falls Lake Watershed. The "upper" watershed and its tributaries are those located upstream of I-85. The "middle" watershed is that area between I-85 and Highway 50 (Creedmoor Road). The "lower" watershed is the area between Highway 50 and the Falls Lake Dam. The USGS gages shown are those that provide realtime flow data. Stage only gages in the watershed are not included on this figure.

3 Group 1 Hydrologic and Watershed Models

These models were identified as existing tools that provide flow estimates for different portions of the Falls Lake watershed. They were reviewed to see if the resolution of the flow estimates is sufficient for UNRBA uses, if the models as is will not be sufficient, and whether updates to the model could provide cost-effective flow estimates at the locations where this information is needed.

3.1 Neuse River Basin Hydrologic Model

The OASIS based Neuse Basin Hydrologic Model is a planning level model used primarily for water supply planning. The purpose of the model is to help State agencies evaluate the availability of water for communities and instream uses under various water management and drought scenarios.

Past Use

The OASIS model has not been used to generate daily or sub-daily (smaller increments than daily flows) flows to develop hydrodynamic models or to predict flows in ungaged tributaries.

Limitations

> OASIS is used for “assessing the impacts of different water allocation policies and facilities over the historic record of inflows. It works on a daily time step and is intended for drought management and capital expansion planning. It is not intended for use in hydraulic routing nor flood management, although it can be linked to other models for those purposes (Hydrologics 2009)” as flow inputs to the hydraulic models.

> The baseline scenario was developed assuming year 2010 water demands future flow predictions would need to include updated water demands.

> OASIS is calibrated to monthly flows, so extending the model to predicting flows at a smaller time step may be inaccurate. Inputs from wastewater treatment plants and water supply demands are specified as monthly averages.

> OASIS uses a mass balance approach to predict the volume of flow from drainages that are not directly simulated as nodes. All of the ungaged Falls Lake tributaries for which we would want to predict flows fall into this category.

> Flows from nongaged areas are accounted for by scaling gaged flows, similar to the basin proration approach.

Accuracy of Flow Predictions

Accuracy was not evaluated for this model because it cannot be used to predict flows at a daily time step for ungaged tributaries in the lower Falls Lake watershed. For future model updates the UNRBA needs daily flow inputs at all 17 tributary input locations required by the EFDC model.

Level of Effort

NA

Costs

NA

Best Use for the UNRBA

The model's calibrated time step does not match what is needed for updating the Falls Lake Nutrient Response Model. Flows for the middle and lower tributaries to Falls Lake were estimated using a mass balance approach, which will not easily provide daily flow data for ungaged locations in the future and due to the way the model is configured, does not provide flow at jurisdictional boundaries. Updating OASIS to provide the flow data that the UNRBA needs is not a cost effective decision compared to the good alternatives that are available. Daily flow estimates could be estimated for each tributary and jurisdictional boundary and then input into the model. This work would have to be done in cooperation with NCDWR since this is a proprietary model that is managed and updated by the State of North Carolina in cooperation with HydroLogics.

3.2 Watershed Flow and ALLocation (WaterFALL^{TM}) Watershed Modeling Tool

WaterFALL (Watershed Flow and ALLocation) is a proprietary watershed model and decision-support tool developed and marketed by Research Triangle Institute International (RTI). According to RTI's marketing brochure[1], the model itself is a modified version of the hydrologic model, Generalized Water Loading Function (GWLF). The GWLF is a semi-distributed model that considers spatial heterogeneity such as land use, soil moisture, etc. within each modeled subbasin. The model operates on a daily time step and produces output at monthly or annual intervals. For example the GWLF model outputs monthly accumulated nutrient loads based on a daily water balance.

The WaterFALL Model appears to have a user-friendly web-based, GIS interface that accepts geography and drainage area inputs from EPA's enhanced National Hydrography Dataset (NHDPlusV1)[2]. Released in 2006, NHDPlusV1 includes the 2006 version of the 1:100k National Hydrography Dataset (NHD) and the 2004 version of the 30m National Elevation Dataset. This dataset represents the drainage network and was designed for use in analysis of surface water systems and for general mapping.

Accuracy of Flow Predictions

Model performance metrics are not publically available but could be requested from RTI.

Limitations

> Although RTI will provide users with WaterFALL validation methods upon request, model performance has not been vetted by independent parties. Detailed documentation, as either marketing materials or peer-reviewed articles on the model, cases studies, and model performance, is unavailable.

> In 2011, NHDPlusV1 was replaced in its entirety by NHDPlusV2.1, which is considered "far superior" to its predecessor[3]. Significant improvements include use of updated hydrography, new interconnections, correction of flow routing, and added spatial detail using high resolution imagery to verify hydrography and interconnections. Mean annual flow estimates were also updated. Users of NHDPlusV1 were urged to convert their programs to accept NHDPlusV2.1 data. Unless it has been recently updated, WaterFALL models built for the Upper Neuse basin and the surrounding region were developed and calibrated using NHDPlusV1 data (1960-2006). In addition, NHDPlusV2.1 is maintained through a 3rd party vendor, Horizon Systems.

> Model outputs may not be available or accurate at the timestep needed for updating the Falls Lake Nutrient Response Model.

Past Use

WaterFALL has not been used to generate daily or subdaily flows to develop hydrodynamic models. It has been modified to investigate the potential impacts of global climate change on water availability across Latin America. In the past few years, RTI partnered with The Nature Conservancy on a South Atlantic Landscape Conservation Cooperative (SALCC) funded project to understand climate change and urban growth models on stream flows and ecological systems.

Level of Effort

Uncertain

Costs

As previously noted, WaterFALL is proprietary. Associated costs would include model customization (perhaps updating to incorporate NHDPlusV2.1) and calibration, user training, and as-needed technical support.

[1] RTI Int. "WaterFALL – Watershed Flow and Allocation Modeling System Using NHDPlus." http://www.rti.org/brochures/waterfall.pdf

[2] "NHDPlus Version 1 (Archive)" http://www.horizon-systems.com/NHDPlus/NHDPlusV1_home.php

[3] "NHDPlus Version 2" http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php

[4] http://api.ning.com/files/G16f2WzxUHhiyFmvyMXXg41u7i-lOSmvCnrBjifWbmj5PKrOPuX*fK-q5ex9bqAO-Za4GqoHhr9Fy12WvXua5rG4wnsaYJmk/TNC_flows_for_web.pdf

[5] http://api.ning.com/files/hzHalJRlCScsrNHy-zd*NVjO5HZ88XSEFhbsbmF8qk07W9DiIGld2t7wFONhz179ct*8t3sDzdPOo4ir5REEPYf64645iFD2/Predictingbaselinealteredandfutureinstreamflows March202013.pdf

Best Use for the UNRBA

The benefits and cost of using this model are unknown at this time.

3.3 Falls Lake WARMF Watershed Model

The NCDWR developed the WARMF watershed model in part to predict flows and nutrient loads to Falls Lake. The WARMF model is a mechanistic model that uses model inputs such as meteorology, soil type, topography, and land use to predict flows and water quality in the Falls Lake watershed. The model operates as a lumped parameter model on 114 catchments that were delineated using a 30m digital elevation model. Within a lumped parameter watershed model, the hydrologic and water quality processes within a catchment are aggregated together. Within each catchment, the model assumes equal distribution of the watershed characteristics. A 30m digital elevation model (DEM) is three dimensional representation of the land surface based on a dataset of elevations measured at regularly spaced intervals. For the 30m model the watershed area is divided into squares with 30 meter long sides. Any watershed feature that is smaller than the 30 meter cells will not be detected. Digital Elevation Models are commonly used to map and model drainage areas and land uses.

The WARMF results were taken from the Falls Lake Watershed Analysis Risk Management Framework (WARMF) Development Final Report (NCDENR 2009). The NCDENR Report includes published WARMF model performance for the six gages identified in Table 3-1 (NCDENR 2009). The report can be found at the following location: http://portal.ncdenr.org/c/document_library/get_file?uuid=ccb8d8f8-a74b-415f-97f9-5e5f621255e6&groupId=38364

Past Use

The WARMF model has been used by USEPA and several State agencies to develop watershed loading estimates and TMDLs.

Limitations

> The existing WARMF model developed by NCDWR uses a 2001 National Land Cover Dataset that also incorporates NCDOT road right-of-way data. Using the model to predict flows in future years to correlate with the UNRBA monitoring program would require revising the land cover data set and recalibrating the model.

> Because the model is a lumped parameter model, catchment delineations must correspond to the location where flows are needed. Higher resolution delineation of specific watersheds in the model would be needed to quantify flows and water quality at jurisdictional boundaries or other locations not defined by the current model.

> The model has not been calibrated to predict flows in the smaller tributaries in the lower part of the Falls Lake watershed and the NCDENR final model report cautions against using WARMF results to predict flows in these areas (NCDENR 2009).

Table 3-1 USGS Gages and One Ungaged Location in the Falls Lake Watershed Used to Evaluate Flow Estimation Methods

Stream	USGS Gage Number and accuracy rating[1] for most recent year available.	Drainage Area (sq. mi.)	Period of Record for Daily Flows	Annual Avg. Mean Daily Flow (POR)[2]	Annual Avg. Mean Daily Flow 2011	Description and Predominant Characteristics[3]
Gaged Locations						
WARMF Calibration locations						
Knap of Reeds at WWTP outfall near Butner, NC	02086624 Fair	43	1982-10-01 to 2014-01-02 (with multi-year data gaps)	38.1 cfs (1983-2012)	9.89 cfs	Lower part of Knap of Reeds Creek watershed Downstream of SGWASA WWTP (permitted flow of 8.5 cfs) and Lake Butner Land use forest (66%) and cropland (14%) Hydrologic soil groups B (43%) and C (51%) Geologic formation TB (18%) and CSB (82%)
Ellerbe Creek near Gorman, NC	02086849 Good	21.9	1982-10-01 to 2014-01-02 (with multi-year data gaps)	40.0 cfs (1983-2012)	31.1 cfs	Lower part of Ellerbe Creek watershed Downstream of the North Durham WRF (permitted flow of 31 cfs) Land use developed (75%) and forest (16%) Hydrologic soil groups B (12%), C (17%), and D (61%) Geologic formation TB (94%) and CSB (6%)
Eno River at Hillsborough, NC	02085000 Good	66	1927-10-01 to 2014-01-02	58.7 cfs (1928-2012)	16.4 cfs	Upper part of the Eno River watershed Downstream of Lake Orange, and West Fork of the Eno River Reservoir Land use forest (56%) and cropland (25%) Hydrologic soil groups B (72%) and C (24%) Geologic formation CSB (100%)
Eno River near Durham, NC	02085070 Good	141	1963-09-01 to 2014-01-02 Mean daily flow since 10/1/1985 = 118.8 cfs	123 cfs (1963-2012)	42.1 cfs	Lower part of the Eno River watershed Downstream of the Hillsborough WWTP (permitted flow rate of 4.6 cfs) Land use forest (59%) and cropland (17%) Hydrologic soil groups B (76%) and C (21%) Geologic formation TB (2%) and CSB (98%)
Flat River above Lake Michie	02085500 Good	149	1925-08-01 to 2014-01-02	140 cfs (1925-2012)	48 cfs	Middle part of the Flat River Watershed Upstream of Lake Michie Land use forest (57%) and cropland (29%) Hydrologic soil groups B (54%) and C (44%) Geologic formation CSB (100%)
Little River at SR1461 Near Orange Factory, NC	0208521324 Fair	78.2	1987-09-30 to 2014-01-02	67.8 cfs (1987-2012)	21.1 cfs	Middle part of Little River watershed Upstream of Little River reservoir Land use forest (60%) and cropland (26%) Hydrologic soil groups B (69%) and C (27%) Geologic formation CSB (100%)

Stream	USGS Gage Number and accuracy rating[1] for most recent year available.	Drainage Area (sq. mi.)	Period of Record for Daily Flows	Annual Avg. Mean Daily Flow (POR)[2]	Annual Avg. Mean Daily Flow 2011	Description and Predominant Characteristics[3]
Gaged Locations						
USGS Gage Locations in Upper Watershed where WARMF was not calibrated (limited to sites with data available after 1999; excludes gages directly downstream from Lake Michie and the Little River Reservoir)						
Sevenmile Creek	02084909 Poor	14.1	1981-06-24 to 2004-10-21	13.4 cfs (1981-2004)	NA	Bottom of Sevenmile Creek Tributary to Eno River at Hillsborough Land use forest (68%) cropland (16%) developed (10%) Hydrologic soil groups B (74%) C (20%) Geologic Formation CSB (100%)
Mountain Creek at SR1617 near Bahama, NC	0208524090 Good	7.97	1994-10-01 to 2014-01-02	6.47 cfs (1995-2012)	2.12 cfs	Bottom end of Mountain Creek watershed Upstream of Little River Reservoir Land use forest (52%) cropland (32%) Hydrologic soil groups B (77%) and C (16%) Geologic Formation CSB (100%)
Unnamed Tributary to the Flat River	0208650112 Good	1.14	1988-03-01 to 2012-09-30	0.88 cfs (1988-2012)	0.29 cfs	Lower part of the Flat River Watershed Land use forest (93%) Hydrologic soil groups B (74%), and C (26%) Geologic Formation CSB (100%)
UNGAGED Location						
Robertson Creek at Brassfield Road	NA	12.2	None	NA	NA	Bottom end of Robertson Creek watershed Upstream of Beaverdam Arm of Falls Lake Land use forest (55%) cropland (16%) grassland (11%) developed (10%) Hydrologic soil groups C (90%) Geologic Formation TB (98%)

[1]Accuracy Rating: rating by USGS describing accuracy of flow measurements for a particular time period at a particular gage. Excellent: 95% of daily discharge values are within 5% of true value; Good: within 10%; Fair: within 15%; Poor: less than “Fair” accuracy.

[2]POR=Period of Record

[3]Geologic Areas: TB=Triassic Basin, CSB=Carolina Slate Belt, RB=Raleigh Belt

Accuracy of Flow Predictions

The WARMF model performance for the model's validation period (2007) is provided in Table 3-2 (From DENR 2009). Predictions outside of the recommended ranges are shaded in Table 3-2. The recommended criteria included in Table 3-2 come from the Falls Lake Watershed WARMF Final Report (NCDENR 2009). The year 2007 was a drought of record and the high positive flow statistics indicate that the model seems to over predict flows during this extreme drought year, particularly as the drought persisted into the fall. The model predicts most accurately at locations with contributions from wastewater treatment plants (Knap of Reeds and Ellerbe Creek at Gorman).

Table 3-2 WARMF Model Predictions for 2007 – Validation Year. Shaded cells indicate values that are outside of the recommended range for hydrologic model performance.

Statistic	Reco-mmended Criteria	Knap of Reeds	Flat River above Lake Michie	Little River above Reservoir	Eno near Hills-borough	Eno near Durham	Ellerbe Creek at Gorham
Total predicted instream flow volume	±10%	5.6%	1.7%	-8.5%	*-19.5%*	*13.4%*	-7.6%
Total volume of highest 10%of flows	±15%	6.8%	-3.0%	13.9%	-13.2%	*18.7%*	-7.6%
Total volume of lowest 50%of flows	±10%	*15.9%*	*115.6%*	*60.8%*	*62.5%*	*115.2%*	-10.5%
Total 1st quarter flow volume	±30%	9.6%	*606.8%*	10.5%	-15.6%	16.5%	-4.6%
Total 2nd quarter flow volume	±30%	-3.9%	-0.5%	*-55.8%*	*-39.2%*	-10.8%	-15.8%
Total 3rd quarter flow volume	±30%	16.1%	-10.0%	*193.9%*	*140.4%*	*365.7%*	2.4%
Total 4th quarter flow volume	±30%	Model ended in September 2007					

Level of Effort

Updating the WARMF watershed model to predict flows in all areas needed by the UNRBA would require revisions to the land use and meteorology data set for a different calibration year, additional subwatershed delineations, and calibration to smaller watershed areas. This would require about 3 to 6 months of time and labor to calibrate the model for all locations where flow predictions would be generated. The meteorological data (temperature and precipitation for example) would have to be updated for each year the model is used to estimate flows.

Additional Costs

The existing NCDWQ WARMF model is publically available. There are no licensing fees for acquiring or running the model.

Best Use for the UNRBA

The WARMF model may be useful for predicting flows in the middle lake tributaries of Ellerbe and Little Lick Creeks where the City of Durham is in the process of revising the Falls Lake WARMF model by sub-delineating some of the catchments and reducing the time step from daily to hourly.

4 Group 2 Alternative Flow Estimation Methods

The two Group 2 flow estimation methods, the Basin Proration Method (also called drainage area ratio method) and the USGS Streamflow Regionalization Method (also referred to as the Archfield method), were used to estimate flows at gaged and ungaged locations. Both approaches use flows from nearby gaged sites (donor sites) to estimate flows at ungaged locations. The Basin Proration method is a simple approach that is widely used. The USGS Streamflow Regionalization method was developed in 2013 by Archfield et al. and applied across the multi-state Connecticut River Basin. This method predicts flows at an ungaged location based on its watershed characteristics.

Flow predictions were compared at a number of gaged locations and at one ungaged tributary (Robertson Creek) in the lower section of Falls Lake (Table 3-1). An ungaged tributary in the lower section of the Falls Lake watershed was included in order to explore model predictions in a region with different underlying geology than the currently gaged locations (Figure 2-1). Using pairwise comparisons of model predictions and observations, each methodology’s results were compared to flows reported by USGS. The accuracy of the predictions can be measured at gaged locations by visually evaluating time series plots and by calculating the Relative Error (RE) and the Coefficient of Efficiency (CE), from Nash and Sutcliffe 1970, described in Appendix A. The RE measures difference between the predictions and the observations. An RE can be close to zero, meaning that mean conditions were predicted extremely well. A model can have an RE of close to zero, but still not do a good job of predicting the variability around the mean. The CE is used to identify how well model predictions reflect the variability seen in the actual data. When interpreting the CE, perfect predictions would have a CE of 1.0. If the CE is equal to zero, the model does not predict daily flow any better than the mean value over the period of record. Values of CE below zero indicate the model is a worse predictor of flow than the mean value.

The flow estimation methods discussed in this section do not have built-in mechanisms for including wastewater flow or water withdrawals in their predictions. Flow predictions from these methods will not be accurate downstream of WWTP sites without implementing supplemental steps to account for wastewater returns or water withdrawals.

4.1 Basin Proration Method

The basin proration method, sometimes called the drainage area ratio method, is a frequently used approach where flows at a gaged location (referred to as the donor gage) are scaled by a ratio of drainage areas to predict flows at an ungaged location. The ratio is calculated as drainage area of the non-gaged location divided by drainage area of the gaged location:

$$Ungaged\ Flow = \text{Gaged}\ Flow \times \frac{Drainage\ Area\ at\ Ungaged\ Location}{Drainage\ Area\ at\ Gage}$$

The method assumes that each unit of area in the watershed contributes equally to the runoff observed in the stream. For example: flow predicted for a 50 mi^2 watershed from a gaged site with a drainage area of 100 mi^2 would be exactly half that of the donor site. Factors that alter flow which are unrelated to watershed area (such as WWTP discharges, reservoir withdrawals, rainfall coverage, or land use and geology) limit the accuracy of this approach. When the method is applied to Ellerbe Creek below the North Durham Water Reclamation Facility (WRF) (USGS gage 02086849) the predictions using the nearby Eno River gage as a donor miss most of the large flow events and also under-predict base flows (Figure 4-1).

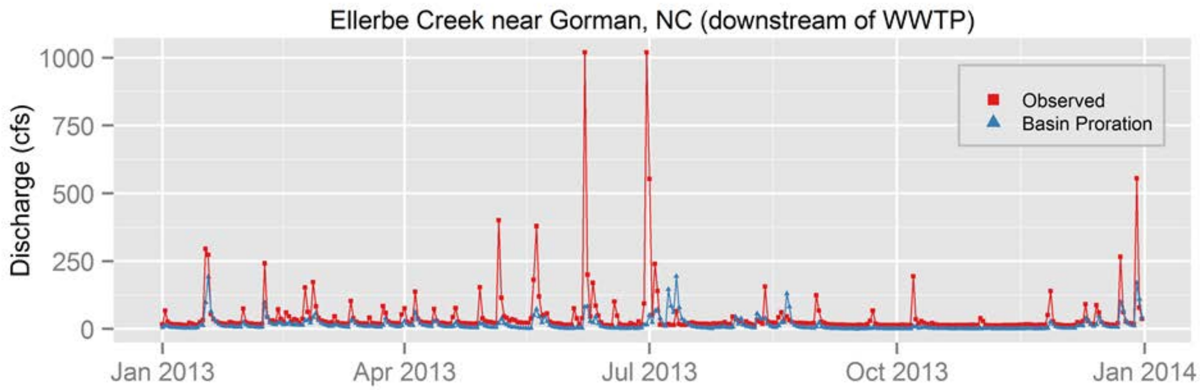

Figure 4-1 Time series of observations and predictions at the Ellerbe Creek site downstream of the City of Durham WRF. The basin proration method misses the peaks and elevated baseflow attributable to the WRF discharge

Because the basin proration method directly scales flow from a donor site, the use of different donor sites will likely produce different flow predictions. To demonstrate the degree of sensitivity of flow estimation to donor site selection the basin proration method was tested using three different donor sites for each test location: Eno River at Hillsborough (USGS Gage 020085000), Little River at SR 1461 (USGS Gage 0208521324), and a third donor was identified for each test location using a map-correlation technique. The map correlation approach selects the site that is statistically most likely to have similar flows as the test location (Archfield and Vogel 2010). The map correlation technique selects the gage predicted to have the best correlation in daily flows with the ungaged site based on distance and observed correlations among all gages in the network. A more detailed description of the map-correlation approach is included in Appendix A.

4.1.1 Basin Proration Results

The basin proration method was used to predict flows at each of seven gaged locations in the Upper Falls Lake watershed not directly downstream from WWTP discharges or large impoundments. Statistics showing the coefficients of efficiency and relative errors for the flow predictions are shown in Table 4-1 for a selection of sites; a set of tables for all test locations can be found in Appendix A.

Predictions of flow do vary with the selection of a donor gage, highlighting the importance of selecting an appropriate gage. Figure 4-2 shows predictions of flow in the Eno River (at Durham) using two different donor gages (Mountain Creek and Eno River at Hillsborough). The two flow predictions are plotted with the actual measured flow for the years 2010 through 2013 (See Appendix B for figures showing years 1995-2013). Using the Eno River gage at Hillsborough as the donor gage to estimate Eno River flow at Durham produces more accurate flow estimates than using Mountain Creek as the donor gage. The Mountain Creek gage predicted higher flow peaks and higher low flows (green line) than what was actually observed in the Eno River at Durham (red line) over the time period shown. Over the entire period evaluated, however, the relative error is close to zero (0.09%) (Table 4-1), indicating that using this method with flows from Mountain Creek predicts the long-term flow volume (also the long-term average daily flow) with very little bias. The low coefficient of efficiency (0.37), however, indicates that the day-to-day predictions are not very good. The flow statistics for the predictions made using the Eno River at Hillsborough gage (blue line) confirm the goodness-of-fit seen by eye: high coefficient of efficiency (>0.9) and low relative error (<2%). The contrast between the predictions shown in this figure illustrates the entire range seen in goodness-of-fit for our test locations: no predictions are better than the Eno River (Hillsborough) prediction of Eno River (Durham) (CE=0.90) and no predictions are worse that the

Mountain Creek prediction of Eno River (Durham) (CE=0.37) (Figure 4-4). Appendix B includes flow series predictions and measured observations for multiple years at many of the other gaged sites in the upper Falls Lake watershed.

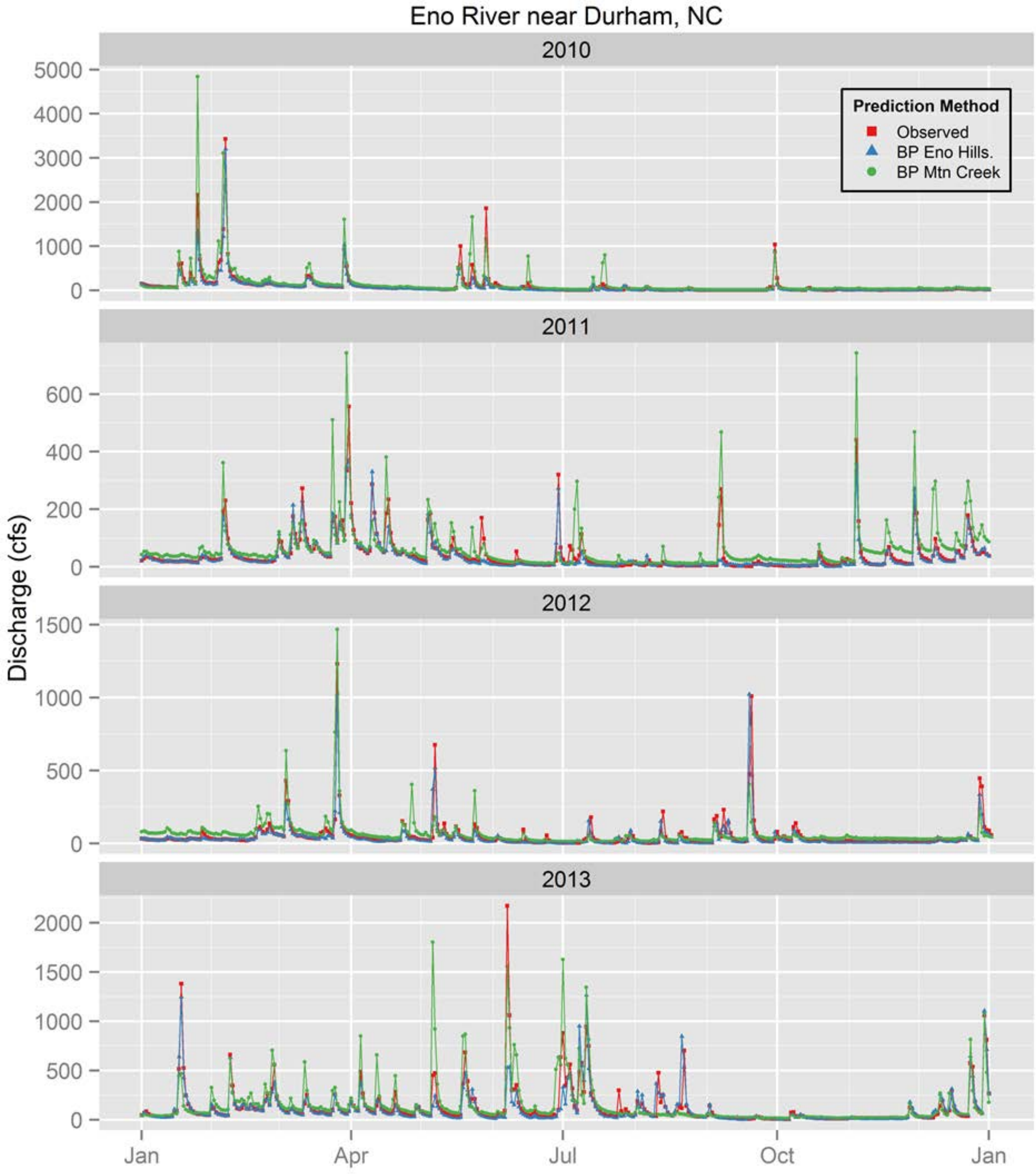

Figure 4-2 **Observed and predicted flows for the Eno River gage near Durham, NC (Gage 02085070) using two different sites as donors; Eno River at Hillsboro and Mountain Creek at SR 1617 near Bahama.**

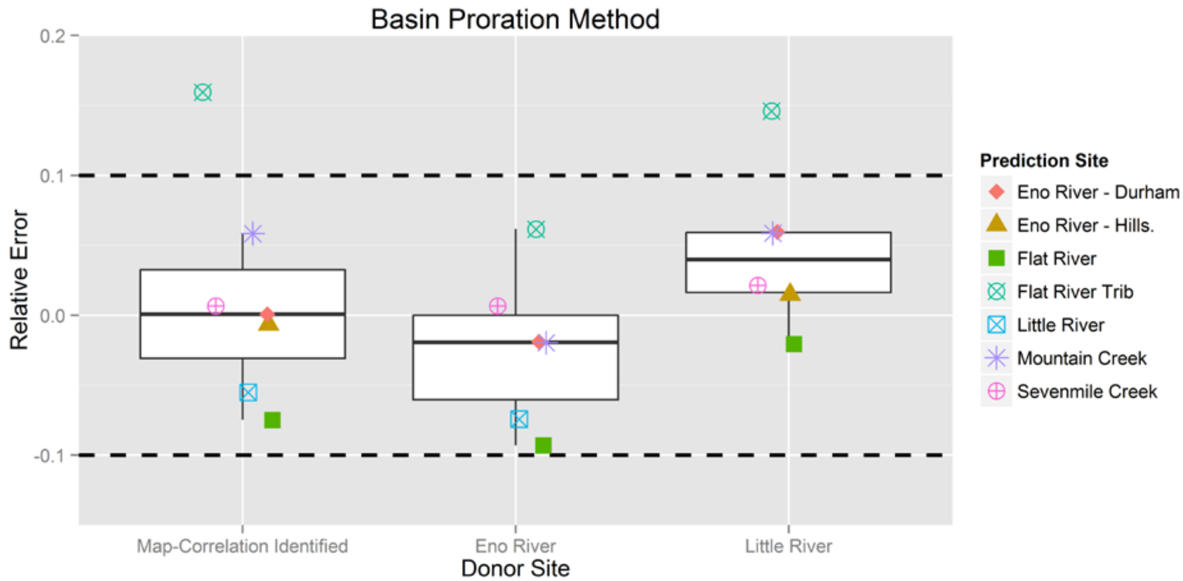

Figure 4-3 **Relative error (RE) in mean daily flow predictions at seven locations (y axis) made using basin proration with different donor sites (x axis).** An RE equal to zero indicates the average model prediction is equal to the average observed value and RE values within ±0.1 are considered acceptable. The relative error shown is for the period of record over which data are available at both the donor site and the site for which predictions were made (see Table 3-1). The points for the "map-correlation identified" site show the result using site-specific donors. Each site (each point) in this category may have been produced using a different donor gage.

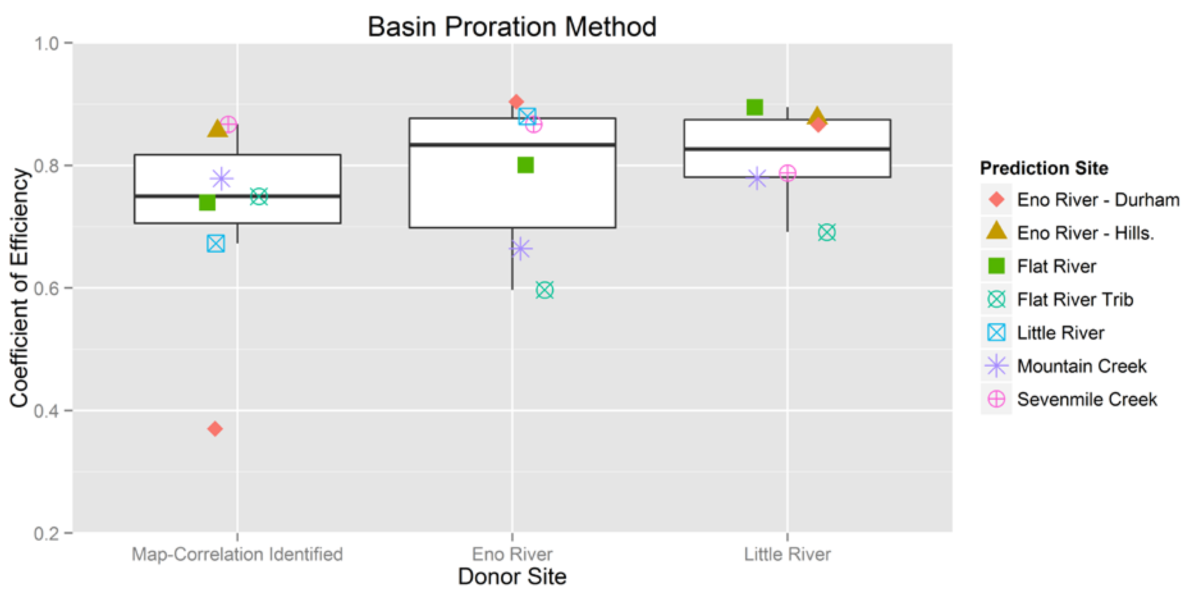

Figure 4-4 **The Coefficient of Efficiency (CE) for mean daily flow predictions (y axis) made using basin proration with different donor sites (x axis).** A CE equal to 1.0 indicates the model perfectly predicts the day to day variation in flow, while a value of zero indicates the model is only good at predicting the average flow over the period of record. The CE shown is for the period of record over which data are available at both the donor site and the site for which predictions were made (see Table 3-1). The points for the "map-correlation identified" site show the result using site-specific donors. Each site (each point) in this category may have been produced using a different donor gage.

The goodness of fit statistics for the different Basin Proration predictions are shown in Figures 4-3 and 4-4. In Figure 4-3, box plots illustrate the distribution of relative errors for model predictions at the seven Falls Lake watershed gages with the actual data-points overlain on top. The boxes range from the 25th to 75th percentile with median relative error show in the middle. The Map Correlation grouping shows the relative error in mean daily flows predicted from using the donor gage with the highest predicted correlation of daily flow to the flow prediction site. The Eno River grouping shows flow estimates based on using the Eno River at Hillsborough (gage 02085000) as the donor gage. The Little River grouping shows flow estimates based on using the Little River upstream of the Little River Reservoir (gage 0208521324) as the donor gage. The dashed horizontal reference lines are shown for +/- 10% error which has been suggested as a performance target for flow prediction models (NCDENR 2009).

The predictions of the average daily mean flows (and also total flow volume) over the period of record had relative errors within +/- 10% of measured flow for all sites predicted by the Eno River gage and for all but one site when predicted by the Little River flow (Figure 4-3). In that case, the outlier still had predictions within 15% of measured values and the site is a very small catchment (1.1 mi^2) for a tributary to the Flat River (USGS Gage 0208650112). Overall the median bias (the thick central line in the boxes) for sites predicted by the Eno River was -1.9% and the median bias for sites predicted by the Little River was 4.0%.

The coefficients of efficiency for all predictions were between 0.37 and 0.90 for all sites, with most values falling between 0.60 and 0.90. As expected, the coefficient of efficiency does not appear to be uniformly better for any single donor site than another: the choice of a donor gage is specific to the site in question and no single site will be the best donor for all locations.

In addition to the evaluation of statistics describing the predictions of total flow (i.e. relative error and coefficient of efficiency presented above), it is also important to review how well predictions match observed flows specifically during times of high flow and low flows, and also how they match the seasonality of flow. Table 4-1 compares the relative errors in predictions over different subsets of the observations using different donor gages. These are the same model performance metrics used in the WARMF model report (NCDENR 2009). For flows at both Eno River locations, the basin proration method produces flow estimates that fall within the recommended ranges for total flows, high flows, and for total flows by season. The relative error in predictions for the lowest 50% of flows falls outside the +/- 10% range for some donor gages, but in each case at least one donor produces estimates within the recommended tolerance. While the percentage error is greater for these low flow predictions, these are calculated for low flows. The absolute error associated with a 10% error in the low flows is much smaller than a 10% error in the high flows.

Table 4-1 Basin Proration Model Predictions for Two Eno River Locations. Observed Flow Compared to Flow Predictions Using two different donor gages. Shaded cells indicate values outside of the recommended ranges. Statistics are calculated over the entire period for which data were available at both the donor site and the site for which predictions were made.

		Predicted Flows at Eno River at Hillsborough: 02085000				Predicted Flows at Eno River near Durham: 02085070			
	Target Criteria	Observed (mean daily cfs)	Basin Proration Donor sites			Observed (mean daily cfs)	Basin Proration Donor sites		
			Map-correlation selected (Seven mile Creek)	Little River	Eno River at Hillsb.		Map-correlation selected (Mountain Creek)	Little River	Eno River at Hillsb.
Coefficient of Efficiency		--	0.856	0.877	--	--	0.37	0.866	0.904
Mean Daily Flow	+/- 10%	63.6	0.63%	1.47%	--	113	0.088%	5.95%	1.89%
Highest 10% of flows	+/- 15%	--	-1.35%	0.041%	--	--	2.79%	7.86%	-1.8%
Lowest 50% of flows	+/- 10%	--	10.7%	6.15%	--	--	-18.7%	-12.1%	-9.75%
1st quarter flow	+/- 30%	118	1.31%	2.99%	--	185	-1.09%	7.56%	-1.0%
2nd quarter flow	+/- 30%	65.1	-2.64%	-5.23%	--	113	-5.33%	0.669%	-1.38%
3rd quarter flow	+/- 30%	31.2	-3.26%	7.35%	--	72.7	12.1%	0.284%	-9.52%
4th quarter flow	+/- 30%	41.1	-0.974%	3.19%	--	81.9	-0.472%	14.2%	2.01%

[1]MC=Donor gage selected by map-correlation method

Past Use

This technique is commonly used for estimating flows in ungaged locations. For example, NCDWQ used this method for estimating daily inflows to Falls Lake to develop the EFDC lake response model.

Limitations

> The quality of predictions varies with donor gage selection. For an ungaged location with multiple potential donor gages, it is not possible to know which donor gage will produce the most accurate predictions and the user must use his or her best judgment to select a representative gage. This can be accomplished using the map correlation approach, selection based on shared watershed characteristics (land use, soil characteristics, etc.), or a combination of these approaches.

> The influence of wastewater treatment plants and impoundments must also be considered during donor gage selection and site flow predictions. The presence of these factors limits the accuracy of the flow predictions. The accuracy can be improved if WWTP discharge rates or water withdrawal quantities are known and omitted from or added to the fraction of flow that is scaled by the basin proration method, but this can be a time consuming data collection and preparation effort.

> No gages are located in the middle and lower half of the watershed to verify the accuracy of this technique for this portion of the basin. However, given the limited sensitivity of the Falls Lake Nutrient Response model to inputs from these ungaged tributaries, (Cardno ENTRIX Model Sensitivity TM), this may be an acceptable level of uncertainty. Alternatively, the addition of a USGS gage to this section of the basin would provide data for verification of the method as well as actual flow data.

Accuracy of Flow Predictions

The basin proration method is able to predict mean daily flows within 10% accuracy at sites without substantial flow alteration (wastewater flow or water withdrawals). Each predicted site had at least one donor gage that produced predictions accounting for 71% of the variability. See Section 5 of this document for a comparison of flow-prediction accuracy over all flow-estimation methods.

Level of Effort

The costs to apply this method are relatively low and include labor for downloading the USGS data, setting up, testing, and maintaining the spreadsheet and/or statistical models for donor site selection. Good fits (RE close to zero and CE close to 1) can be obtained with donor gages which are selected based on simple criteria. Slightly better fits might be obtained with a more quantified approach to donor gage selection. One possible approach identified by Cardno ENTRIX is the map-correlation method described in Sections 4.1.1 and A-2. This enhancement to the Basin Proration method could be implemented relatively easily and its application is evaluated in this TM. Additional improvements could use quantification of catchment characteristics to identify the most similar gaged locations for use as donor sites or predictions could be made based on multiple donor sites with the mean value used as the prediction.

Additional Costs

There are no licensing fees or additional costs associated with using this method.

Best Use for the UNRBA

This is a very cost-effective and reasonably accurate method to use to predict daily flows at ungaged jurisdictional boundaries and tributaries in the middle and lower sections of Falls Lake. Cardno ENTRIX has developed a modification to this method using the map correlation technique for selecting donor gages which could further improve the accuracy of flow predictions using this method. As noted, gage addition to the middle and lower section of the Lake could improve the accuracy of this method by providing a donor site near these areas. Should this method be selected, the benefits and costs of a new flow station will need to be evaluated further.

4.2 USGS Streamflow Regionalization Method

The basin proration method borrows streamflow from a neighboring stream gage and scales it proportionally to the drainage area. A streamflow regionalization approach expands the basin proration method by allowing the scaling to take into consideration additional catchment characteristics. Specifically, the UGSG Streamflow Regionalization approach uses many gaged stations and their catchment traits to create a set of regression models that are able to estimate a flow duration curve for an ungaged location. These watershed traits could include any feature for which region-wide data are readily available such as drainage area, land cover (e.g. percent forest, wetland, and impervious surfaces), soil types, geology, catchment slope and elevation, latitude or longitude, and mean annual precipitation. Further, the method allows different characteristics to inform different portions (high flow versus low flow) of the flow duration curve.

The addition of predictor variables other than drainage area, gives the Streamflow Regionalization Method the potential to more accurately predict streamflow throughout the Falls Lake catchment than the Basin Proration Method. To take full advantage of that potential, a large number of donor gages are required in order to encompass the full range of watershed traits over which predictions are desired. For example, if impervious surfaces are identified as an important predictor of flow, and predictions are desired for watersheds with impervious surfaces ranging from 5 to 20%, then the watersheds of the donor gages used in the analyses must also have that range of characteristics. The set of gaged catchments within the Falls Lake watershed do not fully represent the traits of watersheds in the lower part of the Falls Lake watershed. Most of the lower watersheds are smaller than the gaged watersheds in the upper section of Falls Lake. They also tend to be shorter and steeper. The gaged upper watersheds are primarily in Carolina Slate Belt, but the lower watersheds are a mix of Carolina Slate Belt, Triassic Basin, and Raleigh Belt. Therefore, to obtain a wide representation of watershed characteristics, data were included from gages across the North Carolina Piedmont for this analysis (Table A-1, Appendix A).

The methods and evaluations described below closely follow the approach described in Archfield et al. (2013) while noting areas where changes to the method might yield improved predictions (See section 4.2.2 “Potential Method Improvements”, below). Because application of this method was conducted as a pilot test of the approach, a reasonable model fit was obtained, but a rigorous fitting procedure to assure selection of the *best* possible model was not completed.

The Streamflow Regionalization method (Archfield method) includes three main steps: development of a flow duration curve for the ungaged site using a quantile regression method; selecting the best donor gage using the map-correlation method; and using the predicted flow duration curve to identify daily flow based on the observed flow percentile at the donor gage. The Archfield method is described in detail in Appendix A, Section A-3 and more details can be found in Archfield et al. (2013).

4.2.1 <u>USGS Regionalization Method Results</u>

The Streamflow Regionalization Method was evaluated using data from 69 USGS gages in the North Carolina Piedmont (Table A-1). The area included in the analysis was expanded beyond the gages of the Falls Lake catchment in order to obtain a large number of stream gages with a long record of flow (minimum of 15 years) and a wide diversity of catchment characteristics necessary for producing a robust model capable of predicting flows under a range of catchment characteristics. Flow predictions were made for each of the 69 gaged sites by running the model individually for each site while excluding data specific to that site from use in model development. The resulting flow predictions were then evaluated in the same way as the basin proration predictions described in Section 4.1. Representative time series of predictions are shown in Figure 4-5 and additional time series for multiple locations are presented in Appendix B. Fit statistics were calculated for each site and examined for all sites together and specifically for the Falls Lake gages. Relative error and the coefficient of efficiency (Nash and Sutcliffe 1970) are presented in Figure 4-6 and Figure 4-7, respectively.

Compared to the basin proration approach, the Streamflow Regionalization Method has a similar coefficient of efficiency but a higher relative error. Since relative error is sensitive to fluctuations in flows across all ranges of exceedance probabilities, and the coefficient of efficiency is more sensitive to higher flows, these results suggest that the regionalization method performs at least as well as the basin proration method for higher flows but does not do as well at baseflows. The Streamflow Regionalization Method does not appear to be providing a significant improvement in flow prediction accuracy over the basin proration method with the map-correlation enhancement (Figure 4-6 and Figure 4-7).

Table 4-2 compares the predicted to observed flows using different donor gages using the model performance metrics used in the WARMF model report (NCDENR 2009). The Streamflow Regionalization method did a pretty good job of predicting the highest 10% of flows, but its least accurate area of predictions were the lowest 50% of flows. It particularly overpredicted the lowest 50% of flows at the sites with the smallest watershed areas (Mountain Creek and the Tributary to the Flat River).

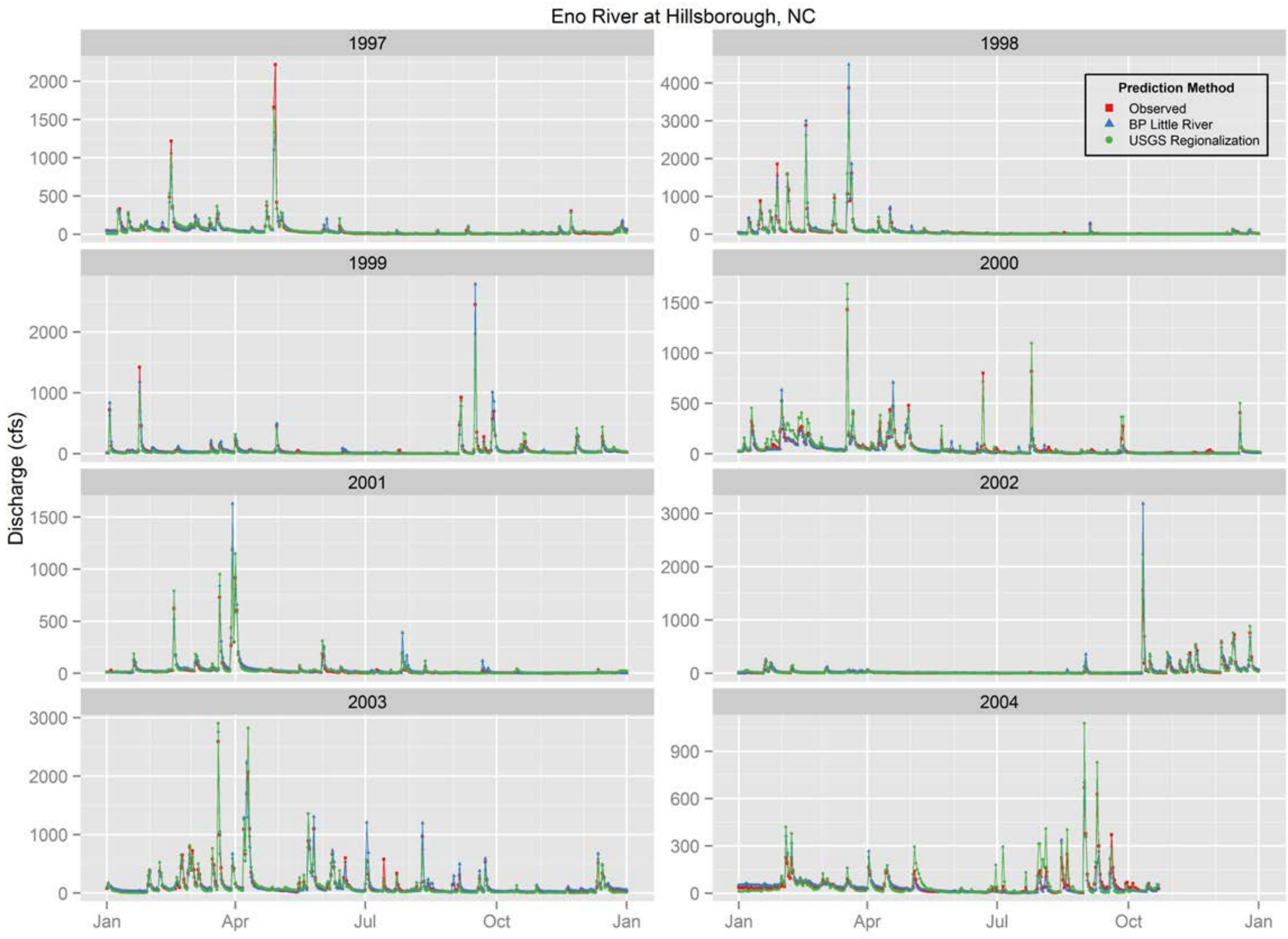

Figure 4-5 **Observed and predicted flows for the Eno River at Hillsborough comparing the regionalization and basin proration methods for a range of years.**

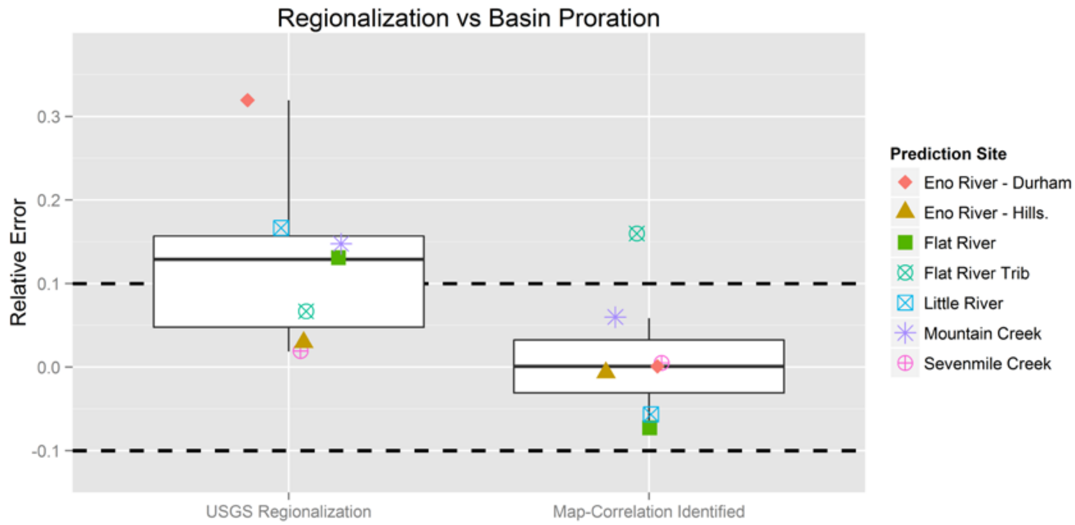

Figure 4-6 **Relative error in mean daily flow predictions (y axis) made using the same donor sites (x axis) for the regionalization and basin proration methods.** An RE equal to zero is the optimal value; it indicates the average model prediction is equal to the average observed value. Models producing RE values of 0 ± 0.10 (dashed horizontal lines) are generally recognized as reasonable. The relative error shown is for the period of record over which data are available at both the donor site and the site for which predictions were made (see Table 3-1). **.**

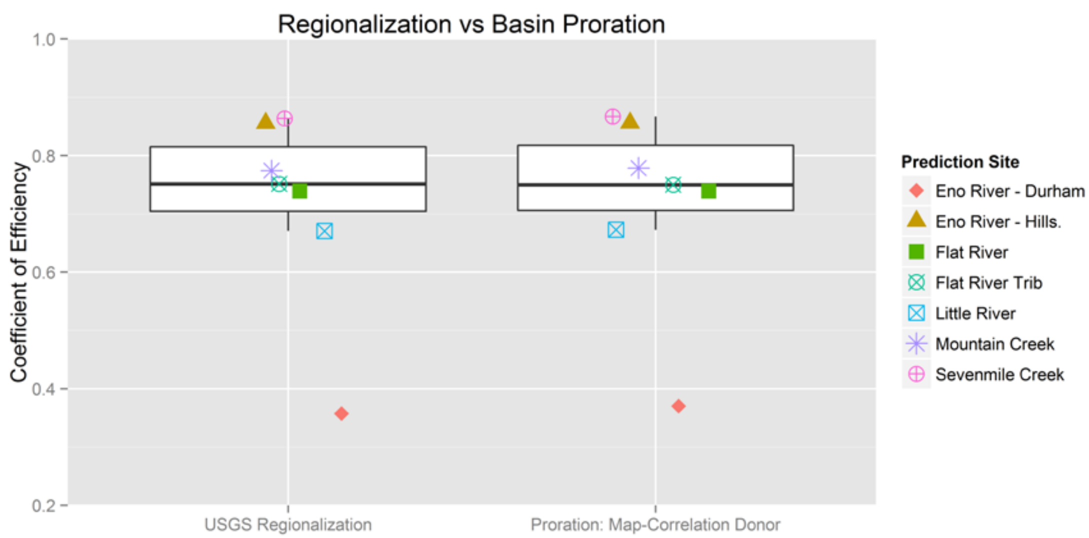

Figure 4-7 **The Coefficient of Efficiency for mean daily flow predictions (y axis) made using the regionalization and basin proration approaches with the same donor sites (x axis).** The CE shown is for the period of record over which data are available at both the donor site and the site for which predictions were made.

Table 4-2 USGS Streamflow Regionalization Model Predictions for Gages in Falls Watershed. Observed Flow Compared to Flow Predictions. Statistics are calculated over the entire period for which data were available for both the donor site and the prediction site. See table A-1 (in Appendix A) for a complete list of donor gages and their periods of record. Shaded cells indicate values outside of the range of recommended criteria for hydrologic flow model performance (NCDENR 2009).

Prediction Site:	Sevenmile Creek	Eno River at Hillsborough	Eno River near Durham	Little River above Reservoir	Mountain Creek	Flat River above Reservoir	Flat River Tributary
Donor Gage:	2084909	2085000	2085070	208521324	208524090	2085500	208650112
Statistic							
Coefficient of Efficiency	0.864	0.856	0.357	0.671	0.774	0.739	0.751
Total predicted instream flow	1.87%	2.78%	31.9%	16.6%	14.8%	12.9%	6.76%
Highest 10% of flows	-1.11%	1.28%	17.3%	6.32%	-0.003%	-1.99%	-9.62%
Lowest 50% of flows	17.3%	25.1%	81.7%	93.7%	139.%	87.3%	192.%
1st quarter flow	1.7%	4.07%	26.9%	11.7%	15.3%	8.16%	-1.09%
2nd quarter flow	3.23%	0.16%	26.8%	17.4%	16.2%	11.8%	10.7%
3rd quarter flow	1.91%	3.11%	44.%	34.%	0.336%	31.4%	16.5%
4th quarter flow	0.284%	2.97%	38.9%	12.3%	25.8%	9.78%	15.3%

4.2.2 Potential Method Improvements

The USGS Regionalization Method does not use drainage area to predict flow at the lowest flows. It uses adjacent flows to estimate the next lowest flows (flow at 95% exceedance probability is a function of flow at the 90% exceedance probability). The results indicate that predicting low flows using the basin proration method may offer significant improvements in the relative error of the predictions. The degree to which this would improve the coefficient of efficiency of the predictions has not been tested.

The performance of the USGS Streamflow Regionalization Method as pilot tested is conservative for a number of reasons. Cardno ENTRIX has identified three different modifications that could be implemented to improve the accuracy of the flow predictions:

1. The regional flow gages used in the analyses were not filtered to exclude those significantly influenced by wastewater flow or reservoirs. Preventing these from being used by the method would result in tighter model fits for the flow duration curve development *and* prevent such sites from being used as donor sites. In order to filter these gages, each gage location would have to be examined individually along with maps showing reservoirs and NPDES permit holders along with other data sources.
2. A more thorough and formal model fitting procedure should be conducted to ensure the best possible model is being used to predict flows at each portion of the flow duration curve (FDC). While this step is necessary prior to any formal use of the method, the current model likely includes the most significant predictors available. As part of the analyses conducted by Cardno ENTRIX a few additional flow predictors were added and subtracted and the model response was very small.
3. The USGS Streamflow Regionalization Method seems to perform most poorly at low flows (Table 3-2) in the North Carolina Piedmont. Alterations could be made to allow the low flows (e.g., flows at exceedance probabilities greater than 85 or 90%) to be scaled proportionally to drainage area. Implementing a simple version of this approach would be straightforward, however determining the best alterations necessary and re-evaluating model performance would involve significant time in modeling and statistical analysis.

Past Use

The general idea of flow regionalization has been widely explored and is an active area of research (insert long string of references here).Mahammoud 2008, Shu and Ouarda 2012, Sivapalan et al. 2003, Zhang and Chiew, 2009). The specific method implemented here (Archfield 2013) is used by the USGS, has been applied to the entire Connecticut River Basin, and has been vetted by the USGS and academic peer review process.

Limitations

- The limitations are very similar to those described for the Basin Proration Method.
- The influence of wastewater treatment plants and impoundments must be considered during donor gage selection and site flow predictions. The presence of these factors limits the accuracy of the flow predictions. The accuracy can be improved if WWTP discharge rates or water withdrawal quantities are known and omitted from or added to the fraction of flow that is scaled by the basin proration method, but this can be a time consuming data collection and preparation effort.
- No gages are located in the middle and lower half of the watershed to verify the accuracy of this technique for this portion of the basin. However, given the limited sensitivity of the Falls Lake Nutrient Response model to inputs from these ungaged tributaries, (Cardno ENTRIX Model Sensitivity TM), this may be an acceptable level of uncertainty. Alternatively, the addition of a USGS gage to this section of the basin would provide data for verification of the method as well as actual flow data.

> Baseflow predictions appear to be the most inaccurate area for this method. Cardno ENTRIX has identified a method that could be used to improve prediction accuracies for the low flows.

Accuracy of Flow Predictions

The USGS Streamflow Regionalization Model does an excellent job of predicting mean daily flow to within 10% of observed values. The CE for all models was 0.67 or higher for all locations except the Eno River near Durham. The method tends to overpredict low flows but Cardno ENTRIX has identified a few improvements that could be made to improve the predictions in this range of flows.

Level of Effort

Labor to improve the model set up and methods for estimating highest and lowest flows. About 85% of the labor has already been done. The regional flow data has been obtained and the watershed characteristics identified. The model regressions have been set up and initial evaluations completed.

Costs

There are no licensing or model registration fees.

Best Use for the UNRBA

The USGS Streamflow Regionalization Model provides a peer reviewed method for estimating flows in ungaged areas throughout the Falls Lake watershed. Its prediction accuracies are similar to those obtained with the Basin Proration approach. Making a few modifications to the method may improve the model's prediction accuracies, particularly at low flows. Applying and testing this method is more time consuming than use of the Basin Proration Method, although much of the work to set up the "best" model has already been done. Specific portions of the USGS Streamflow Regionalizaton Model can be borrowed for use to improve the accuracy of Basin Proration flow estimates.

5 Comparing Prediction Methods

Three of the flow estimation methods evaluated show reasonable potential for use in determining future daily flows for the UNRBA at ungaged tributary loading sites and jurisdictional boundaries: the WARMF Watershed Model; the Basin Proration Method; and the USGS Streamflow Regionalization Method. This section compares the relative accuracy of each method at gaged sites within the upper watershed and at an ungaged tributary, Robertson Creek, that drains into the lower section of Falls Lake.

5.1.1 Comparing Flow Predictions at Gaged Sites

Figures 5-1 and 5-2 compare the RE and CE associated with flow predictions using the three different methods to predict flows at the seven gaged sites in the Upper Falls Watershed that do not experience significant flow alteration. Taken together, both measures of fit (RE and CE) indicate that the Basin Proration Method and the USGS Streamflow Regionalization Method outperform the WARMF watershed model for upper Falls Lake catchments and show promise for predicting flows in the remainder of the Falls Lake watershed.

Figure 5-1 indicates that the Streamflow Regionalization Method is over predicting average daily flows by about 12% on average, the WARMF method is underpredicting flows by about 4% on average, and the Basin Proration method is generally able to predict flows within less than +/-5%. The WARMF model has the lowest mean CE of the three methods. The basin proration method produces higher CEs than the WARMF model, except when Eno River flows at Durham are predicted from the map-correlation selected donor site (Figure 5-2). WARMF predictions were not available for Sevenmile Creek, Mountain Creek, and the tributary to the Flat River for comparison. However the Eno River site is better predicted by the basin proration method when based on flows from either the Little River or the upstream Eno River site (Figure 5-1). In practice, it would make sense to predict flows in one river from nearby gages in the same river when available. The one test we have of predicting flow at a site in a river based on an upstream site in the same waterbody (Eno River in Durham predicted from Eno River at Hillsborough) indicates that this method can be used to predict flows at jurisdictional boundaries with a CE of 0.90 and a relative error of less than 2% when using gages located within the same river basin. The map-correlation method does not incorporate this information and instead selected a closer gage with a much smaller drainage area (Mountain Creek, area = 8 mi^2).

5.1.2 Comparing Flow Predictions at an Ungaged Site

Each method was used to predict flows at a small watershed in the Lower Falls Lake Watershed (Robertson Creek at Brassfield Road, watershed area of 12.2 mi^2). Robertson Creek is a tributary to the Beaverdam Arm of Falls Lake. Since this is an ungaged watershed the model predictions were compared to each other instead of to observed flows. Figure 4-3 provides a time series prediction from each model for a three and a half year period that corresponds with the WARMF model's calibration and validation years. The WARMF model was not calibrated for Robertson Creek. The Streamflow Regionalization method used the Tar River gage (02081500) as a donor gage and the Basin Proration Method used the Little River gage (0208521324) as a donor. The WARMF model output was scaled by drainage area to match the location of interest (scaling factor = 12.04 mi^2 / 15.4 mi^2).

The WARMF model tends to predict higher flows than the other two methods. The Streamflow Regionalization Method predicts flows that are lower than what is predicted by WARMF in most cases, but are usually higher than what is predicted by the Basin Proration Method. For much of the 3.5 year period the Streamflow Regionalization and Basin Proration Methods produce relatively similar estimates.

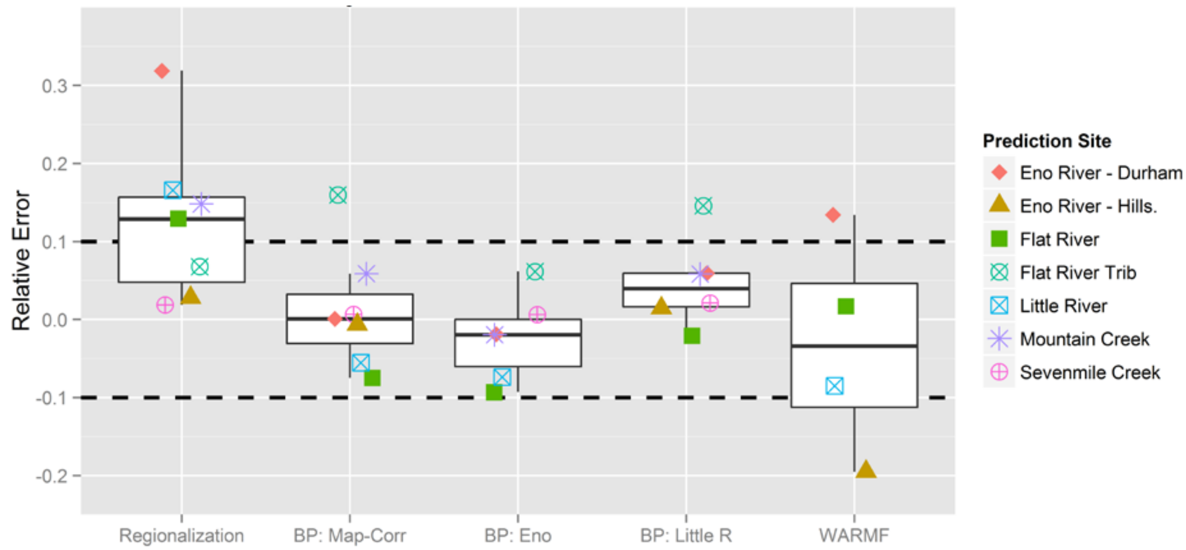

Figure 5-1 **Relative error in mean daily flow predictions (y axis) made using the regionalization and the basin proration method (BP) with different donor sites (x axis) compared to WARMF estimates. Except for WARMF, the RE shown is for the period of record over which data are available at both the donor site and the site for which predictions were made. For WARMF, the fits are only for the year 2007, the year in which the model was validated.**

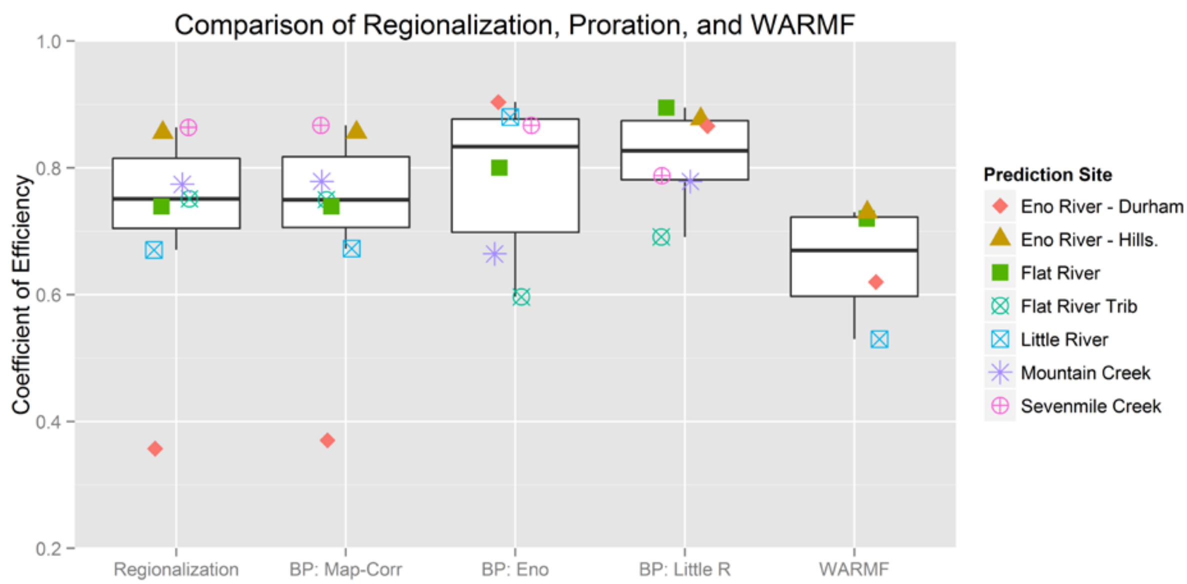

Figure 5-2 **The Coefficient of Efficiency for mean daily flow predictions (y axis) made using regionalization and basin proration with different donor sites (x axis). The map-correlation process was used to select the donor gage used in the basin proration. Except for WARMF, the CE shown is for the period of record over which data are available at both the donor site and the site for which predictions were made. For WARMF, the fits are only for the year 2007, the year in which the model was validated.**

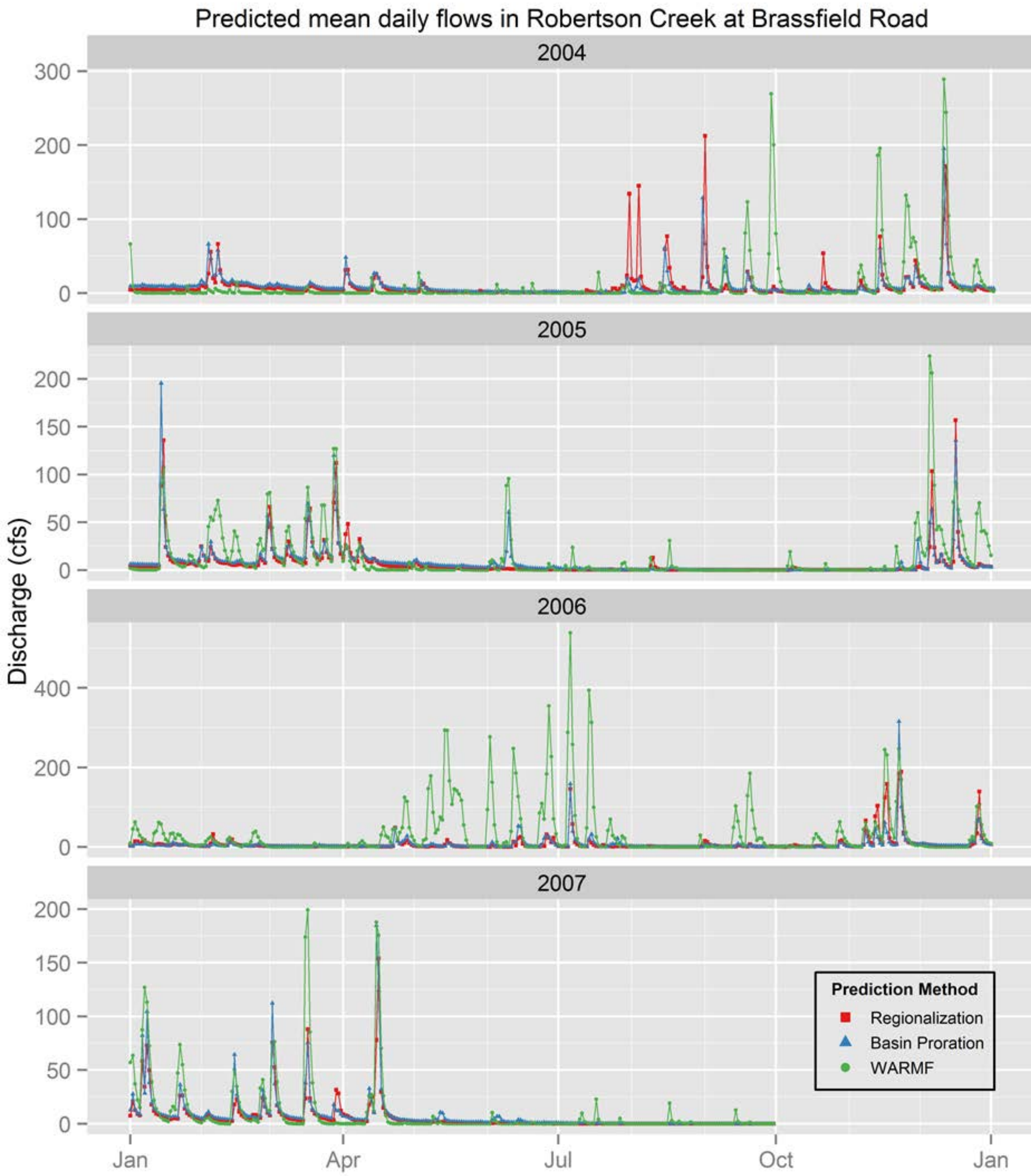

Figure 5-3 Comparison of flow predictions made for an ungaged site on Robertson Creek (at Brassfield Road crossing) using three different methods:

6 Implications for the Monitoring Program

Evaluation of the Falls Lake Nutrient Response Model's sensitivity to changes in flow and nutrient loading indicate that the model is less responsive to changes in loading from the Middle and Lower Falls Lake tributaries. Because of this lower sensitivity, Cardno ENTRIX recommends that flow prediction models be used to estimate daily flows for a number of these tributaries. Model estimates can be used to predict flow at these locations and at many of the jurisdictional boundaries throughout the watershed in lieu of installation of USGS gages. The use of models instead of measured data from USGS gages will produce less accurate flow measurements, but will provide a significant cost reduction for the UNRBA. The loss of accuracy is relatively minimal and models can be applied in areas where this loss of accuracy is less than what can be likely be detected by the Falls Lake Nutrient Response Model.

Both the Basin Proration and USGS Streamflow Regionalization Methods do a good job of predicting flow, usually within about +/-10% of the mean daily flow. In addition these methods tend not to overpredict flow, particularly for large flows, which could lead to higher estimates of nutrient loading than is actually occurring. Both methods can overpredict the lowest flows. The installation of two USGS gages in select Middle and Lower tributary locations would help provide local data that can be used to improve the low flow predictions. One gage should be placed in an area that represents primarily Triassic Basin conditions and the other gage should be placed in a location that is primarily within the Raleigh Belt. Gages will be strategically placed in areas that best represent the geology and land use characteristics common to groups of tributaries in these Falls Lake areas.

In summary, Cardno ENTRIX has identified two promising low-cost approaches for estimating streamflow at ungaged sites. Confidence in these approaches can be increased through data collection in catchments with traits that are currently under-represented in available data sources. This will provide the UNRBA with the flexibility to use multiple methods to predict flows and minimize the number of new USGS gages that need to be installed and maintained.

7 References

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UNRBA Monitoring Program
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APPENDIX

A

EVALUATION OF THE ACCURACY OF FLOW PREDICTION METHODS

Appendix A Evaluation of the Accuracy of Flow Prediction Methods

A.1 Statistical Evaluation of Flow Predictions

Several fit statistics were used in our evaluation of flow predictions because no single statistic is able to fully evaluate the model performance over all ranges of values (Wilmott 1981, Legates and McCabe, Jr. 1999, Krause and others, 2005).

A.1.1 Relative Error

Relative error provides a quantitative way to compare model predictions to observed values. When comparing a model's ability to predict flow at a specific gage, flow from that gage was not included in the calculations.

$$Relative\ Error = \frac{Predicted\ Flow\ at\ Gage - Observed\ Flow\ at\ Gage}{Observed\ Flow\ at\ Gage}$$

A.1.2 Coefficient of Efficiency

The coefficient of determination (R^2), a commonly used statistic for comparing model performance, is insensitive to additive or multiplicative differences between the predictions and observations and can be high even if the actual agreement between measured and predicted values is poor. Nash and Sutcliffe (1970) presented an alternative measure, the coefficient of efficiency (CE).

$$CE = 1 - \frac{\sum(Predicted\ Flow - Observed\ Flow)^2}{\sum(Observed\ Flow - \overline{Observed\ Flow})^2}$$

The CE scales similarly to R^2 (values close to one indicate a good fit), but takes into account differences in the observed and predicted means and variances. Both the coefficient of determination and coefficient of efficiency have squared difference terms in their numerators which make them sensitive to large outliers. Therefore, simulations that fit extreme events may have artificially higher R^2 values relative to simulations that do a better job with baseline flows but miss an occasional outlier. To account for these limitations, we also compared model simulations to observations using measures of error such as the relative error between predicted and observed flow over various subsets of the data, including seasonal flows, the lowest 50% of flows, the highest 10% of flows and average flow (Legates and McCabe, Jr. 1999, Lumb et al, 1994, NCDWQ 2009).

A.2 USGS Gages Located in the Piedmont with a Period of Record of at least 15 Years that can Potentially be used as Donor sites for Flow Prediction

Table A-1 List of stream gages used (a) to estimate streamflow using the USGS Regionalization Method and (b) as potential donor gages for the map-correlation method of donor site selection.

Station Number	Station Name	Period of Record
02068500	Dan River near Francisco, NC	1 September 1924 - 31 December 2013
02070500	Mayo River near Price, NC	1 August 1929 - 31 December 2013
02074000	Smith River at Eden, NC	1 October 1939 - 31 December 2013
02077200	Hyco Creek near Leasburg, NC	1 August 1964 - 31 December 2013
02077303	Hyco River below Abay D near McGehees Mill, NC	1 October 1973 - 31 December 2013
02077670	Mayo Creek near Bethel Hill, NC	29 July 1977 - 31 December 2013
02081500	Tar River near Tar River, NC	1 October 1939 - 31 December 2013
02081747	Tar River at Us 401 at Louisburg, NC	7 November 1963 - 31 December 2013
02082506	Tar River below Tar River Reservoir near Rocky Mount, NC	1 August 1972 - 29 February 2012
02082585	Tar River at NC 97 at Rocky Mount, NC	1 August 1976 - 31 December 2013
02082770	Swift Creek at Hilliardston, NC	1 August 1963 - 31 December 2013
02082950	Little Fishing Creek near White Oak, NC	1 October 1959 - 31 December 2013
02083000	Fishing Creek near Enfield, NC	1 October 1926 - 31 December 2013
02083500	Tar River at Tarboro, NC	1 January 1900 - 31 December 2013
02083800	Conetoe Creek near Bethel, NC	1 December 1956 - 30 June 2002
02084160	Chicod Creek at SR1760 near Simpson, NC	1 October 1975 - 31 December 2013
02084909	Sevenmile Creek near Efland, NC	24 June 1981 - 21 October 2004
02085000	Eno River at Hillsborough, NC	1 October 1927 - 31 December 2013
02085070	Eno River near Durham, NC	1 September 1963 - 31 December 2013
02085500	Flat River at Bahama, NC	1 August 1925 - 31 December 2013
02087275	Crabtree Creek at Hwy 70 at Raleigh, NC	1 June 1997 - 31 December 2013
02087324	Crabtree Creek at US 1 at Raleigh, NC	1 June 1990 - 31 December 2013
02087359	Walnut Creek at Sunnybrook Drive near Raleigh, NC	1 May 1996 - 31 December 2013
02087500	Neuse River near Clayton, NC	1 August 1927 - 31 December 2013
02088000	Middle Creek near Clayton, NC	1 October 1939 - 31 December 2013
02088500	Little River near Princeton, NC	1 March 1930 - 31 December 2013
02089500	Neuse River at Kinston, NC	1 March 1930 - 31 December 2013
02090380	Contentnea Creek near Lucama, NC	1 October 1964 - 31 December 2013
02091000	Nahunta Swamp near Shine, NC	1 April 1954 - 31 December 2013

Station Number	Station Name	Period of Record
02091500	Contentnea Creek at Hookerton, NC	1 December 1928 - 31 December 2013
02091814	Neuse River near Fort Barnwell, NC	1 October 1996 - 31 December 2013
02093800	Reedy Fork near Oak Ridge, NC	1 October 1955 - 31 December 2013
02094500	Reedy Fork near Gibsonville, NC	1 October 1928 - 31 December 2013
02094770	South Buffalo Creek at Us 220 at Greensboro, NC	1 August 1998 - 31 December 2013
02094775	Ryan Creek Below Us 220 at Greensboro, NC	1 August 1998 - 31 December 2013
02095000	South Buffalo Creek near Greensboro, NC	1 September 1928 - 31 December 2013
02095271	North Buffalo Creek at Church St at Greensboro, NC	1 August 1998 - 31 December 2013
02095500	North Buffalo Creek near Greensboro, NC	1 September 1928 - 31 December 2013
02096500	Haw River at Haw River, NC	1 October 1928 - 31 December 2013
02096846	Cane Creek near Orange Grove, NC	1 November 1988 - 31 December 2013
02096960	Haw River near Bynum, NC	26 September 1973 - 31 December 2013
02097314	New Hope Creek near Blands, NC	1 October 1982 - 31 December 2013
02097464	Morgan Creek near White Cross, NC	1 November 1988 - 31 December 2013
02097517	Morgan Creek near Chapel Hill, NC	1 November 1982 - 31 December 2013
02099000	East Fork Deep River near High Point, NC	1 October 1928 - 31 December 2013
02099500	Deep River near Randleman, NC	1 October 1928 - 30 September 2004
02100500	Deep River at Ramseur, NC	1 April 1923 - 31 December 2013
02101800	Tick Creek near Mount Vernon Springs, NC	1 July 1958 - 31 December 2013
02102192	Buckhorn Creek near Corinth, NC	1 June 1972 - 31 December 2013
02102500	Cape Fear River at Lillington, NC	1 January 1924 - 31 December 2013
02102908	Flat Creek near Inverness, NC	1 June 1968 - 31 December 2013
02103000	Little River at Manchester, NC	1 October 1938 - 31 December 2013
02104220	Rockfish Creek at Raeford, NC	1 July 1988 - 31 December 2013
02106500	Black River near Tomahawk, NC	1 October 1951 - 31 December 2013
02133500	Drowning Creek near Hoffman, NC	1 October 1939 - 31 December 2013
02133624	Lumber River near Maxton, NC	1 June 1987 - 31 December 2013
02134480	Big Swamp near Tarheel, NC	1 October 1985 - 31 December 2013
0208521324	Little River at SR1461 near Orange Factory, NC	30 September 1987 - 31 December 2013
0208524090	Mountain Creek at SR1617 near Bahama, NC	1 October 1994 - 31 December 2013
0208650112	Flat River Tributary near Willardville, NC	1 March 1988 - 30 September 2012
0208726005	Crabtree Creek at Ebenezer Church Road near Raleigh, NC	1 December 1987 - 31 December 2013
0208732534	Pigeon House Creek at Cameron Village at Raleigh, NC	19 August 1987 - 31 December 2013

Station Number	Station Name	Period of Record
0208732885	Marsh Creek near New Hope, NC	1 January 1984 - 31 December 2013
0208735012	Rocky Branch Below Pullen Drive at Raleigh, NC	26 June 1992 - 31 December 2013
0208758850	Swift Creek near McCullars Crossroads, NC	1 December 1987 - 31 December 2013
0208925200	Bear Creek at Mays Store, NC	1 October 1987 - 31 December 2013
0209553650	Buffalo Creek at SR2819 near McLeansville, NC	1 August 1998 - 31 December 2013
0209741955	Northeast Creek at SR1100 near Genlee, NC	1 October 1982 - 31 December 2013
0210166029	Rocky River at SR1300 near Crutchfield Crossroads, NC	1 May 1988 - 31 December 2013

A.3 Improvements to Basin Proration Method Donor Site Selection

The effectiveness of the drainage area ratio approach is in large part dependent upon the selection of the donor gage. The user must carefully select a representative gage with similar watershed characteristics (land cover, soil characteristics, etc.). The influence of wastewater treatment plants and impoundments must also be considered in gage selection. This error can be overcome if discharge rates from the WWTP are known and omitted from the fraction of flow that is scaled by the basin proration method.

To reduce the subjectivity inherent in donor site selection, we tested a map-correlation approach to selecting donor gages (Archfield and Vogel, 2010) which has been shown to yield better predictions of streamflow than simply selecting the nearest gage. In this method, a donor site is selected based on a statistical prediction of its correlation with the site of interest. For each site of interest, geostatistics are used to determine which of the gages in the region are predicted to have the most correlated daily time series of flow. An overview of the approach is presented here. For all 69 gages in the region, a correlation matrix was developed to identify how well daily mean flows are correlated between each pair of sites. Using this correlation matrix, the relationship between the distance from each stream gage and its correlation with each of the other stream gages in the region was determined by fitting a spherical variogram model to the measured semivariance and separation distances (Isaaks and Srivastava 1989, Archfield and Vogel 2010). The fitted variogram parameters and the correlation matrix were used with ordinary kriging (Isaaks and Srivastava 1989, Diggle and Ribeiro 2007) to predict the correlation between a given stream gage and any location on a map. For each site at which predictions are desired, the process above was conducted 68 times (excluding data from the site at which we want to predict) to obtain a predicted correlation between the prediction site and each of the other gages in the region. The donor site that was predicted to have the highest correlation with the prediction site was then selected as the donor gage. All statistical analyses were performed in the R statistical program (R Development Core Team, 2013) with the associated geoR software library (Diggle and Ribeiro 2007).

When flows were predicted using the donor sites identified by the map-correlation method, the median relative error among the Falls Lake locations was less than 0.1% (mean 1.3%) with all sites being within +/- 7.5% except the tributary to the Flat River with a drainage area of 1.1 mi^2 (relative error = 16%). When examined for the entire region, the median bias using the map correlation method was -2.0% (mean -0.48%). The basin proration method produces relative error values smaller than the WARMF model predictions for all comparable sites except the Flat River, regardless of the donor site used.

A.4 USGS Regionalization Method Details

For purposes of evaluating this method, we closely followed the three step approach described in Archfield et al. (2013). Additional details can be found in Archfield et al. (2013).

1. Develop quantile regression model for predicting flow duration curves at ungaged sites (Figure A-1). Figure A-1 shows the individual regression points on the flow duration curve (FDC).

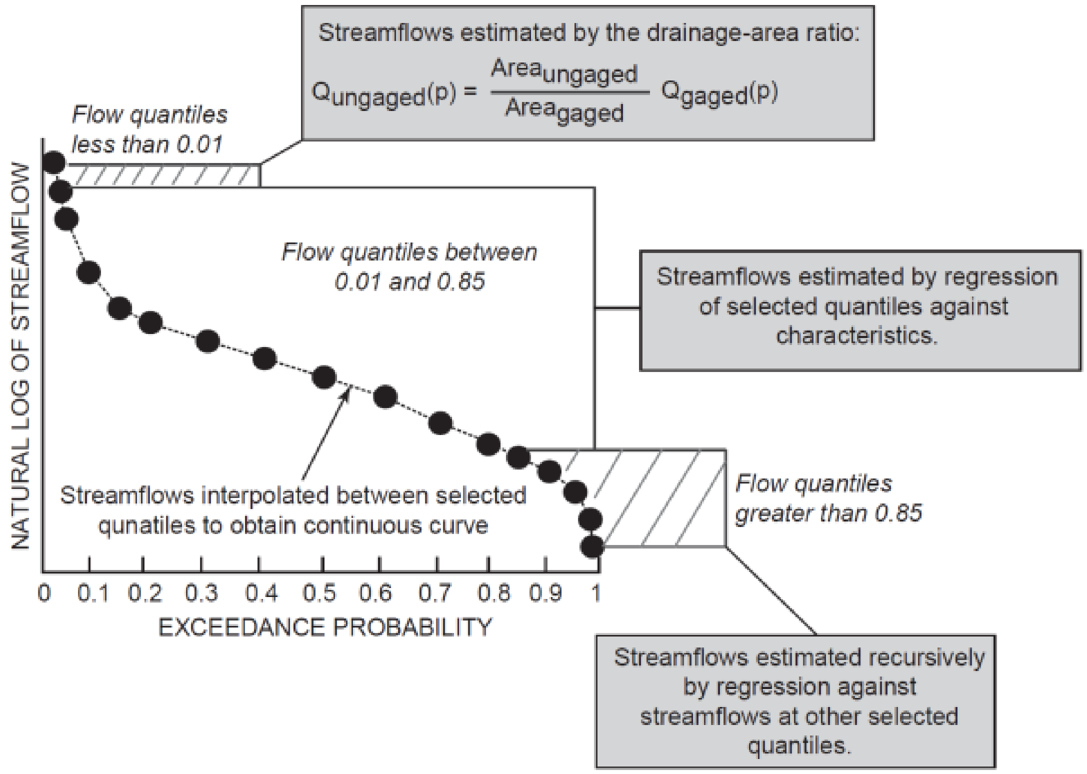

Figure A-1 Diagram showing the methods used to estimate a continuous daily flow duration curve at an ungaged location. (Figure from Archfield et al. 2013)

Site-specific flow duration curves were calculated using USGS streamflow data for the period of record at each site. Catchments were delineated for each of the USGS gages using the USGS Streamstats web service (http://water.usgs.gov/osw/streamstats/) and catchment characteristics and land cover were identified for each. Following the approach of Archfield et al. (2013), a set of regression equations were created to relate streamflow for a given exceedance probability to catchment characteristics for the following exceedance probabilities: 0.02, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.85. The catchment traits or watershed characteristics found to be most informative in the regressions were drainage area (natural log transformed), land cover in percent coverage for forest, wetlands, water, and impervious surfaces, percent of catchment in hydrologic soil type ‘C’ (SSURGO), catchment slope, mean annual precipitation, and latitude.

Results of the model regressions are presented in Table A-2. All regressions were highly significant (p-value << 0.001) and had R^2 values above 0.95.

Archfield et al. (2013) found that predicting streamflow for exceedance probabilities greater than 0.85 or less than 0.02 via regression using catchment traits was unreliable and instead streamflow at exceedance probabilities greater than 0.85 were calculated using recursive regression with the only predictor being the streamflow at the previous quantile. For example, the prediction of streamflow at the 90% exceedance probability was based solely on a regression with flows at the 85% exceedance probability. This procedure was followed for streamflows at the 0.9, 0.95, 0.98, 0.99, and 0.999938 exceedance probabilities.

The set of regression equations developed above were used to predict streamflow at the set of quantiles from 0.02 to 0.999938 exceedance probability for each test site. A flow duration curve for each site was estimated by log-linear interpolation for exceedance probabilities falling between these quantiles. Archfield found that flows at exceedance probabilities less than 0.02 (extreme stormflow events) were not well predicted using the regression technique and recommended that flow-predictions in this range be based solely on drainage-area ratios.

Table A-2. Regression fit statistics, explanatory variables, and estimated regression coefficients for streamflow percentiles estimated from catchment characteristics using multiple least squares regression. (*The bias correction factor was computed from Duan, 1983 following the methods of Archfield et al. 2013.) Although the model fits very well (all R^2 values are above 0.91), this remains a preliminary model fit for pilot testing the USGS regionalization approach. Further refinements in model structure and a more formal model selection procedure would need to be conducted for each exceedance probability before the formal adoption of the method. Coefficients in bold are significant at $p < 0.01$. Coefficients not significant at the p=0.05 level are shown in blue. Predictor variables associated with these non-significant coefficients were left in the regression equations for this pilot test since they were significant for other exceedance probabilities.

	Estimated regression coefficients										
Exceedance probability	Constant term	log (Drainage Area)	Basin Slope	Latitude of outlet	Mean annual precipitation	Impervious surfaces	Hydrologic Soil type C	Open water	Wetlands	Bias correction factor*	Model R^2
0.02	**-10.47**	**0.964**	**-0.0352**	**0.3055**	0.04241	0.00957	0.00103	-0.0314	-0.01914	1.010	0.993
0.05	-7.48	**1.014**	-0.0269	0.1667	0.06013	**0.02026**	-0.00046	-0.0099	-0.00457	1.009	0.994
0.1	-3.25	**1.043**	-0.0077	0.0269	0.05635	**0.02358**	-0.00218	0.0020	0.01104	1.008	0.995
0.15	0.61	**1.049**	0.0091	-0.0761	0.04275	**0.02113**	**-0.00317**	-0.0025	0.01872	1.009	0.995
0.2	3.98	**1.053**	0.0219	-0.1618	0.02992	**0.01741**	**-0.00369**	-0.0171	0.02190	1.012	0.994
0.25	6.67	**1.055**	**0.0349**	-0.2233	0.01482	0.01313	**-0.00370**	-0.0329	0.02342	1.015	0.993
0.3	9.12	**1.061**	**0.0460**	**-0.2779**	0.00015	0.00988	-0.00349	**-0.0497**	0.02364	1.018	0.991
0.4	13.51	**1.078**	**0.0644**	**-0.3842**	-0.01941	0.00824	-0.00424	**-0.0930**	0.02213	1.028	0.987
0.5	**20.74**	**1.100**	**0.0856**	**-0.5594**	-0.04503	0.00681	-0.00578	**-0.1677**	0.01402	1.044	0.981
0.6	**23.82**	**1.120**	**0.1083**	**-0.6274**	-0.06694	0.00767	-0.00645	**-0.1970**	0.01325	1.069	0.971
0.7	25.42	**1.143**	**0.1306**	**-0.6704**	-0.07983	0.01353	-0.00751	**-0.1996**	0.01732	1.112	0.957
0.75	26.61	**1.164**	**0.1430**	-0.7016	-0.08820	0.01681	-0.00821	**-0.1933**	0.01854	1.149	0.946
0.8	28.22	**1.195**	**0.1597**	-0.7373	-0.10464	0.02047	-0.00860	**-0.1901**	0.02130	1.207	0.931
0.85	30.71	**1.240**	**0.1776**	-0.7962	-0.12348	0.02333	-0.00901	**-0.1893**	0.02162	1.301	0.912

2. Select donor gage using map correlation method.

After estimating a flow duration curve for the ungaged site, a donor gage must be selected to relate daily flows to the estimated flow duration curve (Figure A-2). The donor gage is selected using the map correlation method (see section A-3 for details) to find the gage predicted to have the most highly correlated daily flows with the ungaged location.

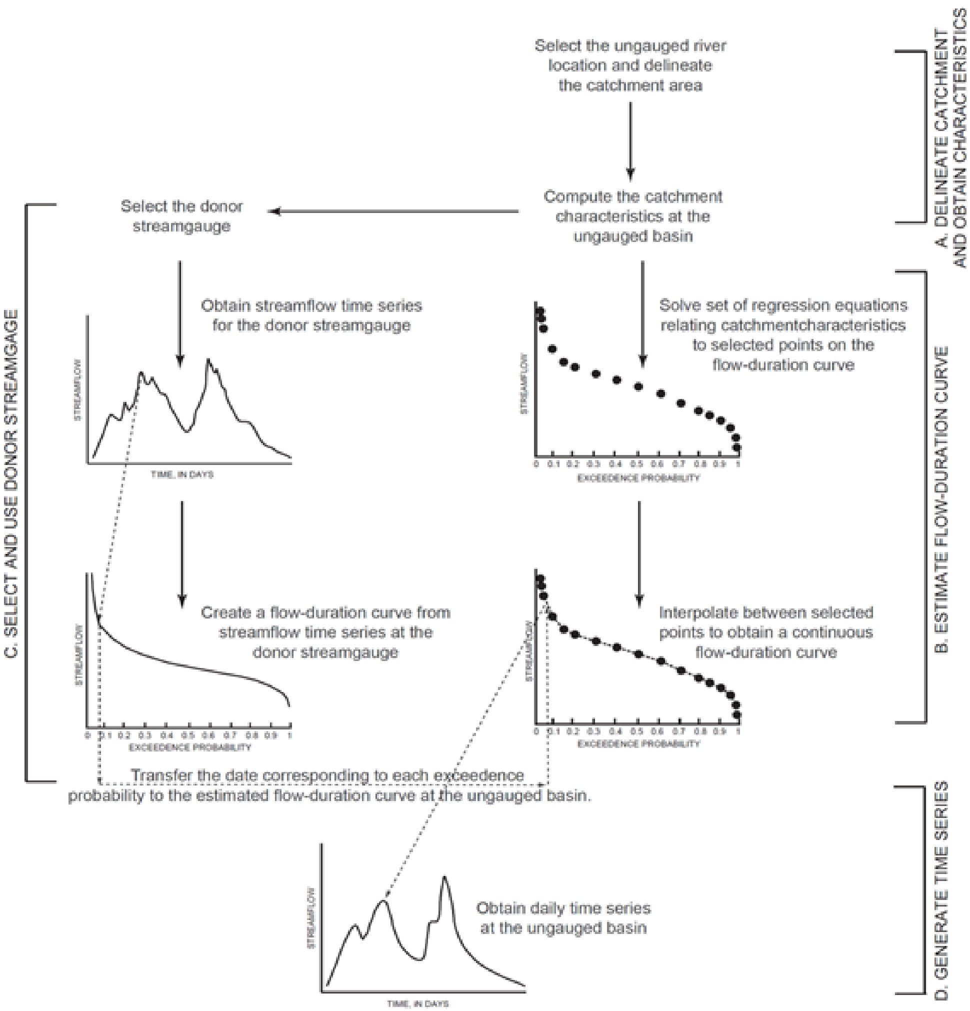

Figure A-2 Diagram of the process to estimate unregulated daily stream flow at ungaged locations (Figure from Archfield et al. 2013).

3. Scale daily flows from donor gage to the ungaged location using the predicted flow-duration curve.

Daily flows at the donor site over the prediction interval were related to that site's flow duration curve to identify the daily exceedance probabilities associated with each day's flow. Streamflow at the ungaged site was then estimated by assigning the flow at the same exceedance probability from the predicted flow duration curve (Figure A-2).

A.5 Assessment of Basin Proration Prediction Accuracy

Table A-3 Prediction Evaluation Metrics for flow estimates at Sevenmile Creek using three different donor gages. Statistics are calculated over the entire period for which data were available at both the donor site and the site for which predictions were made.

Sevenmile Creek: 02084909				
	Observed	Basin Proration		
	(mean daily cfs)	Map-correlation Selected (Eno River at Hillsborough)	Little River	Eno River at Durham
Coefficient of Efficiency	--	0.867	0.788	0.867
Mean daily flow	13.5	0.634%	2.11%	0.634%
Highest 10% of flows	--	-6.44%	-6.54%	-6.44%
Lowest 50% of flows	--	45.4%	54.5%	45.4%
1st quarter flow	25.6	-1.29%	1.66%	-1.29%
2nd quarter flow	13.5	2.71%	-2.66%	2.71%
3rd quarter flow	6.43	3.37%	11.%	3.37%
4th quarter flow	8.68	0.983%	4.2%	0.983%

Table A-4 **Prediction Evaluation Metrics for flow estimates in the Eno River using three different donor gages. Statistics are calculated over the entire period for which data were available at both the donor site and the site for which predictions were made.**

	Eno River at Hillsborough: 02085000				Eno River near Durham: 02085070			
	Observed	Basin Proration			Observed	Basin Proration		
	(mean daily cfs)	Map-correlation Selected (Sevenmile Creek)	Little River	Eno River	(mean daily cfs)	Map-correlation Selected (Mountain Creek)	Little River	Eno River
Coefficient of Efficiency	--	0.856	0.877	--	--	0.37	0.866	0.904
Mean Daily Flow	63.6	0.63%	1.47%	--	113	0.088%	5.95%	1.89%
Highest 10% of flows	--	-1.35%	0.041%	--	--	2.79%	7.86%	-1.8%
Lowest 50% of flows	--	10.7%	6.15%	--	--	-18.7%	-12.1%	-9.75%
1st quarter flow	118	1.31%	2.99%	--	185	-1.09%	7.56%	-1.%
2nd quarter flow	65.1	-2.64%	-5.23%	--	113	-5.33%	0.669%	-1.38%
3rd quarter flow	31.2	-3.26%	7.35%	--	72.7	12.1%	0.284%	-9.52%
4th quarter flow	41.1	-0.974%	3.19%	--	81.9	-0.472%	14.2%	2.01%

Table A-5 Prediction Evaluation Metrics for flow estimates in the Little River and Mountain Creek using three different donor gages. Statistics are calculated over the entire period for which data were available at both the donor site and the site for which predictions were made.

	Little River: 0208521324				Mountain Creek: 0208524090			
	Observed	Basin Proration			Observed	Basin Proration		
Donor:	(mean daily cfs)	Map-correlation Selected (Mountain Creek)	Little River	Eno River	(mean daily cfs)	Map-correlation Selected (Little River)	Little River	Eno River
Coefficient of Efficiency	--	0.673	--	0.88	--	0.779	0.779	0.664
Mean Daily Flow	65.7	5.53%	--	7.4%	6.37	5.86%	5.86%	1.98%
Highest 10% of flows	--	-6.05%	--	-12.7%	--	-5.17%	-5.17%	-16.6%
Lowest 50% of flows	--	6.85%	--	30.2%	--	64.%	64.%	82.%
1st quarter flow	110	-8.05%	--	-7.96%	10.4	8.75%	8.75%	0.092%
2nd quarter flow	62.8	-5.96%	--	-2.04%	6.06	6.33%	6.33%	4.17%
3rd quarter flow	40.2	11.7%	--	-9.78%	4.61	-10.5%	-10.5%	-19.3%
4th quarter flow	51.6	-12.8%	--	-10.7%	4.61	14.7%	14.7%	2.49%

Table A-6 Prediction Evaluation Metrics for flow estimates for the Flat River and an Unnamed Tributary to the Flat River Upstream of Lake Michie using three different donor gages. Statistics are calculated over the entire period for which data were available at both the donor site and the site for which predictions were made.

	Flat River: 02085500				Flat River Tributary: 0208650112			
	Observed	Basin Proration			Observed	Basin Proration		
	(mean daily cfs)	Map-correlation Selected (Mountain Creek)	Little River	Eno River	(mean daily cfs)	Map-correlation Selected (Flat River)	Little River	Eno River
Coefficient of Efficiency	--	0.739	0.895	0.8	--	0.75	0.691	0.597
Mean Daily Flow	128	7.48%	2.06%	9.31%	0.88	16.%	14.6%	6.16%
Highest 10% of flows	--	-13.%	-6.68%	-17.3%	--	-6.09%	-8.66%	-19.4%
Lowest 50% of flows	--	6.5%	9.24%	30.1%	--	282.%	282.%	310.%
1st quarter flow	212	-9.61%	-1.7%	-9.53%	1.65	5.8%	4.58%	-3.56%
2nd quarter flow	124	-9.28%	-3.54%	-5.5%	0.814	21.6%	18.5%	16.%
3rd quarter flow	77.7	9.7%	-1.82%	-11.4%	0.428	28.2%	27.4%	12.2%
4th quarter flow	99.2	-13.9%	-1.22%	-11.7%	0.638	26.5%	26.8%	14.5%

A.6 Assessment of USGS Streamflow Regionalization Method Prediction Accuracy

Table A-7 Prediction Evaluation Metrics for flow estimates at seven gaged tributaries in the Upper Falls Lake Watershed.

Statistic	Sevenmile Creek	Eno River at Hillsborough	Eno River near Durham	Little River	Mountain Creek	Flat River	Flat River Tributary
	2084909	2085000	2085070	208521324	208524090	2085500	208650112
Coefficient of Efficiency	0.864	0.856	0.357	0.671	0.774	0.739	0.751
Total predicted instream flow volume	1.87%	2.78%	31.9%	16.6%	14.8%	12.9%	6.76%
Total volume of highest 10% of flows	-1.11%	1.28%	17.3%	6.32%	-0.003%	-1.99%	-9.62%
Total volume of lowest 50% of flows	17.3%	25.1%	81.7%	93.7%	139.%	87.3%	192.%
Total 1st quarter flow volume	1.7%	4.07%	26.9%	11.7%	15.3%	8.16%	-1.09%
Total 2nd quarter flow volume	3.23%	0.16%	26.8%	17.4%	16.2%	11.8%	10.7%
Total 3rd quarter flow volume	1.91%	3.11%	44.%	34.%	0.336%	31.4%	16.5%
Total 4th quarter flow volume	0.284%	2.97%	38.9%	12.3%	25.8%	9.78%	15.3%

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APPENDIX

B

FLOW PREDICTION TIME SERIES BY BASIN PRORATION AND USGS STREAMFLOW REGIONALIZATION METHODS

Appendix B
Flow Prediction Time Series by Basin Proration and USGS Streamflow Regionalization Methods

B.1.1 Predictions at Gaged Locations

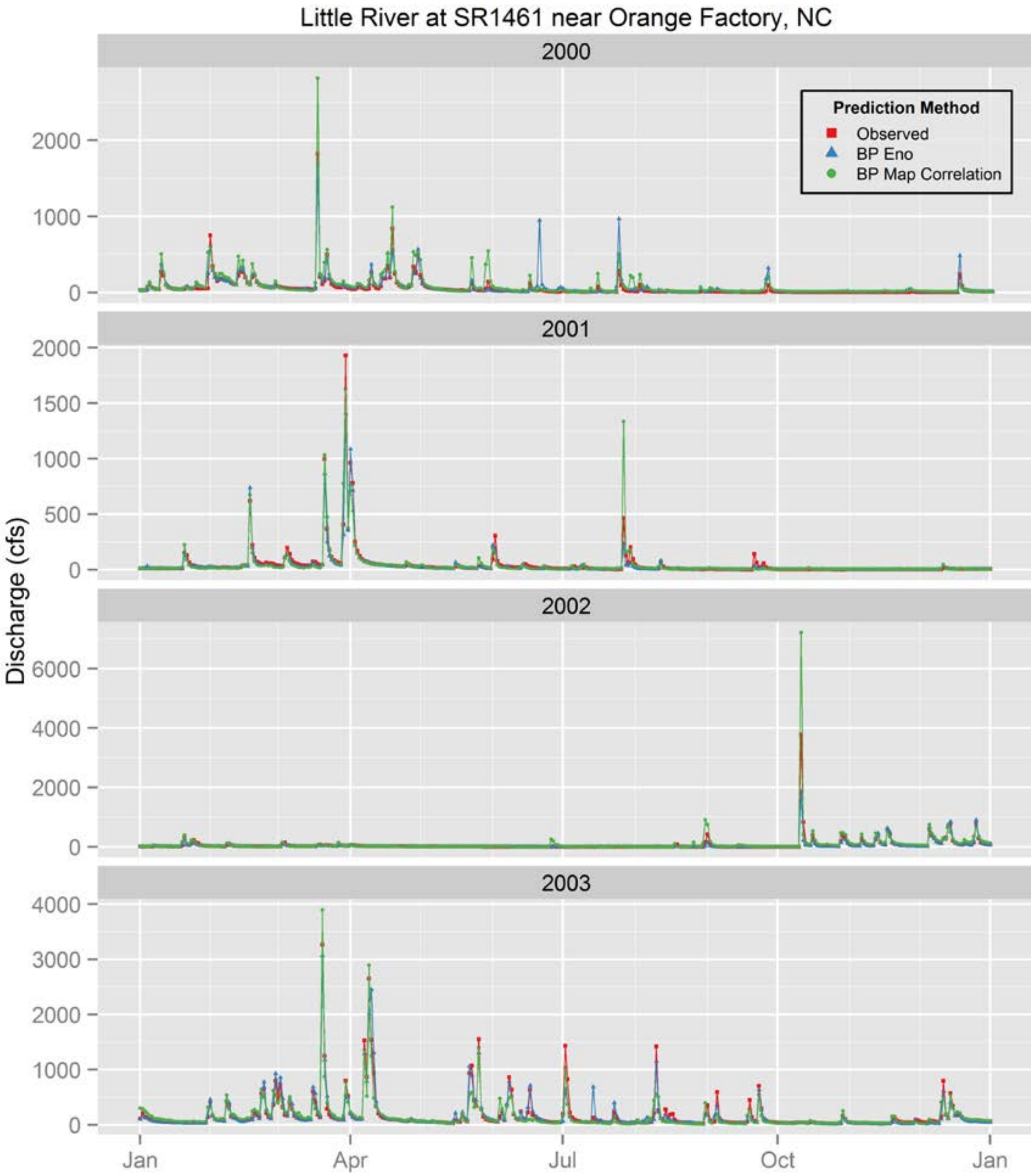

Figure B-1 **Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in the Little River above the Little River Reservoir**

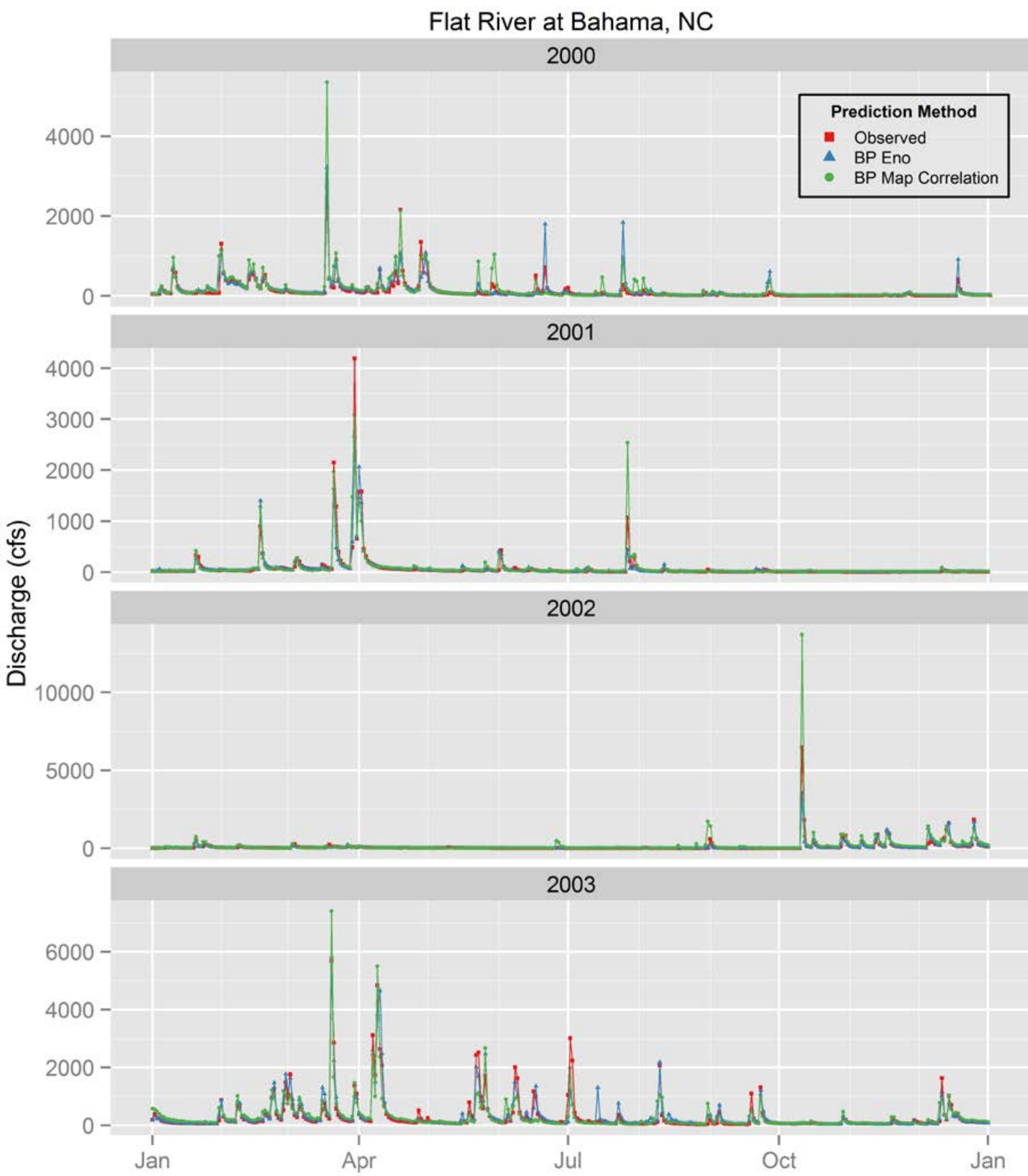

Figure B-2 **Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in the Flat River above Lake Michie.**

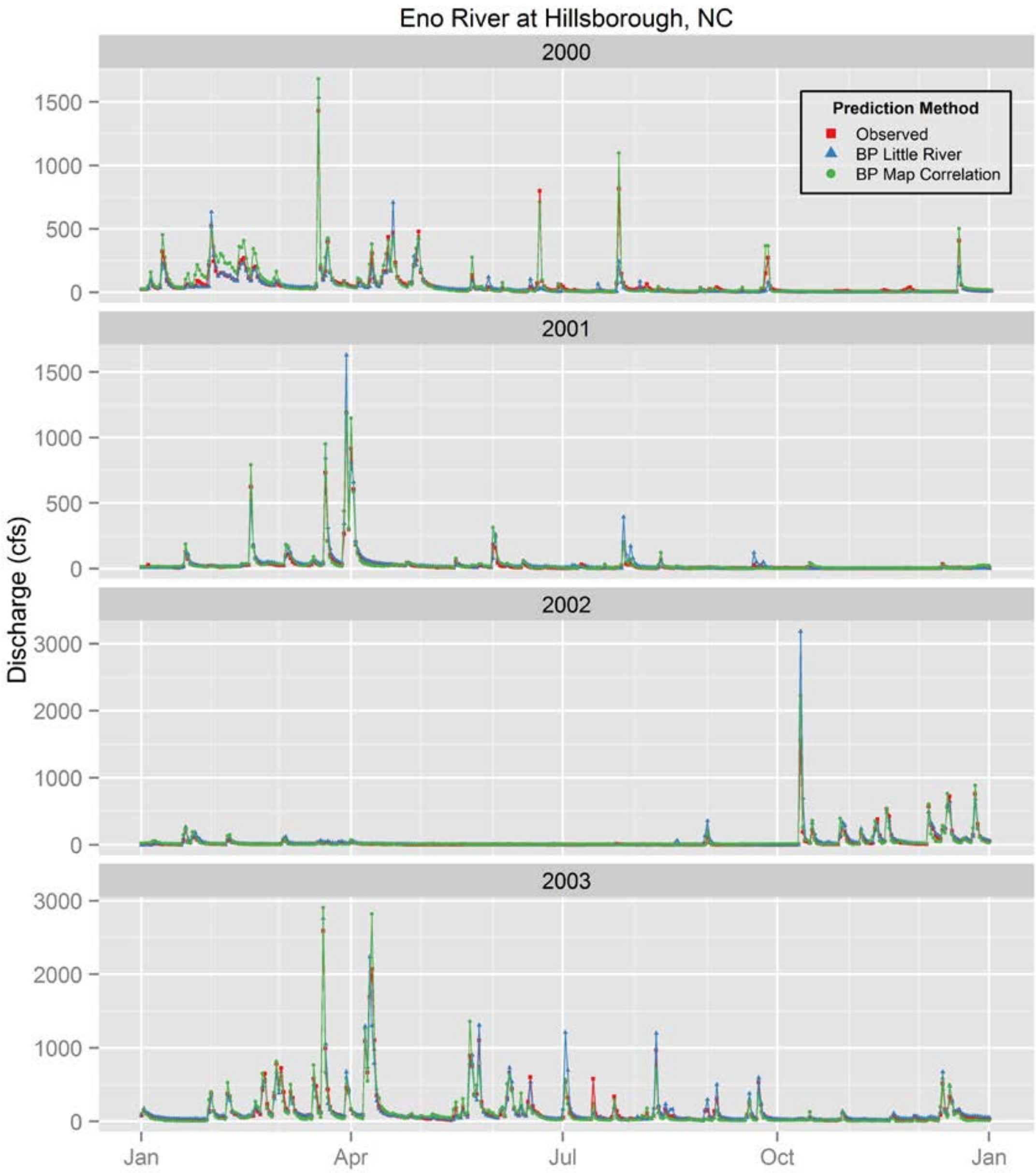

Figure B-3 **Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in Eno River at Hillsborough.**

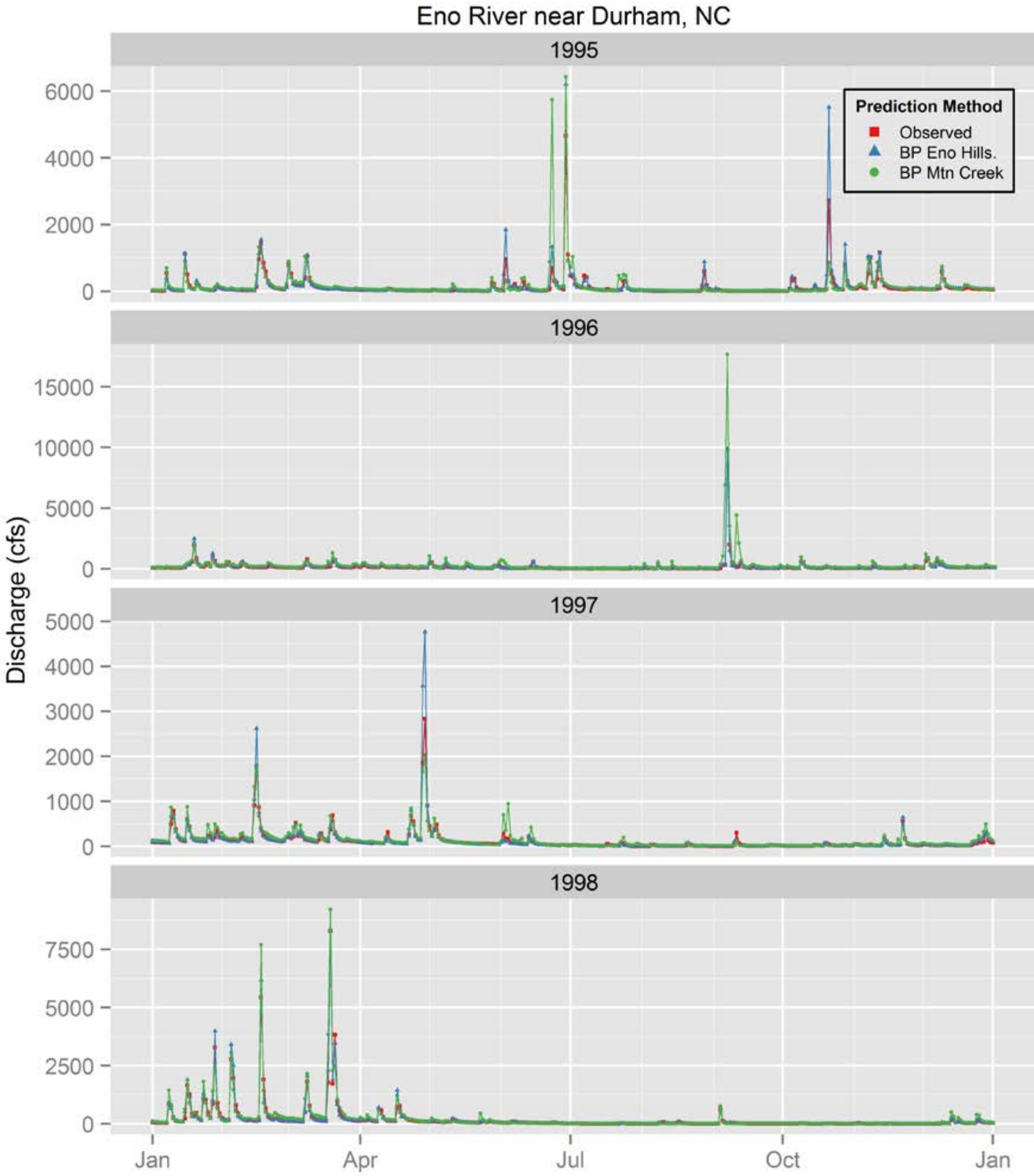

Figure B-4 **Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in Eno River near Durham (1995 through 1998).**

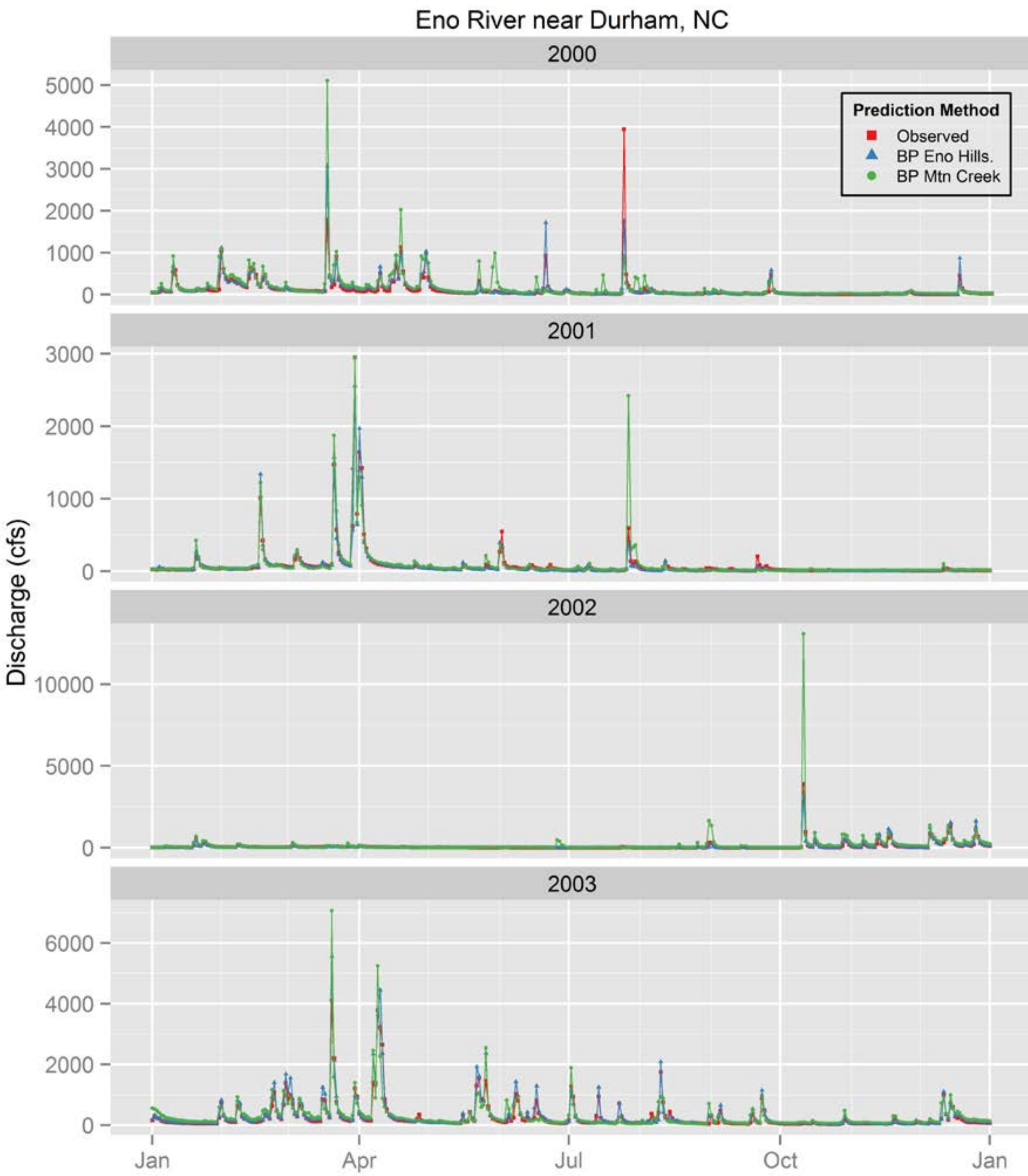

Figure B-5 **Timeseries of flow predictions showing predicted flow based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in Eno River near Durham (2000 through 2003).**

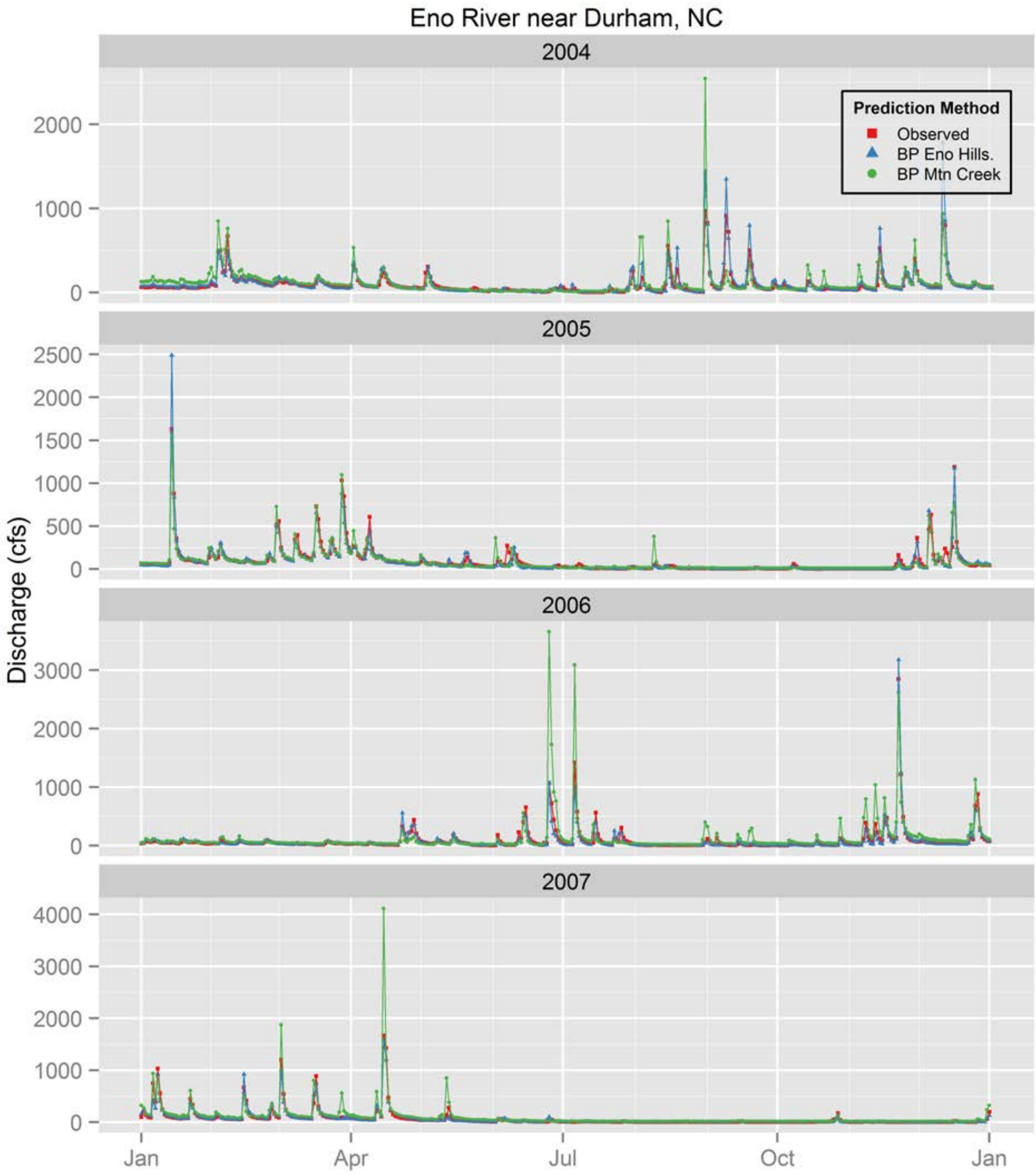

Figure B-6 **Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in Eno River near Durham (2004 through 2007).**

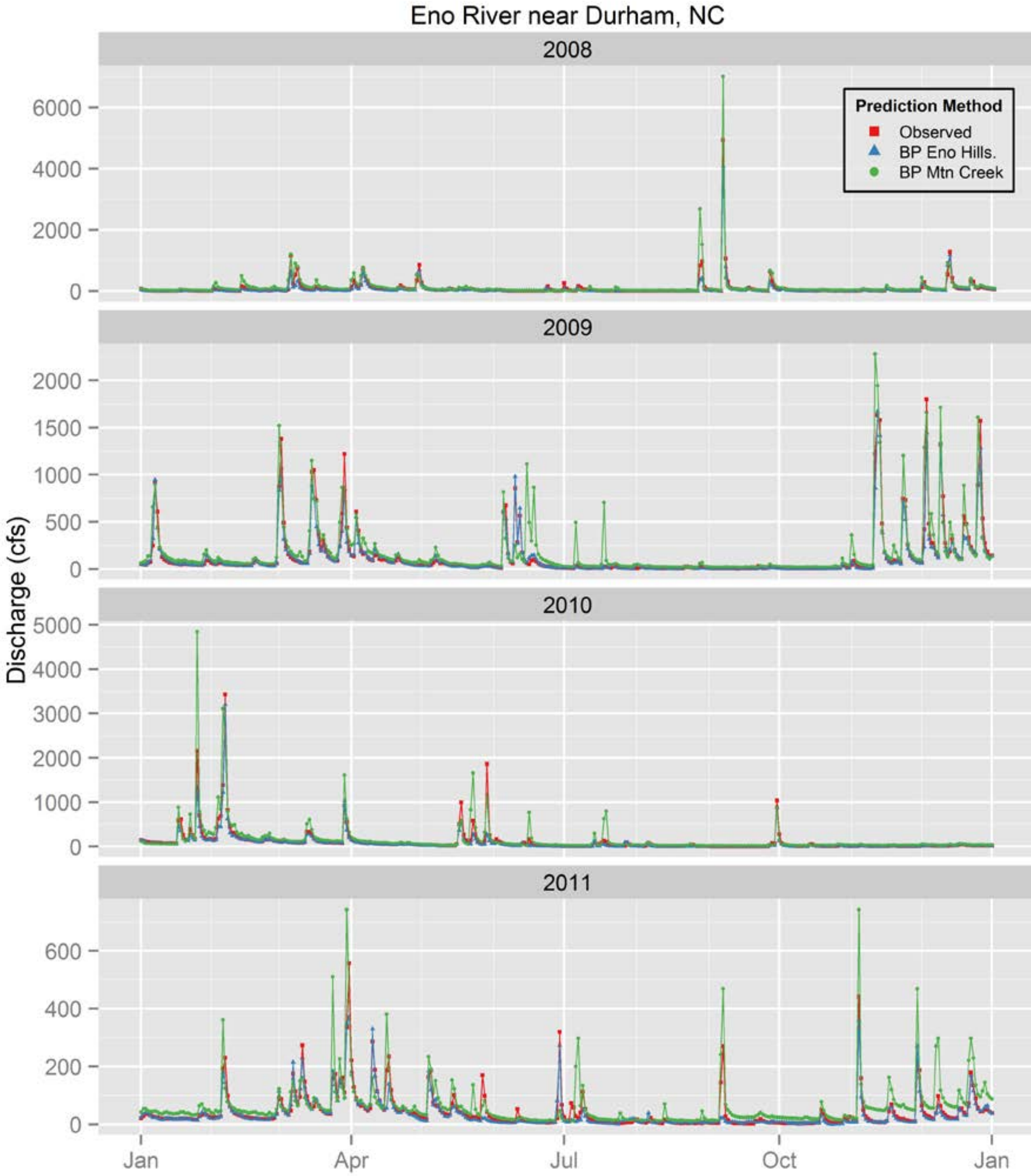

Figure B-7 Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in Eno River near Durham (2008 through 2011).

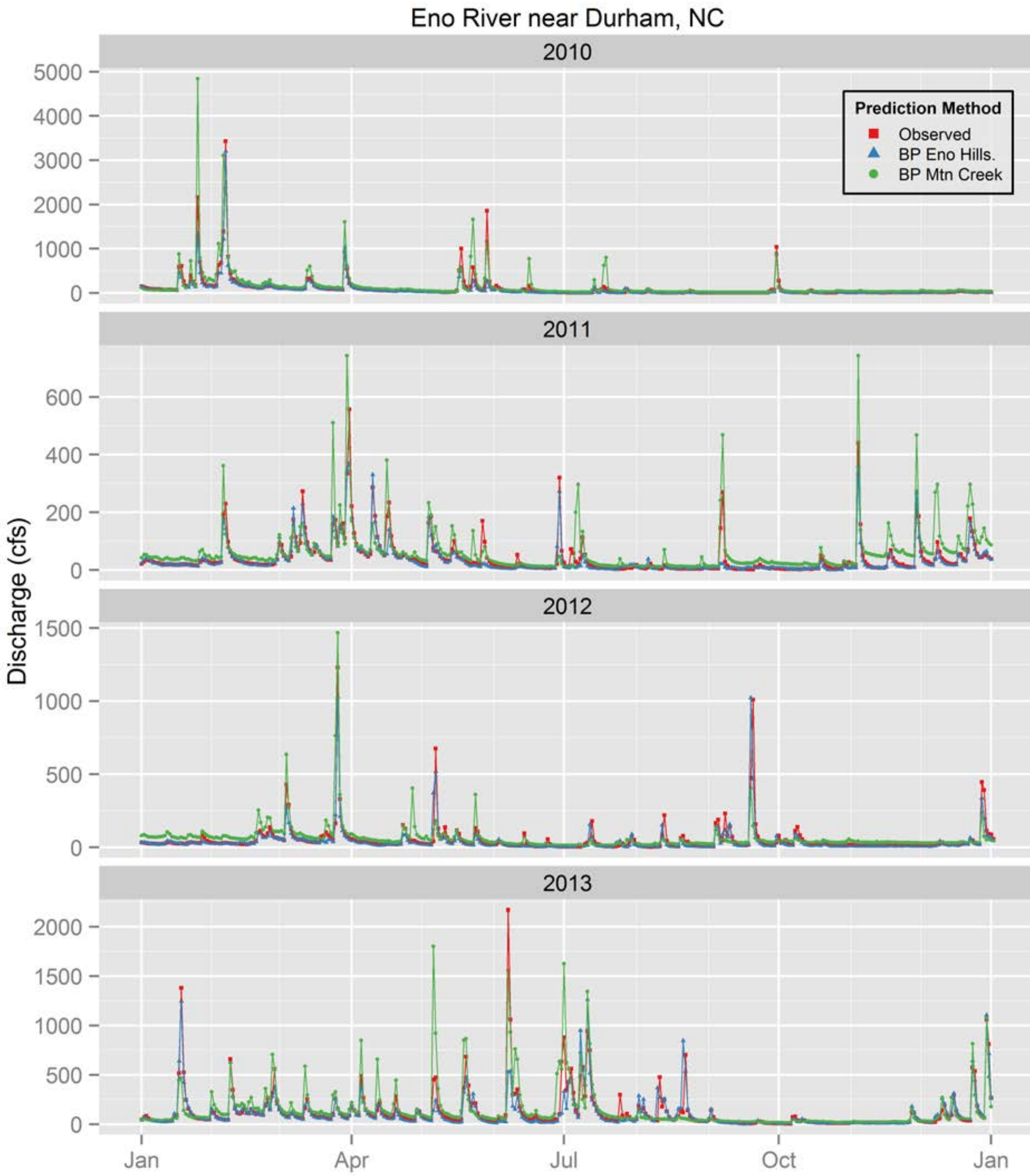

Figure B-8 **Timeseries of flow predictions based on Basin Proration (BP) and BP with map-correlation selection of donor gage compared to actual flow in Eno River near Durham (2010 through 2013).**

B.1.2 Predictions at Ungaged Location

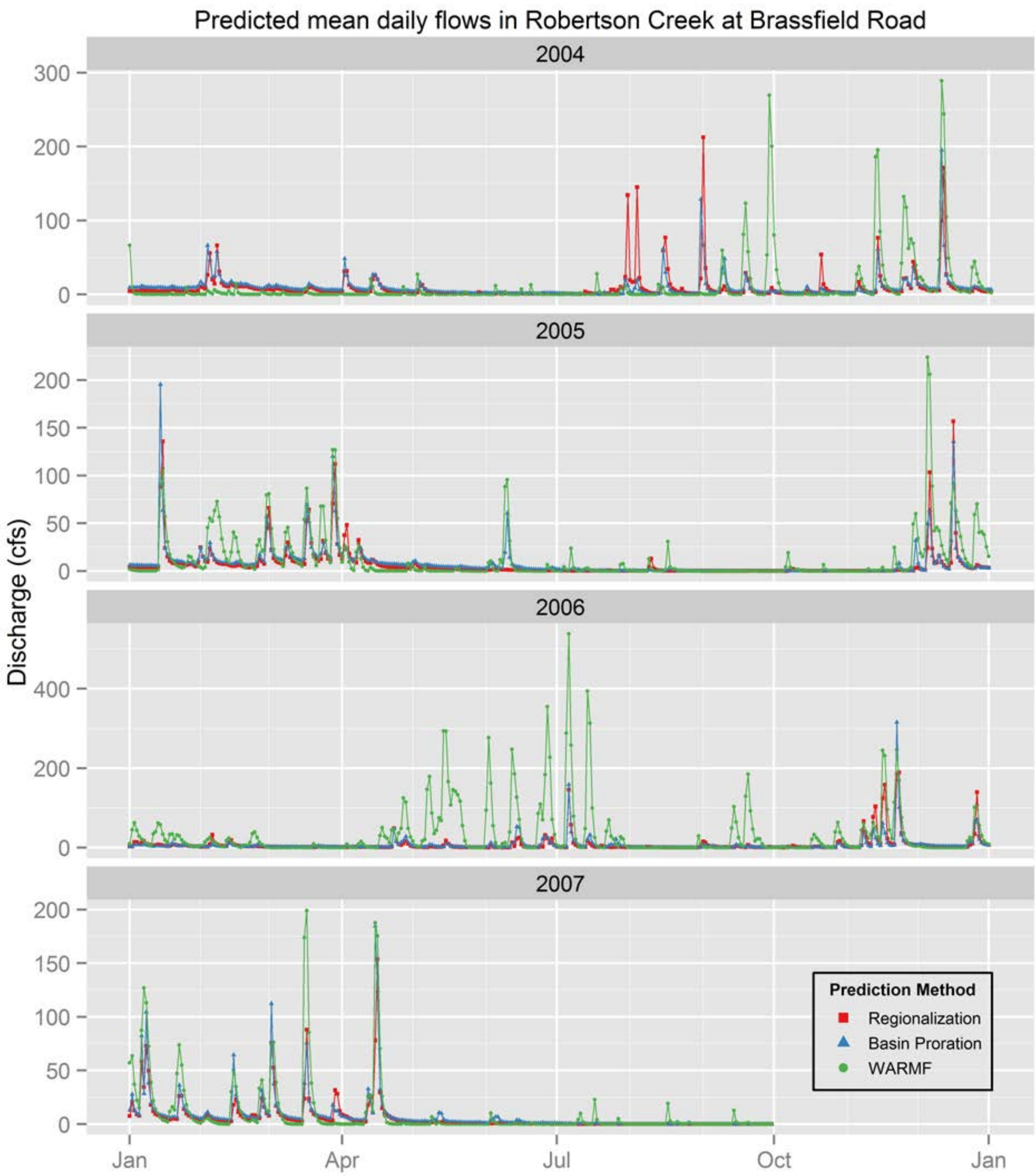

Figure B-9 Timeseries of flow comparing Basin Proration (BP), USGS Streamflow Regionalization, and WARMF models predictions at an Ungaged Tributary location in the Lower Falls Lake Watershed. Robertson Creek near Brassfield Road (2004 through 2007).