EVALUATING EFFECTS OF PUMP-STORAGE WATER WITHDRAWALS USING AN INDIVIDUAL-BASED METAPOPULATION MODEL OF A BENTHIC FISH SPECIES

Rachel A. Katz[1] and S. Kyle McKay[1,2]

AUTHORS: [1]Odum School of Ecology, University of Georgia, Athens, Georgia, 30605, [2]Environmental Laboratory, U.S. Army Engineer Research and Development Center, Athens, Georgia, 30606.
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Abstract. As demand on freshwater resources increases, managers are increasingly tasked with identifying water withdrawal, storage, and management strategies that minimize impacts on aquatic species. Identifying critical features of the flow regime that sustain particular ecological processes can be difficult due to site and species-specific characteristics. Our goal was to simulate trade-offs between differing water withdrawal strategies for an off-channel, pump-storage reservoir and the ecological-flow requirements of flow-dependent taxa. Using a case study of a 30-km reach of the Middle Oconee River near Athens, we evaluated multiple demographic models for selecting a flow management strategy for maintaining abundance of a native fish species, the Turquoise darter (*Etheostoma inscriptum*). We developed and applied an individual-based metapopulation model to assess the relative influence of five alternative flow management strategies. Each strategy differed based on the magnitude and timing of water withdrawals. We explicitly incorporated uncertainty in the analysis by applying two alternative flow-survival relationships and stochastic variation in recruitment and survival. The influence of each flow management strategy on fish populations was evaluated based on the mean and standard deviation of darter abundance following a 20-year period of simulated water withdrawals. This evaluation demonstrates the utility of individual-based population models to inform a common freshwater flow management problem, balancing economic and ecological flow requirements.

INTRODUCTION

Globally, the expansion of human populations has increased demand on freshwater ecosystem goods and services (MEA 2005). In particular, streamflow alteration by dams, water diversions, and urbanization have altered ecological processes as well as the distribution of aquatic biota (Freeman et al. 2001, Bunn and Arthington 2002, Richter et al. 2003, Death et al. 2009, Poff et al. 2010). As demands on water increase, managers must be able to evaluate the trade-offs between flow management strategies and ecological impacts (Arthington et al. 2006).

Historically, flow management has been guided by the concept of "minimum flow levels," or MFLs (Bovee and Milhous 1978), and flow variability has not often been integrated into environmental flow decision-making (Richter 2010, Poff et al. 2010), despite its widely recognized role in structuring aquatic communities (Poff et al. 1997, Richter et al. 1997, Bunn and Arthington 2002). Under drought conditions, the effects of maintaining particular streamflow levels may be directly linked to ecological outcomes (Matthews and Marsh-Mathews 2003). In contrast, the ecological effects of short-term flow variability caused by water withdrawals (e.g., daily low flows) are poorly understood. Off-channel water storage facilities are increasingly viewed as viable options for improving municipal water supply throughout the southeastern U.S. As such, tools are required to evaluate long term effects of water withdrawals on aquatic populations and ecosystems.

Population models can be useful for simulating the effects of different water use strategies on aquatic organisms. Simulating population processes through individual-based models can also help identify the most influential demographic components, which can be used to inform management decisions and future research needs. Herein, we develop and apply an individual-based metapopulation model for assessing the effects of water withdrawals on a flow-dependent species, the Turquoise darter (*Etheostoma inscriptum*). We focus on this taxon because it is widely distributed in larger-order streams of Atlantic slope drainages of NC, SC, and GA, short-lived (4 year maximum; Rhode 2009), and exhibits sensitivity to flow conditions and relatively high site fidelity (Katz and Freeman, *unpublished data*). Small-bodied fishes can also contribute substantially to stream production (Lotrich 1973, Randall et al. 1995) and are important to other stream ecosystem processes (McIntyre et al. 2008, Vanni 2010).

Our goal is to evaluate the trade-off between a one-time decision of selecting a water withdrawal strategy for a municipal pump-storage reservoir and the status of the Turquoise darter over a 20-year period in the Middle Oconee River near Athens, Georgia. The competing objectives are to: 1) maximize average annual water withdrawal rate and 2) maximize darter abundance. We developed five alternative flow management strategies and a spatially explicit metapopulation model that allowed us to assess the relative effect of each strategy on the ecological outcome. The effects of model uncertainty and stochastic variability are explicitly incorporated into the analysis and their effect on the decision addressed.

CASE STUDY: MIDDLE OCONEE RIVER

This study focused on water withdrawals and fish abundance in a river that has well-documented flow data, is currently used for water supply, and has prior information on fish demographics. The Middle Oconee River is a sixth-order tributary of the Altamaha River system that flows through Athens, Georgia. In 2002, Bear Creek reservoir, an off-channel pump-storage reservoir facility, was constructed as the primary water supply for four surrounding counties. The facility is permitted to extract up to 60 million gallons of water per day (MGD; GAEPD Permit #078-0304-05) from the Middle Oconee and transport it to a 204 ha off-channel reservoir.

Two natural barriers to fish movement were used as boundaries of our study reach. The boundaries included a non-operational dam located 1.7 km below the reservoir intake and a failing mill dam located approximately 30 km downstream of the intake (Fig 1). The study reach drains approximately 1000 km^2 of the Upper Oconee Watershed in the Piedmont physiographic province and has an average annual discharge of 14.3 m^3 s^{-1} (506 cfs, 75 year record; USGS gage #02217500; USGS 2010). Daily discharge data is recorded by USGS approximately in the middle of the reach and was used for the development of each flow management strategy.

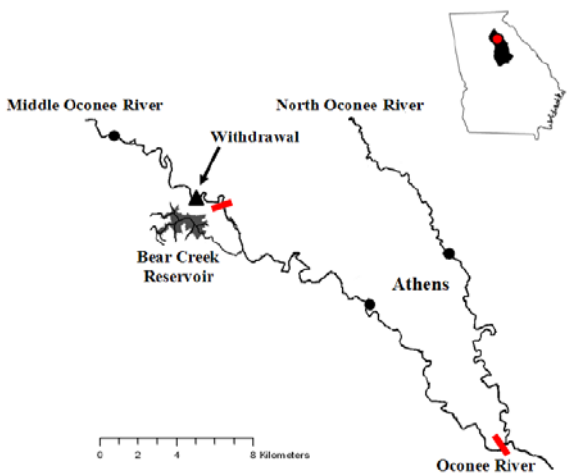

Figure 1: Middle Oconee River study reach within the Upper Oconee River Basin (inset) with reach boundaries (red), location of the pump-storage reservoir intake (triangle) and USGS gages (black).

The ecological metric evaluated was the abundance of Turquoise darters, *Etheostoma inscriptum*, which occurs across the Atlantic-slope drainages of NC, SC, and GA in larger rivers (Rhode 2009). The species prefers shallow-swift habitats covering rocky substrates (Henry et al. 2008, Rhode 2009) and has relatively high site fidelity (Katz and Freeman, *unpublished data*). Low movement rates are typically observed in small benthic fish species (Freeman 1995, Roberts and Angermeier 2007); thus we considered this species to be relatively restricted to shoals (swift-water over coarse substrate habitat), with a limited ability to disperse between shoals. Demographic rates for this species were parameterized based on prior data collected within the Middle Oconee River and literature based on other small non-migratory species, as detailed in below.

FLOW MANAGEMENT STRATEGY DEVELOPMENT

We developed five alternative flow management strategies based on existing and proposed environmental flow methods (Richter 2010, Poff et al. 2010). Two strategies included minimum flow standards, representing the lowest flow conditions expected under regional and local drought conditions (7Q10 = 45 cfs: lowest seven-day flow that reoccurs once every 10 years and 30Q2 = 155 cfs: lowest 30-day flow that reoccurs every 2 years; Carter and Putnam 1978). In addition, we included a low (15%) and high (30%) maximum percent reduction in streamflow that preserves components of flow variability (i.e., a "sustainable boundary", sensu Richter 2010). For comparison, we also included a null model that represented no change in streamflow by not allowing any water withdrawals to occur.

To simulate flows under each management strategy, we removed water daily according to each strategy based on daily discharge recorded from 1980-1999 at the site (Fig 2a). To allow for comparison among strategies, we allowed the maximum permitted withdrawal to occur on each day (60 MGD), unless it did not comply with the water withdrawal strategy. For example, during a drought year discharge was frequently below minimum flow levels such that on these days no water was withdrawn. In addition, only 30% of the flow was permitted to be withdrawn if the maximum permitted amount exceeded the sustainable boundary (i.e., 30% of the flow). We used average withdrawal rate over a 20-year period as a surrogate for the relative economic gain of each withdrawal strategy.

POPULATION MODEL DEVELOPMENT

We used a stochastic individual-based demographic model to evaluate the effects of flow management strategies on the abundance of darters within the 30-km study reach. The model included four demographic processes: reproduction, survival, immigration/emigration, and carrying capacity. The model was primarily parameterized based on a prior 3-year study in a small shoal within the reach (Katz and Freeman, *unpublished data*). Based on the life history of *E. inscriptum*, we simulated population processes on an annual time step (April to April), and defined the spawning and rearing period as the period when individuals are most responsive to changes in streamflow (April to November).

We identified eleven distinct habitat units within the reach where *E. inscriptum* were likely to occur given their affinity for swift-water habitats (i.e., shoals). The area (m^2) of each unit and distance between units (km) was measured using satellite imagery (Google Earth 2010). Within each habitat unit, an initial density of adults was assigned based on the lowest density observed (0.3 individuals per m^2) during the prior study, and initial density of juveniles was assumed to be zero prior to the spawning period (only adults present).

We included both demographic variability and model uncertainty in the demographic-flow interaction in our population model to evaluate the influence of each on the management decision. Demographic variability was represented by annual per-capita recruitment (born and survived), which was drawn annually from a random uniform distribution with a minimum of 0.26 and maximum of 0.49 individuals recruited per adult based on estimates from the prior study. We assumed that all adults contributed to reproduction and that the number of juveniles entering each habitat unit was a function of the recruitment rate and number of initial adults in that unit. New adult abundance was the sum of initial adult abundance and juvenile abundance (Fig 2b).

Two alternative models were developed to represent demographic-flow interaction between monthly flow and survival. New adults were subject to mortality each month during the active period (April-November) according to two alternative survival-flow models: either a linear ($S = -0.0749*CV + 0.9898$) or quadratic ($S = -0.0307CV^2 + 0.0236CV + 0.9320$) relationship to monthly flow variability (measured as the coefficient of variation of monthly discharge, CV). Each model contained random variation, such that the mean survival rate was drawn from a normal distribution with a mean response for each model, and a standard deviation of 0.02 around the mean response (Fig 2c). These two relations were constructed based on mean values predicted from the prior study, which was conducted during two drought years and one higher-flow year. The functional form of each flow-survival relationship was based on published accounts suggesting that survival decreases with increasing flow variation during spawning and rearing periods (Freeman et al. 1988, Grossman et al. 1998, Labbe and Faush 2000, Freeman et al. 2001, Craven et al. 2010).

After the active period (November), all surviving adults were assumed to remain in each shoal until the onset of the spawning season (April). We assumed that the highest densities would occur during the lowest flow periods in response to decreased habitat availability. Hence, prior to the next recruitment period, the density of individuals in each habitat unit was assumed to be influenced by a carrying capacity, which was identified as the highest density observed during a prior drought period (3 individuals per m^2). If the density of adults in a given unit was greater than the carrying capacity, excess individuals emigrated out of the unit. Emigration into a neighboring habitat unit was spatially-explicit and dependent on the distance between units. Previous studies have shown that small bodied fishes typically move short distances, and the direction of movement does not exhibit directional bias (Skalski and Gilliam 2000, Roberts and Angermeier 2004). Although movement patterns of *E. inscriptum* are unknown, we assumed that if the distance between shoals was less than 1 km, then 50% of individuals moved upstream and 50% moved downstream. If the distance between shoals was greater than 1 km, all of the emigrating individuals died.

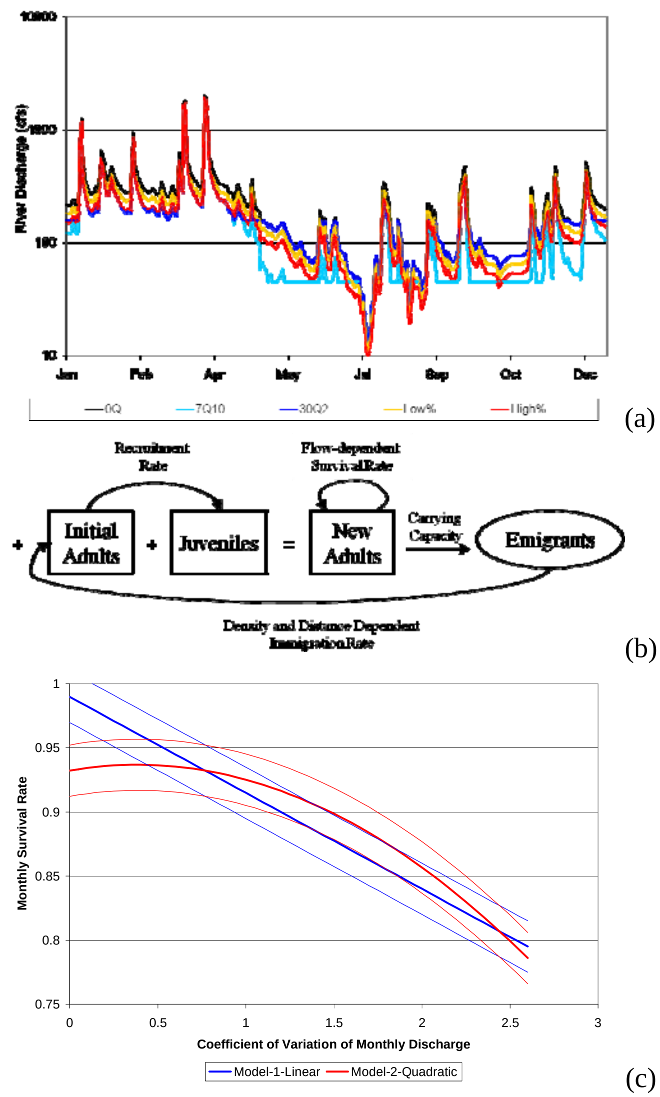

Figure 2: Effects of flow management strategies in a typical flow year, conceptual representation of the population model, and survival model uncertainty.

After individuals emigrated (or died), we simulated the annual time step repeatedly over a 20-year period (Fig 2b). Each 20-year simulation was repeated over 10,000 randomized iterations to capture annual variation in responses, and the abundance of darters during the final time period was averaged over the all iterations. For each flow management strategy, we normalized the average and standard deviation of abundance at year 20 by abundance predictions of the null model (i.e., no withdrawal) to assess the relative impacts of each strategy on fish abundance.

MODEL SENSITIVITY

Prior to evaluating the flow management strategies, we performed a sensitivity analysis to identify model parameters having the greatest impact on the outcome (i.e., abundance; Clemen 1996). A one-way analysis was performed by varying the values of each component independently to determine its influence, while other components remain constant. If there was prior support for a specified range in a model component (i.e., published values), that range was used. Otherwise, each component was varied by 50%. For example, initial density was drawn from a random uniform distribution with a minimum of 0.15 and a maximum of 0.45. Recruitment was drawn from a random uniform distribution from 0.26 to 0.49 with a central tendency of 0.375. For survival rates, the standard deviation was drawn from a random uniform distribution with a minimum of 0.0001 (effectively zero) and a maximum of 0.1. In addition, the influence of carrying capacity per shoal ranged from 1 to 5 individuals per m^2. Lastly, we assessed the influence of the maximum distance that successful immigration could occur by varying distance based on a random uniform distribution from 0.5 to 1.5 km. To facilitate comparisons, we used 1,000 iterations per component, and average fish abundance in year 20 was compared to abundance prediction of the null model (i.e., no water withdrawals). Model sensitivity was assessed using the linear survival model and the null withdrawal scenario.

RESULTS

The abundance of Turquoise darters within the 30-km study reach was highly variable across input parameter ranges and among survival models. Uncertainty in the relation between survival and streamflow resulted in highly variable predictions of abundance. For example, under the null withdrawal scenario, the quadratic model resulted in fewer individuals by an order of magnitude over the simulation period compared to the linear model (Fig 3). However, trends in abundance were similar across iterations, and the model serves as a tool for comparison of the relative effects of withdrawal.

Year-20 fish abundance varied for each survival model and among flow management strategies (Fig 4). All strategies results in an average withdrawal rate greater than 30 MGD (Fig 4), with the greatest rate occurring under the 7Q10 strategy (56 MGD). The linear survival-flow model resulted in overall lower abundances compared to the quadratic survival-flow model. Both models showed decreasing abundances with increasing withdrawal rates.

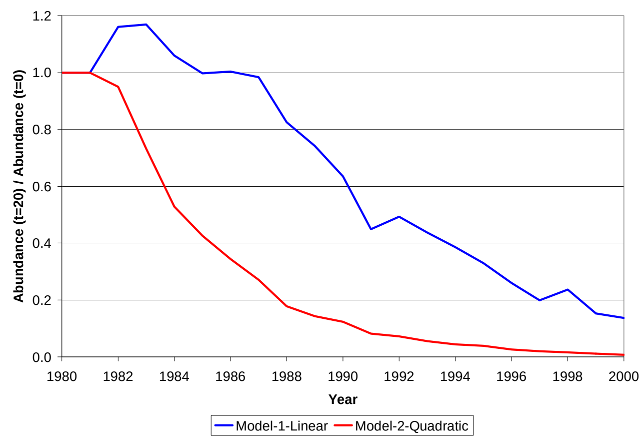

Figure 3: Normalized abundance predictions of two survival models for the null withdrawal strategy.

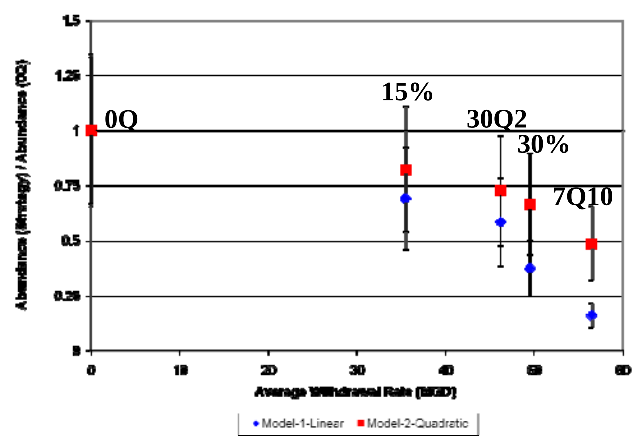

Figure 4: Normalized abundance (SD) of darters and average withdrawal rate for each flow management scenario.

Our sensitivity analysis showed that year-20 abundances were substantially influenced by variability in demographic rates, but generally not to initial conditions (Fig 5). Variation in survival had the greatest influence on year-20 abundance, while both recruitment and initial density has lesser effects. Carrying capacity and emigration distance did not appear to be governing variation in model results for abundance and thus had relatively little influence on our results.

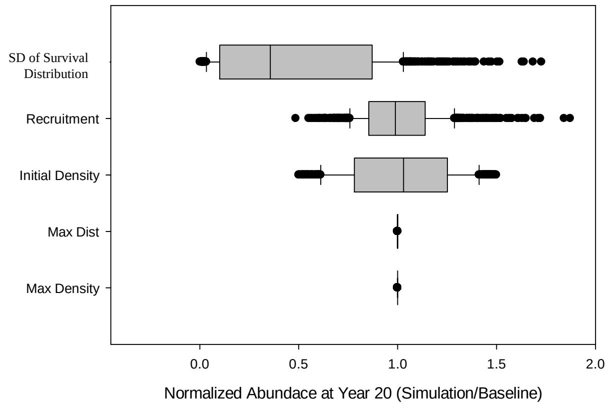

Figure 5: Sensitivity analysis assessing the relative influence of each demographic component to Year-20 darter abundance (linear survival model only).

DISCUSSION

The “best” flow management strategy may be identified as that which adequately balances societal (average water withdrawal rate) and ecological (darter abundance) water requirements. Because desirability is a function of societal values, determining the adequacy of a particular outcome cannot be achieved through modeling alone. For example, based solely on maximizing darter abundance, some of the flow management schemes emerge as more preferable than others. For instance, while withdrawing only 14% more water, the 7Q10 strategy results in 27-57% lower abundance (model 2 and 1 predictions, respectively) compared to the 30% withdrawal strategy.

Using an individual-based metapopulation model to evaluate the influence of demographic rates proved useful for comparing the influence of differing flow management strategies for a pump-storage reservoir. Both prior knowledge of hydrology (long-term daily data) and life history traits (recruitment, survival, movement) were critical for parameterizing the model. Despite our simplistic assumptions regarding withdrawal strategies, this population model proved to be a useful tool for building more complicated population dynamics into a flow management decision. Our sensitivity analysis indicated that survival and recruitment rates largely govern the outcome of our model, and ultimately the preferred flow management strategy. Since small population sizes tend to be more vulnerable to environmental and demographic variability, an alternative management strategy for sustaining ecological-flow requirements may be to reduce variability in population abundance from year to year. Thus, future research could significantly reduce model uncertainty by focusing on improving understanding of temporally variable demographic processes.

This model assumed that water withdrawals were not limited by cost and other regulatory restrictions. Thus, our model should be modified to address key assumptions, including: (1) withdrawing water without regard for reservoir capacity, (2) withdrawing without regard to pump capacity, (3) withdrawing water across the entire day (whereas current pump operation is typically during business hours), and (4) withdrawal at any turbidity level. Moreover, our model did not address water demand and seasonal variation in demand, both of which should be included to rigorously evaluate the trade-offs presented here.

Our population model can also be modified to better address population dynamics of benthic stream fish. Some of our assumptions include (but are not limited to): (1) effects of mean flow conditions such as high flow years and droughts are minimal, (2) over-emphasis of the importance of flow variability on survival, as it likely interacts with mean flow conditions, and (3) all shoals have the same flow impacts on survival despite different geomorphologies and changes in velocity.

With some modification, our approach to simulating trade-offs between water use and aquatic population status may be useful for comparing flow management strategies. Next steps to further inform streamflow management would include verifying the model structure and predictions, building some of the complexity alluded to in the previous paragraph into the model, incorporating additional taxa (e.g., pelagic fishes, mussels, etc.) or ecosystem measures (i.e., turn over or production), incorporating system dynamics (e.g., increasing water demand through time), comparing the model to other flow management software (e.g., The Nature Conservancy’s Indicators of Hydrologic Alteration), and using the model within a formalized decision-making framework (e.g., Bayesian Belief Network or Multi-criteria decision analysis).

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