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FEATURED COLLECTION INTRODUCTION: NORTH CAROLINA ECOLOGICAL FLOWS[1]

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BACKGROUND

In 2010, the state legislature of North Carolina passed landmark legislation (NC Session Law 2010-143) defining ecological flow as "the streamflow necessary to protect ecological integrity." Ecological integrity was defined as "the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system."

The statute directed the state agency in charge of water quality (North Carolina Department of Environmental Quality; hereafter DEQ) to "characterize the ecology in the different river basins and identify the flow necessary to maintain ecological integrity." DEQ was charged with developing basin-wide hydrologic models for each of the 17 major river basins in North Carolina to simulate flows for determining whether adequate water will be available in the future to meet all needs, including essential water uses and ecological flows (*i.e.*, flows that maintain ecological integrity). The statute did not stipulate that ecological flows would be protected, but it did charge DEQ with knowing when and how ecological flows would be affected by state actions.

The statute also directed the agency to "create an Ecological Flows Science Advisory Board (EFSAB) to assist with characterizing the natural ecology and identifying the flow requirements" of the river basins of North Carolina. The resulting 16-member EFSAB was given to understand, both by the statute and by the DEQ directives, that its findings would be used for water resources planning and not for regulatory purposes, and its members were to set aside agency and/or sector allegiances and deliver the highest-quality scientific product possible.

Early in the process, Environmental Defense Fund (EDF), a member of the EFSAB, contracted with RTI International (RTI) to assist with finding and developing the very best information possible on the ecological characteristics of North Carolina's rivers and streams. A small, *ad hoc* advisory science team (hereinafter, the Team) was established with membership including scientists from EDF, RTI, DEQ, U.S. Geological Survey (USGS), NC Wildlife Resources Commission (WRC), and The Nature Conservancy. The goal of the Team was to conduct research and produce scientific products to support the EFSAB effort to develop strategies for determining ecological flows.

The Team collected and standardized preexisting data from various state databases, initially for its

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own use, but also for the benefit of future research. Using collected data and modeled hydrologic data the Team characterized the degree of alteration in streamflows at the stream segment level across the state and explored strategies for: (1) classifying streams both by flow characteristics and by physiological and ecological regions; (2) characterizing the biota of streams and relative sensitivity to flow alterations; and (3) quantifying biological responses to flow alterations. The Team's final products and recommendations were incorporated into the EFSAB's final report to DEQ.

OVERVIEW OF THE FEATURED COLLECTION

The four articles in this collection summarize the main findings of the EFSAB advisory science Team.

Eddy *et al.* (2017a) describe the design and application of the Watershed Flow and Allocation model (WaterFALL®), a proprietary model previously developed by RTI, which was subsequently adopted by the Team as the best and most reliable available model for determining both base flows and streamflows influenced by modified climate, land cover, and discharges/withdrawals. WaterFALL estimates daily streamflows at the fine spatial scale of the enhanced National Hydrography Dataset (NHDPlus) catchments. These streamflows can then be aggregated to any scale used for water management planning. As described in Eddy *et al.* (2017a), WaterFALL was applied across North Carolina with calibration and validation against USGS observed streamflows. This statewide application of WaterFALL provided the hydrologic foundation and data for the subsequent research and articles in this collection.

One initial assumption of the Team was that ecological integrity should be defined differently for different classes of streams and rivers. In keeping with the Ecological Limits of Hydrologic Alteration (ELOHA) framework put forward by Poff *et al.* (2010), it was hypothesized that rivers should be classified according to ecologically meaningful flow metrics (*i.e.*, a hydroecological classification system), and rivers within the same class share the same natural range of hydrologic variability and are therefore similar in terms of biological assemblages and ecological response to flow alternation. Eddy *et al.* (2017b) describes the Team's evaluation of different approaches to stream classification using two systems developed for North Carolina and the southeastern United States. The two hydroecological classification systems did not produce similar results using either observed or modeled daily time series of streamflow data. In addition, both classification systems produced classes that were extremely sensitive to flow metric thresholds that distinguished between the system-specific stream classes. This resulted in stream class assignments being both strongly influenced by the time period of data and highly sensitive to variations between seasons and years; the class assignment of a stream segment could therefore change between years and seasons. The sensitivity of these thresholds appeared to be independent of flow data, as class assignments made by USGS observed streamflows as well as with modeled streamflows from WaterFALL both resulted in changes in stream class assignments. Extrapolation of stream classes from gaged catchments to nongaged catchments was therefore found to be not reliable.

Phelan *et al.* (2017) further supported the finding that a stream classification system was not necessary in developing ecological flow relationships while also determining that defensible flow alteration-biological response relationships (hereafter referred to as "flow-biology" relationships) could be established for rivers and streams at the statewide level. This study describes the development and testing of a method to evaluate the responses of fish and macroinvertebrate communities to reductions in flow (quantified by flow metrics) in North Carolina rivers. This method substituted space for time, successfully establishing negative flow-biology relationships between reductions in flow and the diversity (Shannon-Weaver index) of the riffle-run fish guild and benthic Ephemeroptera, Plecoptera, and Trichoptera richness statewide. Multiple flow metrics evaluating different aspects of flow alteration were tested resulting in 12 significant and negative, linear flow-biology relationships for both benthos and fish. The responses of benthic richness to reduced flows were consistent and generally greater than that of fish diversity. However, the strongest relationship was for the riffle-run fish guild in response to deficits in summer streamflow (summer ecodeficit). Because the final statewide relationships were linear, thresholds for ecological flows could not be easily established. Thresholds are typically used to set water management guidelines or regulations. Given the lack of thresholds, the authors explore a method of setting ecological flows based on the magnitude of change in biological condition (*i.e.*, benthic richness or fish diversity) that is acceptable to society.

Patterson *et al.* (2017) further tested the space-for-time method developed for North Carolina by Phelan *et al.* (2017) to determine relationships between reductions in streamflows and the responses of four habitat-based fish guilds (*i.e.*, riffle, riffle run, pool run, and pool) developed by WRC (Persinger *et al.*, 2011) for fish species in North Carolina. Overall, the authors concluded that the method was sensitive enough to distinguish between the responses of different fish guilds to altered flows. While species which prefer shallow habitats, such as riffles and riffle runs, were found to be the most sensitive to decreases in streamflow, the riffle-run guild was both most ubiquitous and most sensitive to alterations in flow. In addition and consistent with the hypothesized sensitivities, no significant relationships were found for pool or pool-run species. Seasonality was again found to be important with greater sensitivity to reduced streamflow during summer and fall when stream levels are naturally lower. The authors also found grouping all fish habitat guilds together eliminated the findings of any significant flow-biology relationships to reduced streamflow. Therefore, studies of flow-biology relationships that do not establish relationships for each fish guild separately may greatly underestimate the response of fish species to reductions in streamflow.

CONCLUSIONS

Five significant findings related to the development of ecological flows emerged from the work represented in these four articles. First, the diversity of a fish guild and richness of macroinvertebrates showed significant and consistently negative responses to reductions in flow evaluated through a series of modeled hydrologic metrics. Second, the space-for-time analysis approach for establishing flow-biology relationships was validated through the development of statistically significant relationships across both the diversity of multiple fish guilds and the richness of macroinvertebrates. Third, hydroecological stream classification systems were not found to be transferable, and their application did not improve the strength of the relationships between flow alteration and biological response. Fourth, and similarly, classification based on preexisting regional classification systems did not improve the flow-biology relationships. Relationships developed at the statewide level were strongest. Finally, seasonality, as it pertains to flow reduction, was an important differentiator in the significant relationships with greater sensitivity to reduced streamflow during lower flow seasons.

Together these findings indicate, at least for North Carolina, that a statewide approach to limiting reductions in seasonal and annual flows is likely to produce a corresponding conservation of biological diversity and stream integrity systematically across the state; failure to do so will likely have an opposite effect. As noted earlier, Phelan *et al.* (2017) conclude their article with a suggested strategy for water planners within North Carolina to establish ecological flows and a management framework to limit flow impairments and predictable reductions in aquatic biodiversity. Beyond North Carolina, we believe the work of water planners committed to conserving ecological integrity may be simplified through application of our approach and corresponding strategy.

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