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Environmental flows in the context of unconventional natural gas development in the Marcellus Shale

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Abstract. Quantitative flow–ecology relationships are needed to evaluate how water withdrawals for unconventional natural gas development may impact aquatic ecosystems. Addressing this need, we studied current patterns of hydrologic alteration in the Marcellus Shale region and related the estimated flow alteration to fish community measures. We then used these empirical flow–ecology relationships to evaluate alternative surface water withdrawals and environmental flow rules. Reduced high-flow magnitude, dampened rates of change, and increased low-flow magnitudes were apparent regionally, but changes in many of the flow metrics likely to be sensitive to withdrawals also showed substantial regional variation. Fish community measures were significantly related to flow alteration, including declines in species richness with diminished annual runoff, winter low-flow, and summer median-flow. In addition, the relative abundance of intolerant taxa decreased with reduced winter high-flow and increased flow constancy, while fluvial specialist species decreased with reduced winter and annual flows. Stream size strongly mediated both the impact of withdrawal scenarios and the protection afforded by environmental flow standards. Under the most intense withdrawal scenario, 75% of reference headwaters and creeks (drainage areas <99 km^2) experienced at least 78% reduction in summer flow, whereas little change was predicted for larger rivers. Moreover, the least intense withdrawal scenario still reduced summer flows by at least 21% for 50% of headwaters and creeks. The observed 90th quantile flow–ecology relationships indicate that such alteration could reduce species richness by 23% or more. Seasonally varying environmental flow standards and high fixed minimum flows protected the most streams from hydrologic alteration, but common minimum flow standards left numerous locations vulnerable to substantial flow alteration. This study clarifies how additional water demands in the region may adversely affect freshwater biological integrity. The results make clear that policies to limit or prevent water withdrawals from smaller streams can reduce the risk of ecosystem impairment.

Key words: Appalachia; environmental flows; fish; flow regime; hydraulic fracturing; Marcellus Shale.

Introduction

Human alteration of natural flow regimes threatens the structure and function of freshwater ecosystems (Poff et al. 1997, USEPA, 1998). In the context of agricultural and hydropower demands, for example, numerous studies have examined the impacts of water infrastructure on the magnitude, duration, frequency, rate of change, and timing of flows (WCD 2000, Poff and Hart 2002, Arthington 2012). However, the in-stream effects of water-intensive energy development practices remain relatively understudied, despite the recent growth in this sector. Advances in hydraulic fracturing technologies have led to the proliferation of natural gas drilling in previously unrecoverable shale deposits in the USA and Europe with documented potential for further expansion globally (USDOE 2011, 2013).

In this situation, analyses of the available empirical evidence are needed to inform policy makers and natural resource managers seeking to meet human energy demands without sacrificing freshwater ecosystem integrity. An exemption to the U.S. Safe Drinking Water Act included in the Energy Policy Act of 2005 has impeded federal oversight regarding water withdrawals associated with hydraulic fracturing in the USA and has contributed to a piecemeal regulatory framework (Energy Policy Act of 2005: 42 USCS § 15801). Protecting freshwater ecosystems is especially challenging in large multi-state settings such as the Marcellus Shale region (MSR) in the northeastern USA. A complicated nexus of state agencies and interstate river basin commissions presently oversees the regulations and permitting procedures for water

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withdrawals related to high volume hydraulic fracturing (HVHF) in the MSR. This produces regulatory uncertainty for energy developers while limiting the application of proactive, precautionary policies to protect stream ecosystems (Rahm and Riha 2012). Despite this political situation, social surveys indicate that water-related issues are consistently the most frequently cited concern associated with shale gas development in the MSR (Evensen et al. 2014, Ashmoore et al. 2016). Recent volatility in the U.S. energy sector has led to declines in HVHF drilling and exploration (EIA 2016). Such declines may afford a valuable window of opportunity for the proactive design of scientifically credible policy and management plans.

In addition to the potential for ground and surface water contamination from sediment, metals, or other pollutants, HVHF requires large quantities of freshwater (Entrekin et al. 2011, Rahm and Riha 2012, Weltman-Fahs and Taylor 2013, Brittingham et al. 2014). Unconventional gas wells can require up to seven million gallons of water to fully develop, and a single pad may host 20 wells (Rahm and Riha 2012). Wells can be refractured several times to maintain yields over multiple decades (Entrekin et al. 2011), and the costs of moving water from viable withdrawal points to a particular drilling lease may concentrate impacts in space and time. In particular, the hierarchical spatial structure of drainage networks means that well pads may be closest to the smaller headwater streams that are most abundant across the landscape. Such streams are more susceptible to flow depletion, especially during summer months when ecological communities are most vulnerable to thermal stress or elevated contaminant concentrations. In the eastern USA, stream species assemblages have shifted toward fewer and more generalist taxa in response to water withdrawals to meet demand from other nonenergy sectors (Freeman and Marcinek 2006, Kanno and Vokoun 2010). This observation highlights the need to understand how water withdrawals from gas development may alter natural flow regimes, reduce critical habitat, and decrease biological integrity, especially as HVHF occurs in combination with suburban expansion, agricultural intensification, and climate change.

Better understanding of regional flow–ecology relationships could support environmental flow standards for the MSR that serve as a regionally consistent, scientifically credible framework for water withdrawal regulations. Extending the concept of the natural flow regime, environmental flows are "the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Brisbane Declaration 2007). Within the MSR, several projects have integrated regional assessment methods such as the Ecological Limits of Hydrologic Alteration framework (ELOHA) with a semi-quantitative literature review process (Eco-evidence framework; Norris et al. 2012). These efforts generated testable hypotheses, synthesized existing scientific evidence, and offered expert panel-based flow recommendations intended to protect aquatic species diversity across a natural range of hydrologic variability (DePhilip and Moberg 2010, 2013, Taylor et al. 2013).

Building on this work, we sought to investigate and quantify several important flow–ecology relationships identified by regional ELOHA-style projects and to systematically investigate alternative water allocations in the MSR (Buchanan et al. 2015). We characterized the present state of flow alteration, related it to ecological response measures, and analyzed plausible consumptive use scenarios mitigated by a suite of environmental flow standards. We hypothesized that altered surface hydrology under a range of water extraction rates would have the strongest impact on small to moderate river reaches during periods of low-flow. In addition, we hypothesized that richness, total abundance, and the prevalence of intolerant taxa would decline with greater withdrawals as a consequence of habitat degradation/loss or alteration of critical environmental cues (Freeman and Marcinek 2006, Kanno and Vokoun 2010).

Methods

Our approach involved (1) gathering suitable existing flow and biological data, (2) computing flow alteration for nonreference, gaged basins as the deviation between observed and predicted natural flow metrics, (3) calculating ecological response measures for fish sampling sites associated with the nonreference stream reaches, (4) relating the fish community measures to the flow alteration metrics, and (5) simulating scenarios of water withdrawal for HVHF and a set of flow protection standards (Fig. 1).

Study area

The Marcellus Shale formation covers over 170,000 km^2 (Fig. 2) and is estimated to contain over 13 trillion m^3 of recoverable natural gas (Rozell and Reaven 2012). Horizontal drilling and hydraulic fracturing have enabled greater exploitation of this resource, with intense activity in West Virginia and Pennsylvania and contentious development in neighboring states. At the height of the most recent drilling boom, up to 60,000 new wells were projected for Pennsylvania alone by 2030 (Johnson et al. 2010).

Streams in the MSR form the upper reaches of the economically and biogeographically important Susquehanna, Ohio, and Delaware River basins (USGS 2015). The six physiographic provinces and 79 Level IV ecoregions that are present in the MSR reflect its varied geology, topography, and climate (USEPA 2014). This heterogeneity supports diverse stream habitats and considerable aquatic biodiversity, including more than 220 different fish species.

In general, high-flows occur during the spring months (March–June), with the lowest flows occurring in the late summer and early fall (July–September). Winters are often characterized by intermediate flows due to intermittent snowmelt and relatively low evapotranspiration. The

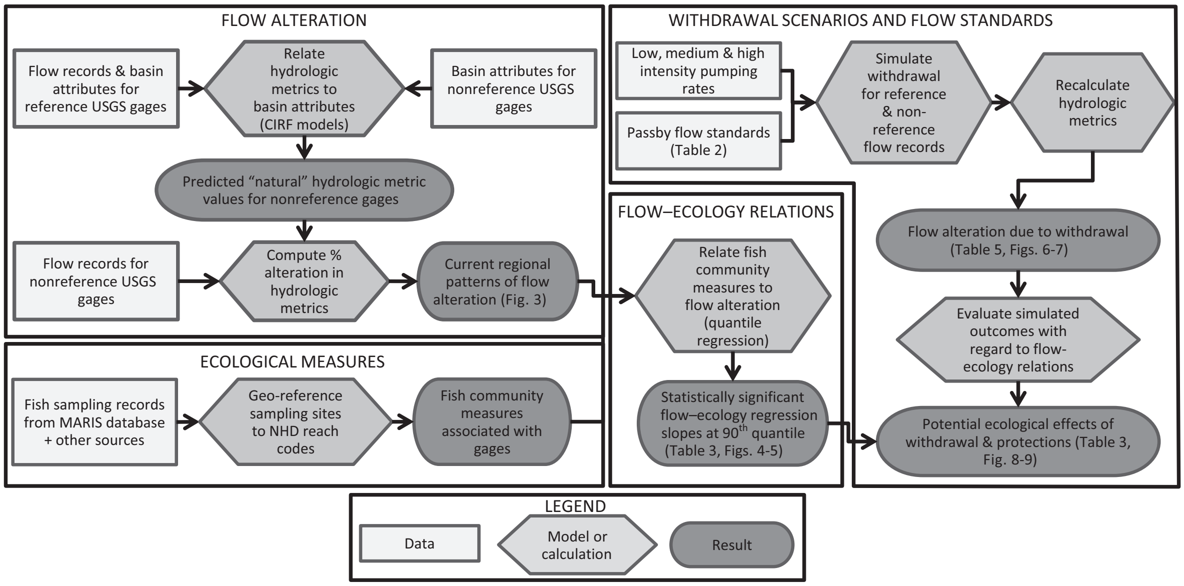

FIG. 1. Conceptual overview of the four main steps in the project workflow.

MSR has abundant precipitation relative to some other areas of shale gas development (e.g., Texas, Colorado, and North Dakota), but additional surface water demands may impair relatively pristine streams and rivers or compound existing stressors in more heavily developed basins.

Hydrologic and landscape data

We defined the study extent as the aggregated boundary of the 661 HUC-8 catchments that intersect the geologic Marcellus Shale region (Fig. 2; HSC 2014, USGS 2015). Following McManamay et al. (2014), we identified the United States Geological Survey (USGS) streamflow gages in this area that offered 15 or more years of continuous data with at least 50% overlap in period of record (Kennard et al. 2010). These were categorized as reference (n = 198) and nonreference (n = 373) gages after additional screening of the categorization and expert review conducted by Falcone et al. (2010). McManamay et al. (2014) assessed gages for disturbance conditions using a three-step procedure: (1) geospatial assessments of the degree of upstream anthropogenic disturbance (e.g., dams, diversions, and native vegetation conversion), (2) expert comments in USGS water reports, and (3) visually examining plots of cumulative flow variation vs. time to identify apparent changes in stream flow attributable to anthropogenic disturbances (Vogl and Lopes 2009). Adapting the Hydrologic Index Tool concepts (Henriksen et al. 2006), we calculated 171 hydrologic metrics (HMs) reflecting the statistical properties of daily discharge records at these stations (EflowStats; R Core Team 2015; *data available online*).[8] These metrics describe various flow regime attributes, often grouped into indicators of discharge magnitude, timing, frequency, duration, and rate of change (Olden and Poff 2003, Gao et al. 2009). For each of the 571 focal gages, we acquired 46 descriptors of basin topography, geology, land use, climate, and anthropogenic development from the GAGES II database (Appendix S1). In order to extend predictions to catchments where GAGES II data were not available, we compiled comparable natural and anthropogenic watershed characteristics from several sources and similarly aggregated these environmental feature values over the entire upstream contributing area.

Flow alteration

Modifying the approach of Carlisle et al. (2010), we fit conditional inference random forest (CIRF) models relating each of the 171 HM to the 46 basin attributes over the 198 reference gages (R package party; Hothorn et al. 2006, Strobl et al. 2008). A traditional random forest approach involves many decision trees, each of which recursively splits a sample of data on a response into progressively finer divisions according to a criteria such as reduced variance in a particular explanatory feature. Extending classic approaches to recursive partitioning, CIRF accommodates nonlinearity and correlations among predictor variables and avoids over-fitting by using permutation tests to calculate the significance of predictor variable splits. We used these models to predict natural values for HM at nonreference gages and computed current flow alteration as the deviation between observed, altered HM values and the corresponding predicted natural values at each nonreference gage (i.e., observed−predicted/predicted). We removed nonreference gages with drainage areas that exceeded the range of the training data by examining model performance across the full set of 373

[8] https://github.com/USGS-R/EflowStats

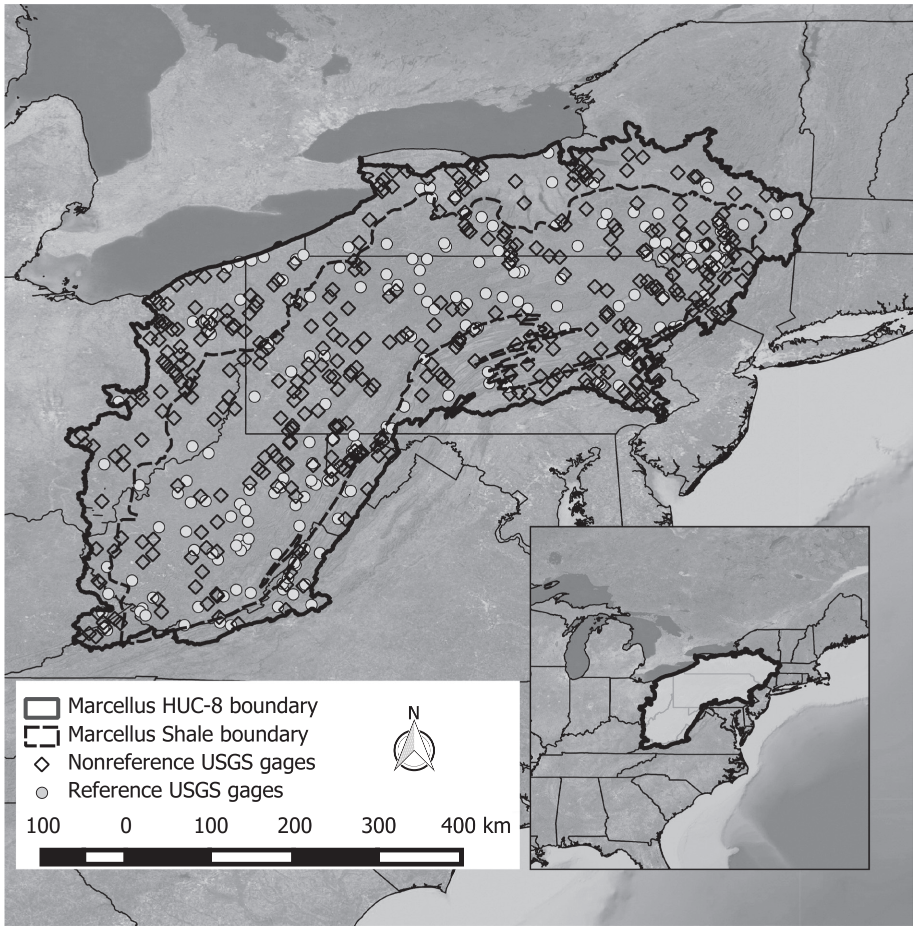

FIG. 2. Analyses were conducted for the region encompassed by the boundaries of all HUC-8 units (outer, solid polygon) that overlap the Marcellus Shale geological extent (inner, dashed polygon).

nonreference gages and selecting 2,500 km^2 as a conservative threshold to ensure informative predictions. We categorized the remaining 298 nonreference gages as headwaters and creeks (<99 km^2; n = 34), small rivers (100–517 km^2; n = 139), and medium tributaries (518–2,500 km^2, n = 125; river size categories based on Olivero and Anderson 2008).

Seeking a conceptually intuitive set of hydrologic metrics for further analysis, we first constrained HMs to those that were back-predicted well at reference gages. An out-of-bag pseudo-R^2 value ≥0.8 ensured acceptable accuracy while retaining an adequate pool of candidate metrics representing major facets of the hydrologic regime (i.e., magnitude, timing, and rate of change). This pool was further narrowed to 18 HM that minimized redundancy, were congruent with environmental flow reports for the Upper Susquehanna and Ohio River basins (DePhilip and Moberg 2010, 2013), and were plausibly sensitive to surface water withdrawals (Table 1). The HM for February, April, August, and October captured critical magnitude and timing features of the flow regime in winter, spring, summer, and fall seasons, respectively. Although flow alteration can involve both reductions and increases relative to natural conditions, we focused on the changes most relevant to water withdrawals. With the exception of fall rate, constancy, and predictability, we hypothesized that water abstraction would reduce HM values.

Fish community data

We focused on fish as the ecological indicator of hydrologic alteration due to data availability, evidence that they may respond more predictably than macroinvertebrates or vegetation (Poff and Zimmerman 2010, McManamay et al. 2013), and the range of known life history characteristics (e.g., life-spans and mobility) that can reveal nuanced changes in aquatic ecosystems (Karr 1981, Barbour et al. 1998). We compiled a geospatial dataset describing fish presence and abundance patterns in the six states of the study region, beginning with Multistate Aquatic Resource Information System (MARIS) fish data for NY, PA, WV, VA, and MD. We then integrated fish survey data from the USGS NAQWA

Table 1. Hydrologic metrics with high predictability from landscape attributes.

Metric	Description	OOB R^2	Flow component
Low winter	median of monthly minimum flows, February (m^3/s)	0.95	seasonal low-flow
Low spring	median of monthly minimum flows, April (m^3/s)	0.94	
Low summer	median of monthly minimum flows, August (m^3/s)	0.90	
Low fall	median of monthly minimum flows, October (m^3/s)	0.90	
Baseflow	baseflow index (dimensionless)	0.90	
Med winter	median of monthly flows, February (m^3/s)	0.97	seasonal median-flow
Med spring	median of monthly flows, April (m^3/s)	0.96	
Med summer	median of monthly flows, August (m^3/s)	0.94	
Med fall	median of monthly flows, October (m^3/s)	0.93	
High winter	median of monthly maximum flows, February (m^3/s)	0.95	seasonal high-flow
High spring	median of monthly maximum flows, April (m^3/s)	0.96	
High summer	median of monthly maximum flows, August (m^3/s)	0.94	
High fall	median of monthly maximum flows, October (m^3/s)	0.93	
Ann runoff	annual runoff (m^3/km^2)	0.90	annual flow
Rise rate	median of $\log_{10}$ of positive flow changes (m^3/s)	0.82	rate of change
Fall rate	median of $\log_{10}$ of negative flow changes (m^3/s)	0.80	
Constancy	temporal invariance of flows (maximized when flow state is same over all seasons and all years)	0.83	timing
Predictability	periodicity of flows (maximized when same seasonal flow pattern is repeated every year)	0.83	

Note: Out-of-bag (OOB) R^2 from conditional inference random forest models trained on reference gages (n = 198).

program, the United States Environmental Protection Agency (USEPA) Mid-Atlantic Environmental Monitoring and Assessment Program, and the Ohio Environmental Protection Agency (OEPA). The dataset included the total number and species of fish observed at a particular sampling site, the location and sampling methodology, and, in some cases, the degree of sampling effort in time or distance units. A subset of records in the MARIS database (roughly 64,000 records) were designated with a target standard indicating that field crews targeted specific fish species and did not necessarily characterize the entire fish assemblage. All such records were removed from assemblage level analyses. The dataset was constrained to sites that could be associated with nonreference USGS gages in the Marcellus study extent, resulting in a total of 5,257 observations of 141 species at 176 distinct sampling sites.

Fish assemblage data associated with nonreference gages allowed us to calculate ecological response measures including species richness, total abundance, relative abundance of disturbance intolerant taxa, and relative abundance of functional trait guilds that reflect shared life history strategies (e.g., fecundity, habitat associations, flow velocity preferences, home range, and trophic position; Appendix S2; DePhilip and Moberg 2010, 2013). Species richness and total abundance were calculated as the total number of species and total number of individuals observed (catch per unit effort in hours) per National Hydrography Dataset reach (NHD; HSC 2014, USGS 2015). Tolerance values were defined following Barbour et al. (1998) and reflect sensitivity to habitat perturbation, particularly impaired water quality. Trait guilds were derived from DePhilip and Moberg (2010, 2013) and reflect the combined efforts and expertise of multiple state, federal, and nonprofit agencies to identify resident species in the MSR thought to be sensitive to flow alteration. Relative abundance metrics were computed in catch per hour; records with no entry for effort were removed. We hypothesized that all ecological response measures would decline with increasing flow alteration.

Flow–ecology relationships

We paired fish sampling sites (n = 176) with nonreference USGS gages (n = 83) according to NHD reach codes. Repeated sampling (multiple sites and visits) for each reach were pooled and mean values calculated to minimize the effect of year-to-year outliers (McManamay et al. 2015). We performed quantile regressions (QR) at the 90th quantile to investigate the statistically significant upper boundaries of the relationship between alteration in the 18 focal HM and the fish community properties (R package quantreg; Cade and Noon 2003, Koenker 2015). As a generalization of traditional least squares regression to the central tendency, QR can reveal trends at the limits of the response distribution given unmeasured factors, such as water chemistry, invasive species, or habitat fragmentation that influence aquatic ecological communities (Knight et al. 2013). Drainage area was included as a covariate in flow–ecology QRs to control for the potential influence of stream size on ecological measures, but we lumped all sampling site–streamflow gage pairs for quantile regressions after preliminary analyses indicated that distinction by hydrologically similar streamflow classes (Appendix S4) was not informative.

Withdrawal scenarios and environmental flow standards

The observed flow–ecology relationships provided the context for simulating consumptive surface water withdrawal over a range of scenarios that reflect the uncertainty around current regulations. Publically available data on permitted surface water withdrawal from the Susquehanna River Basin Commission (SRBC) showed no significant relationship between the volume permitted for abstraction and mean annual flow (SRBC 2013). We therefore defined the low-intensity scenario as the mean SRBC-permitted rate less 1 standard deviation (0.014 m^3/s), the medium-intensity as five times this rate (0.071 m^3/s; mean permitted rate plus 1 SD), and the high-intensity as 10 times this rate (0.142 m^3/s). Tanker trucks that operate on conventional work schedules are a primary means of transport for hydraulic fracturing water, and we therefore assumed 10 h of pumping per day in all scenarios. We did not consider the use of either new groundwater wells or flowback water to meet the demands of well development and operation. These assumptions led to an extraction range of 1,210–12,269 m^3/day, which is congruent with shale gas withdrawal scenarios developed by DePhilip and Moberg (2010) for similarly sized catchments within the Susquehanna River Basin (i.e., 3,407–20,252 m^3/day), as well as actual permitted withdrawal rates observed in the Marcellus Shale Play of Pennsylvania (i.e., 50–18,000 m^3/day; Barth-Naftilan et al. 2015).

These simplified scenarios were intended to provide a conservative estimate of the withdrawal rates that may occur in the field as research has shown that actual withdrawals can be substantially lower than permitted (Shank and Stauffer 2014). For each scenario, we subtracted the appropriate volumes from the mean daily flow records at gages included in the alteration analysis, and then recalculated the set of 18 focal HMs. Simulated alteration in HMs was computed separately for reference and nonreference gages, with the former taken as the difference between simulated (pumped) and observed values. Nonreference gages were determined as both the difference between simulated and observed and between simulated and predicted natural values. The high intensity scenario resulted in complete dewatering of some smaller streams during some months, in which case the calculated alteration was capped at 100%.

Finally, we examined the mitigating effects of six environmental flow rules applied to the withdrawal scenarios. These were implemented as passby flows that established the lower limit at which extractive pumping must cease (Table 2). The three fixed minimums were computed as 10% and 30% of the mean annual flow (MAF), and the 7-d minimum flow with a 10-yr recurrence interval (7Q10). Two time-varying standards were determined as 10% of the mean daily flow from the previous day and as seasonally variable percentages of flow quantiles suggested by the New York Department of Environmental Conservation (NYDEC). A third time-varying standard, based on the most environmentally stringent guidelines from three different Nature Conservancy (TNC) flow recommendation projects conducted in NY and PA, utilized a combination of passby flows and withdrawal caps to protect low- and seasonal-flows, respectively (DePhilip and Moberg 2010, 2013, Taylor et al. 2013; Table 2). As a means to assess regional effects with and without environmental flow standards, we examined boxplots of the simulated alteration in HM across the reference and nonreference gage sets. We also investigated which flow standards afforded the most flexibility to water extraction activities by calculating (1) the percentage of days over the period of record during which pumping was allowed and (2) the percent of the total water needs satisfied by each passby flow standards across the low-, medium-, and high-intensity pumping scenarios.

Results

Patterns of flow alteration and biological responses

Hydrologic alteration displayed an overall trend of decreased high-flows, increased low-flows, and greater

Table 2. Environmental flow standards applied to withdrawal scenarios.

Type	Passby standard	Description
Fixed minimum flow	10% MAF	10% of mean annual flow
	30% MAF	30% of mean annual flow
	7Q10	7-d minimum flow with a 10-yr recurrence interval
	10% PMDF	10% of mean daily flow

		Stream size class	Season	Withdrawal cap	Passby
Variable flow alteration limits	TNC	headwaters and creeks	summer and fall (July–October)	10% of Q60	Q50
			winter and spring	10% of Q60	Q70
		small rivers	summer and fall	10% of Q70	Q75
			winter and spring	10% of Q70	Q80
		medium tributaries	summer and fall	15% of Q70	Q75
			winter and spring	15% of Q70	Q80
	NYDEC	drainage areas ≤129 km^2	passby = Q60		
		drainage areas > 130 km^2	July–September, passby = Q60		
			October–June, passby = Q75		

Notes: The scenarios termed TNC and NYDEC were based on recommendations described in DePhilip and Moberg (2010, 2013), Taylor et al. (2013), and the New York Department of Conservation's Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program (NYDEC 2013). Q50-Q80 flows represent the percent of time a particular flow magnitude is met or exceeded.

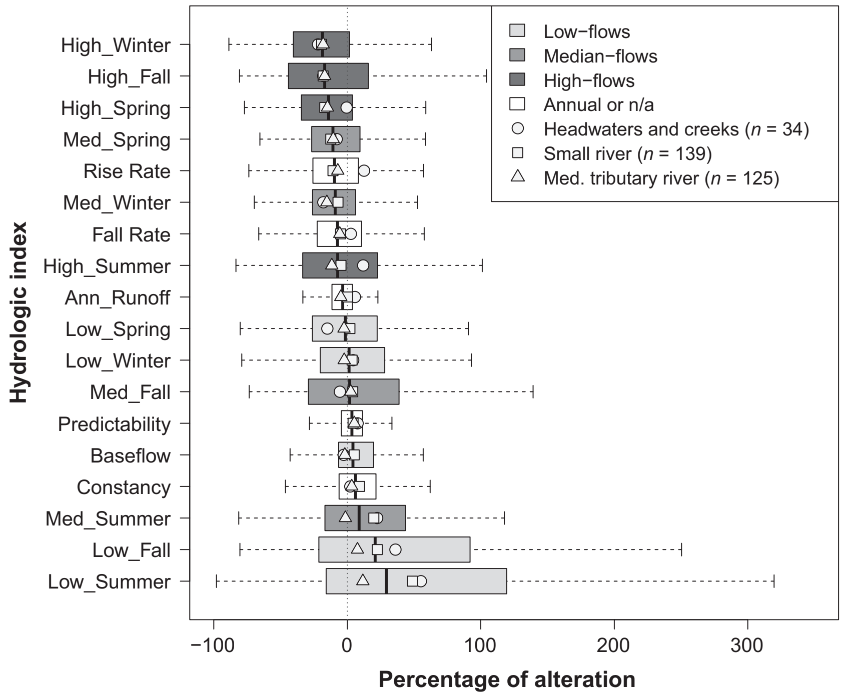

FIG. 3. Observed flow alteration for well-predicted hydrologic metrics (pseudo $R^2 > 0.8$), computed as the deviation between predicted and observed HM values for the 298 nonreference gages with drainage area <2,500 km^2. Median values for headwater and creek reaches (circles), small rivers (squares), and medium rivers (triangles) are illustrated in addition to the full sample median (solid black bars). The dashed vertical line indicates no deviation between the value calculated from the observed flow record and the expected natural value predicted from the per-metric model fit to reference gages. With the exception of Med_Fall, Low_Winter, and Low_Spring, the 95% CIs of all hydrologic indices did not include zero (experienced significant change; Table 1). Vertical bands, boxes and whiskers represent the median, interquartile range (IQR) and 1.5*IQR, respectively.

flow stability (i.e., increased predictability and constancy; Fig. 3), despite little change in the volume of annual discharge. The largest decreases in flood magnitude were evident in the winter and fall, with the small and medium rivers showing more change than the headwater and creek classes. In contrast, the percentage increases in low-flows were greatest in summer and fall, and were strongest for the smallest systems. However, substantial variation across individual gages was apparent, with the range of alteration extending to approximately 100% change in both positive and negative directions for most hydrologic metrics.

The majority of flow ecology relationships exhibited a wedge-shaped pattern, with greater alteration in the HM associated with greater declines in biological measures, but substantial scatter was also evident. Statistically significant flow–ecology relationships occurred for low-, median-, and high-flow HMs, as well as for annual-scale, rate of change, and timing HMs (Table 3, Figs. 4 and 5; Appendix S3). Most statistically significant flow–ecology relationships were associated with reduced flow volumes, but small sample sizes of the paired gage records and fish sampling sites (i.e., <20) may constrain the generality of some observed relationships (e.g., fall rate–species richness relationship in Table 3; see also Appendix S3: Figs. S2 and S3, showing the influence of outliers on the two significant flow–ecology relationships involving total abundance). While not necessarily parallel, slopes of significant 90th and 50th quantile regressions generally indicated a response in the same direction (negative or positive), bolstering the inference that hydrologic alteration was a principle factor limiting communities (Knight et al. 2013).

Overall species richness clearly declined with reductions in the summer median-flow as well as annual runoff (i.e., mean annual flow scaled to drainage area; Fig. 4A–C). However, the positive regression coefficient of the area covariate (Table 3) implies that fish communities in larger streams would be more resilient to flow alteration. Reductions in rise rate (i.e., a slower hydrograph rising limb) were associated with greater richness, whereas richness declined with increased fall rates (i.e., a faster falling limb; Appendix S3; Fig. 4C, respectively). The few sites with increased fall rates were mostly smaller streams, in contrast to the many gages that displayed reduced fall rates (circles vs. triangles in Fig. 3, respectively).

Reduced abundance of intolerant fish species was significantly related to decreased winter high-flows, as well as increased fall rates and constancy (Fig. 4; Appendix S3). These relationships are consistent with the intuitive notion that species intolerant to habitat degradation

Table 3. *P* values, regression slopes, and sample sizes (*n*) of significant ($P < 0.05$) flow–ecology relationships.

Ecological response	HM	*P*-value of flow alteration	Regression coefficient of flow alteration	Regression coefficient of area covariate	*n*	Response to 25% flow alteration (100 km² basin)
Species richness	Summer Median	<0.01	−0.32	0.0004	29	−8
	Annual Runoff	0.01	−0.54	0.0004	42	−13
	Rise Rate	0.02	0.19	−0.0036	43	4
	Constancy†	0.01	0.21	0.0080*	42	6
	Fall Rate†	0.04	−0.32	−0.0040	14	−8
Total abundance	Summer Median	0.04	−2.19	0.0054	16	−54
	Spring High	0.04	−1.13	0.0406*	29	−24
Intolerants	Fall Rate†	0.01	−0.69	−0.0261	14	−20
	High Winter	0.03	−0.44	0.0135	52	−10
	Constancy†	0.04	−0.67	−0.0079	42	−18
	Baseflow	0.05	−1.18	0.0007	17	−29
Nest builders	Fall High Flow	<0.01	−0.87	0.0087	28	−21
Riffle associates	Annual Runoff	0.04	−1.33	−0.0064	23	−34
Riffle obligates	Winter Low	<0.01	−1.43	0.0210*	23	−34
	Annual Runoff	0.02	−1.66	−0.0064	24	−42

Note: Ecological response to a hypothetical 25% alteration in corresponding hydrologic metric (HM) in a 100 km^2 basin is also provided (calculated from regression coefficients).
†Inflated (positive) flow alteration.
**P* value of area covariate <0.05.

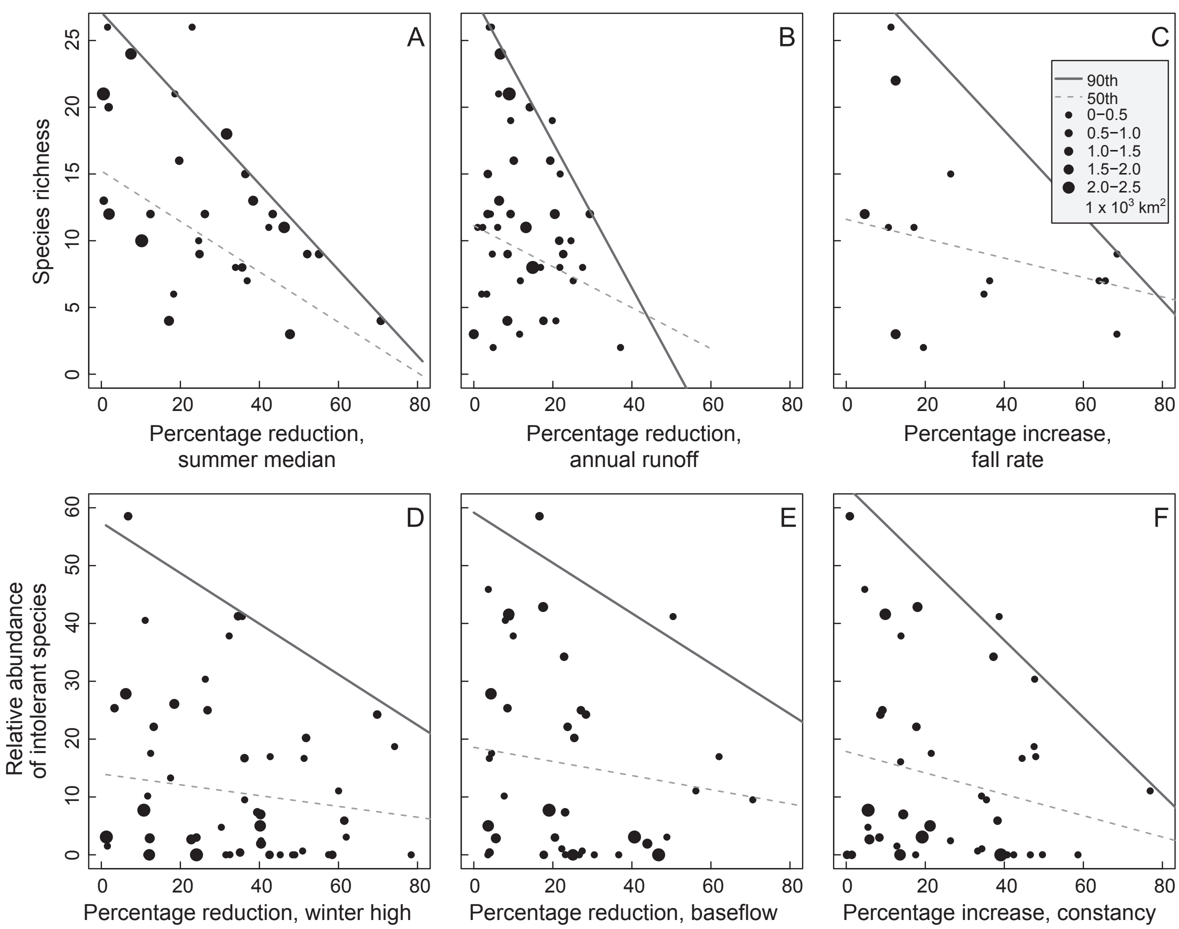

Fig. 4. Flow–ecology relationships for species richness (A–C) and relative abundance (D–F) of intolerant species for 100 km^2 basins. 90th quantile regressions are significant at $\alpha = 0.05$. 50th quantile regressions (gray dashed lines) are shown for reference. Black dots indicate the paired reaches (USGS gage and MARIS sampling sites) displaying each relationship, with dot size scaled to the gage drainage area.

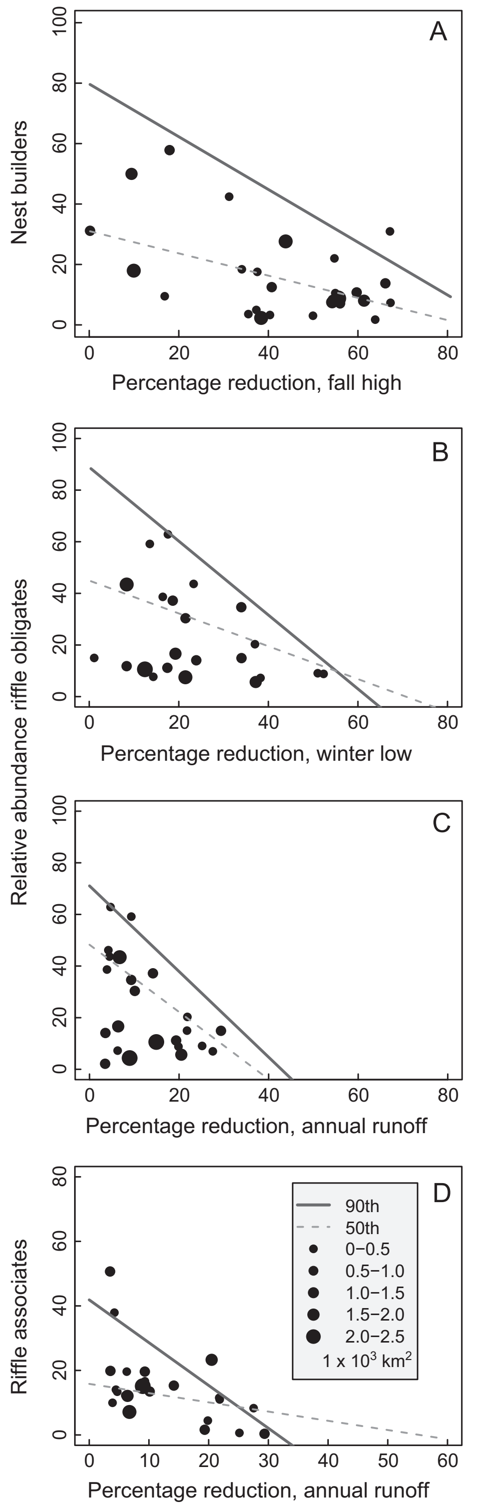

Fig. 5. Flow–ecology relationships for relative abundance of nest builders (A), riffle obligates (B–C) and riffle associates (D) for 100 km² basins.

would decline in the face of progressively altered flow regimes. Though only marginally significant at $\alpha = 0.05$, there were negative trends between proportional abundance of intolerant taxa and reductions in baseflow, as well as summer median-flow (Appendix S3; similar to species richness).

The number of paired fish sampling and flow gage sites necessarily varied among particular relationships, and the sample sizes of the cold headwater guild were inadequate to establish statistically significant flow–ecology relationships ($n < 10$ for most potential cold headwater flow–ecology relationships). However, both riffle obligate and associate guilds exhibited a strong dependence on maintaining adequate winter low-flows and annual flows (Fig. 5B–D). The prevalence of fish categorized as nest builders had a strong negative relationship with reduction in fall high-flows (Fig. 5A). Measures of species richness, percentage of intolerant species, and relative abundance of functional trait guilds did not exhibit strong trends with basin area (illustrated as the size of scatterplot points in Figs. 4 and 5; Appendix S3).

Consumptive extraction scenarios and flow protection

The medium- and high-intensity withdrawal scenarios substantially reduced summer and fall low-flow HMs relative to observed records for both reference and nonreference gages, whereas high-flow metrics showed little change (Fig. 6A). However, the simulated decreases relative to observed flows were substantially greater for reference streams (Fig. 6A; evident as the larger median decrease for light gray reference distributions relative to dark gray nonreference distributions). The high-intensity withdrawals actually mitigated the elevated summer low-flows due to existing flow alteration in the MSR (Fig. 3), such that the simulated median HMs approached the predicted natural values for nonreference gages (Fig. 6B). For example, the median summer low-flow shifted from +30% to nearly zero under the high-intensity scenario. As for the alteration calculated relative to observed values, high flow metrics showed little change relative to the predicted natural for nonreference.

An example hydrograph illustrates the impact of the high-intensity withdrawal scenario and the potential protection offered by passby flow standards (Fig. 7; USGS reference gage 01359750, Moordener Kill at Castleton-on-Hudson, New York, USA). Losses during spring peak flows have little effect, yet flow protection is required to prevent complete dewatering for much of the summer and early fall. The least restrictive standards do prevent this drastic outcome (10% MAF and 7Q10, solid blue and purple respectively), but discharge could be maintained at unnaturally stable levels if withdrawals are maintained at the limit. In contrast, more restrictive or variable

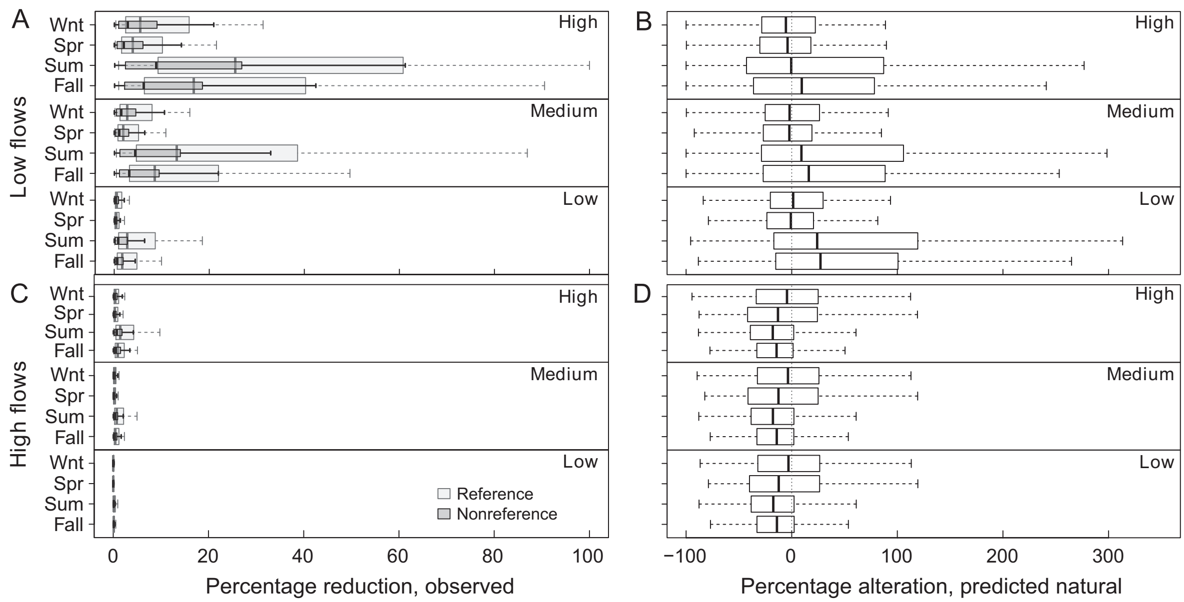

FIG. 6. Potential alteration of high and low-flow characteristics under alternative withdrawal scenarios. Panels (A) and (C) depict alteration for reference (light gray) and nonreference (dark gray) gages calculated as the percent reduction from observed flows, thereby indicating the effect of withdrawals within the context of other changes affecting nonreference gages. Panels (B) and (D) depict nonreference gage alteration calculated as the alteration from predicted natural flow values. Low- (0.014 m^3/s), medium- (0.071 m^3/s), and high-intensity (0.142 m^3/s) withdrawal scenarios were based on current permitted withdrawal rates. Vertical bands, boxes and whiskers represent the median, interquartile range (IQR) and 1.5*IQR, respectively.

passby flow standards allow minimal withdrawals and maintain natural variability during the low flow season.

The observed flow–ecology relationship between summer median-flow and fish species richness (Fig. 4A) offers an example with which to illustrate the potential ecological consequences of the withdrawal scenarios and environmental flow standards across the MSR. The quantile regression slope leads from values of flow alteration to likely declines in species richness, and thereby, to a categorical biological condition gradient such as might be used in an ELOHA setting (Table 3). With this information, and a regional perspective stratified by drainage area and withdrawal-intensity, the influences of stream size and specific flow protection rules are evident (Figs. 8 and 9, Table 4). Under the high intensity withdrawal scenario with no flow protection, all reference headwater and creek gages showed at least 20% alteration in summer median-flow and 75% of reference gages showed at least 78% alteration, placing them in the worst biological condition category (Fig. 8, upper right panel; first quartile of no passby scenario). Even under the lowest intensity withdrawal, roughly 50% of reference headwaters and creeks still experienced at least 21% alteration (Fig. 8, upper left panel; median of no passby scenario). Yet, reference gages with larger drainage areas showed relatively little reduction in summer flows under the highest withdrawal intensity, rarely exceeding biological condition category III (Fig. 8, lower three panels). Nonreference gages were somewhat less sensitive to withdrawals (e.g., Fig. 6A, C), but stream size also mediated the change in summer median-flows (Fig. 9; alteration computed as deviation from observed flow). Medium tributaries experienced limited alteration across pumping intensities (no passby scenarios in Fig. 9), but, even so, 75% of the nonreference headwaters and creeks still exceeded 40% alteration under high intensity withdrawal.

The fixed 30% MAF, daily variable 10% MDF, as well as the seasonally variable TNC standards allowed the least change in summer median-flow at the most reference and nonreference headwaters and creeks under all withdrawal intensities. In contrast, the 7Q10, 10% MAF, and NYDEC flow standards stipulated summer discharge levels that allowed substantial alteration of numerous gages (Figs. 8 and 9). For example, at high withdrawal rates, 50% of the smallest reference systems showed at least 81% reduction in summer median-flow under the 7Q10 standard. Interestingly, with the exception of 30% MAF, 10% MAF becomes the most conservative flow standard for larger stream systems. However, the relative differences between flow standards are less significant in larger streams.

A more in-depth examination of the degree of flow protection offered by each passby standard for the most sensitive stream sizes (headwaters and creeks) reveals marked differences across seasons and flow components (low vs. high-flows). For example, the 10% and 30% MAF passby scenarios resulted in substantial alteration to winter and spring low-flows, yet no alteration occurred during the more sensitive summer and fall low-flow periods (Table 5). In contrast, low-flows across all seasons were well protected by the 10% MDF and TNC standards.

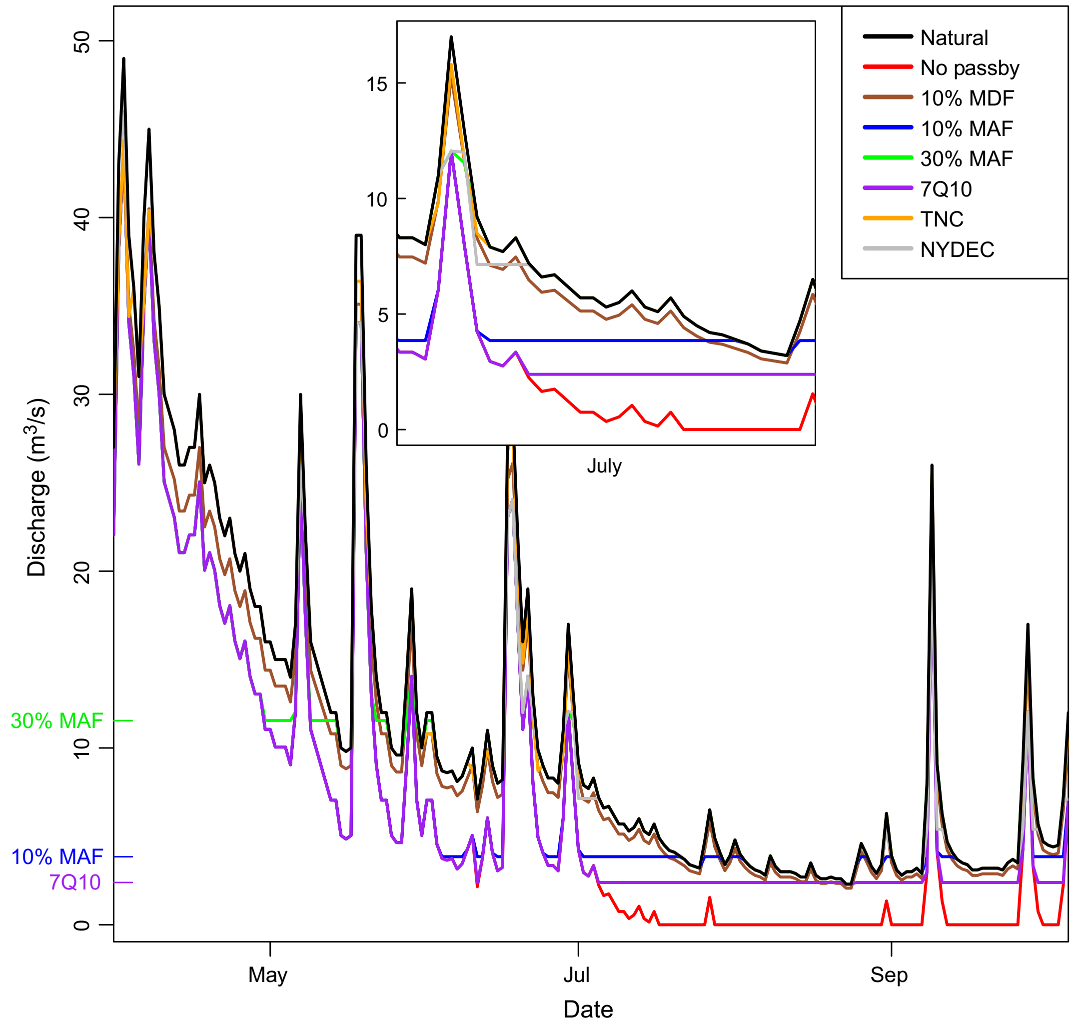

FIG. 7. Example hydrograph illustrating the high withdrawal scenario (solid red) and alternative passby flow standards at USGS reference gage 01359750 (Moordener Kill, Castleton-on-Hudson, New York, USA). Lower (10%) and higher (30%) fixed protection levels were based on the mean annual flow (MAF; solid blue and green lines, respectively) and the 7-d low-flow with 10-yr recurrence interval (7Q10; solid purple). The 10% MDF (brown line) restricts withdrawals to <10% of the mean daily flow. The Nature Conservancy (orange line) and New York Department of Environmental Conservation (gray line) standards refer to variable flow alteration limits based on flow quantiles. For this gage, the 30% MAF fixed standard required the highest absolute flow volume during summer months, allowing no withdrawals on most days.

Differences between passby protections were generally far less pronounced for winter and spring high-flows. However, there were considerable differences in passby protection during summer and fall high-flows. Overall, 7Q10 consistently provided the least flow protection across all seasons and flow components, whereas the TNC standards resulted in the most protection.

In order to visualize overall shifts due to hydrologic change in the context of otherwise good ecological conditions, the effect of a 25% alteration in HMs in a 100 km^2 basin is shown as the predicted value of significantly related ecological responses (Table 3; at 90th quantile regression fits). For example, a 25% decline in summer flow is predicted to result in a loss of eight species, whereas a 25% reduction in annual runoff would eliminate 14 species. Additionally, lack of winter low-flow and fall high-flow protection afforded by 7Q10 and MAF standards predicts substantial declines in riffle obligate and nest builder species abundance based on observed flow–ecology relationships (Table 3, Fig. 5).

Passby standards that provided the most ecological protection (e.g., the least reduction in species richness) were also the most restrictive in terms of (1) the number of days when shale gas developers would be allowed to withdraw water and (2) the percent of total water needs satisfied for a given pumping scenario (Table 6). This trade-off is exemplified by the 30% MAF passby, which, of the fixed minimum flow standards, provides the most ecological protection across reference and nonreference gages, but restricts pumping to an average of 54–65% of

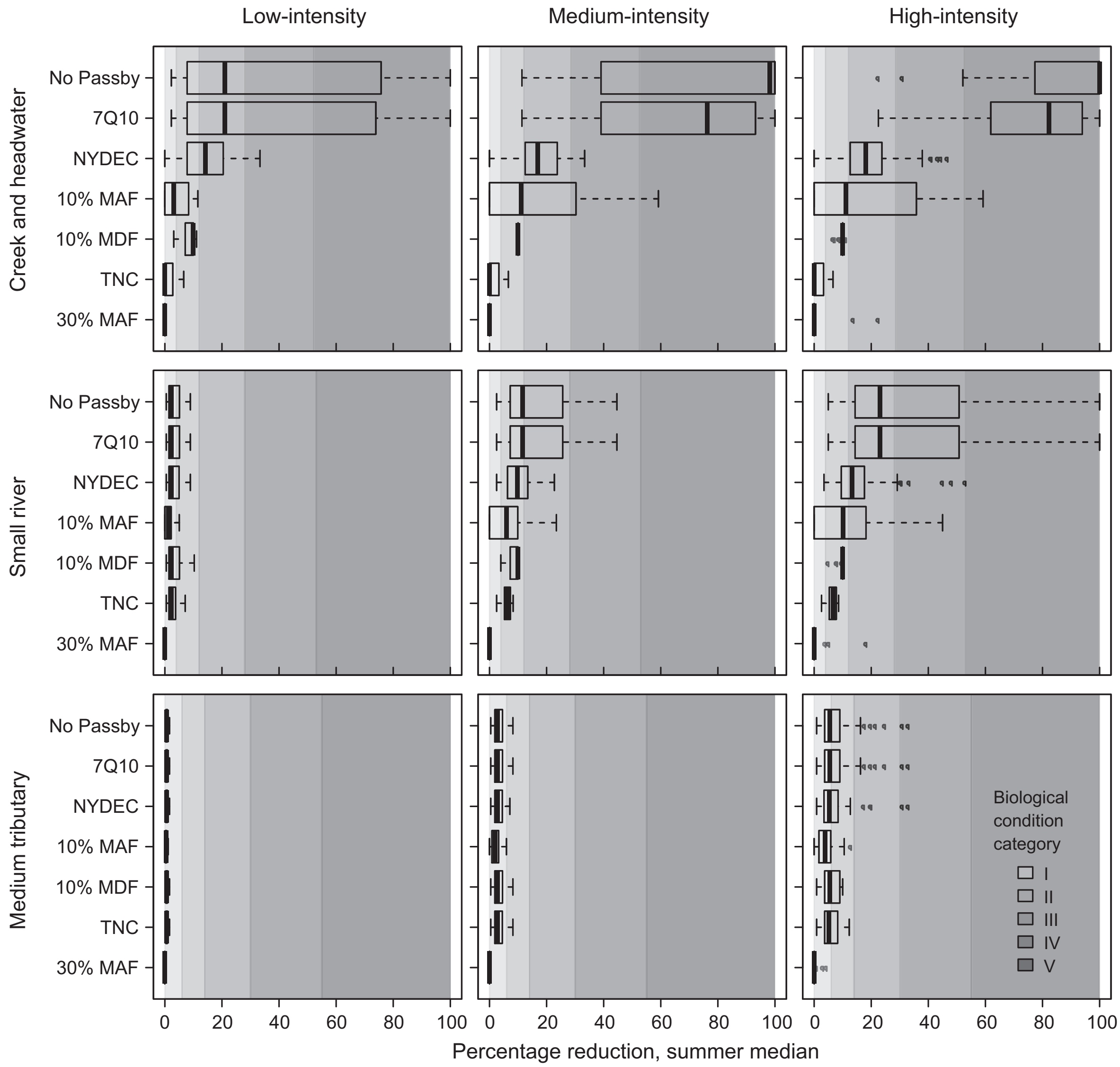

Fig. 8. Boxplots of the percent reduction in summer median-flow for a subsample of the 198 reference gages distinguished by drainage area (headwater/creek ≤99 km^2, n = 42; small river = 100–517 km^2, n = 80; medium tributary = 518–2,500 km^2, n = 65) under increasing intensity of withdrawal (columns; low = 0.014 m^3/s, medium = 0.071 m^3/s, and high 0.142 m^3/s) in conjunction with environmental flow standards (see *methods* for details). Differences in the level of ecohydrological protection under the various flow standards are revealed via contrasting descriptive statistics (e.g., median, interquartile range). Shaded bands indicate increasing aquatic ecosystem impairment based on biological condition categories detailed in Table 4. Vertical bands, boxes, whiskers and points represent the median, interquartile range (IQR), 1.5*IQR and outliers, respectively.

days in headwaters and creeks and an average of 68–78% days in medium tributaries. Additionally, 30% MAF limits the total amount of water available for extraction to 48–77% of the total water needs across pumping scenarios and stream sizes (Table 6). Standards based on TNC recommendations not only provided year round flow protection (Table 6) but also allowed for over 15% more pumping days in small rivers and medium tributaries and considerably more overall water extraction under the low- and medium-intensity pumping scenarios, especially in small rivers and medium tributaries compared to 30% MAF (Table 6). In general, passby flows were more restrictive in terms of meeting human water need for nonreference gages.

Discussion

We found widespread hydrologic alteration in the Marcellus Shale region, with changes in multiple flow regime components across seasons significantly related to declines in fish species richness, the prevalence of disturbance-intolerant taxa, and indicators of specific functional traits. The dominant trend in regional flow alteration due to cumulative historical impacts was

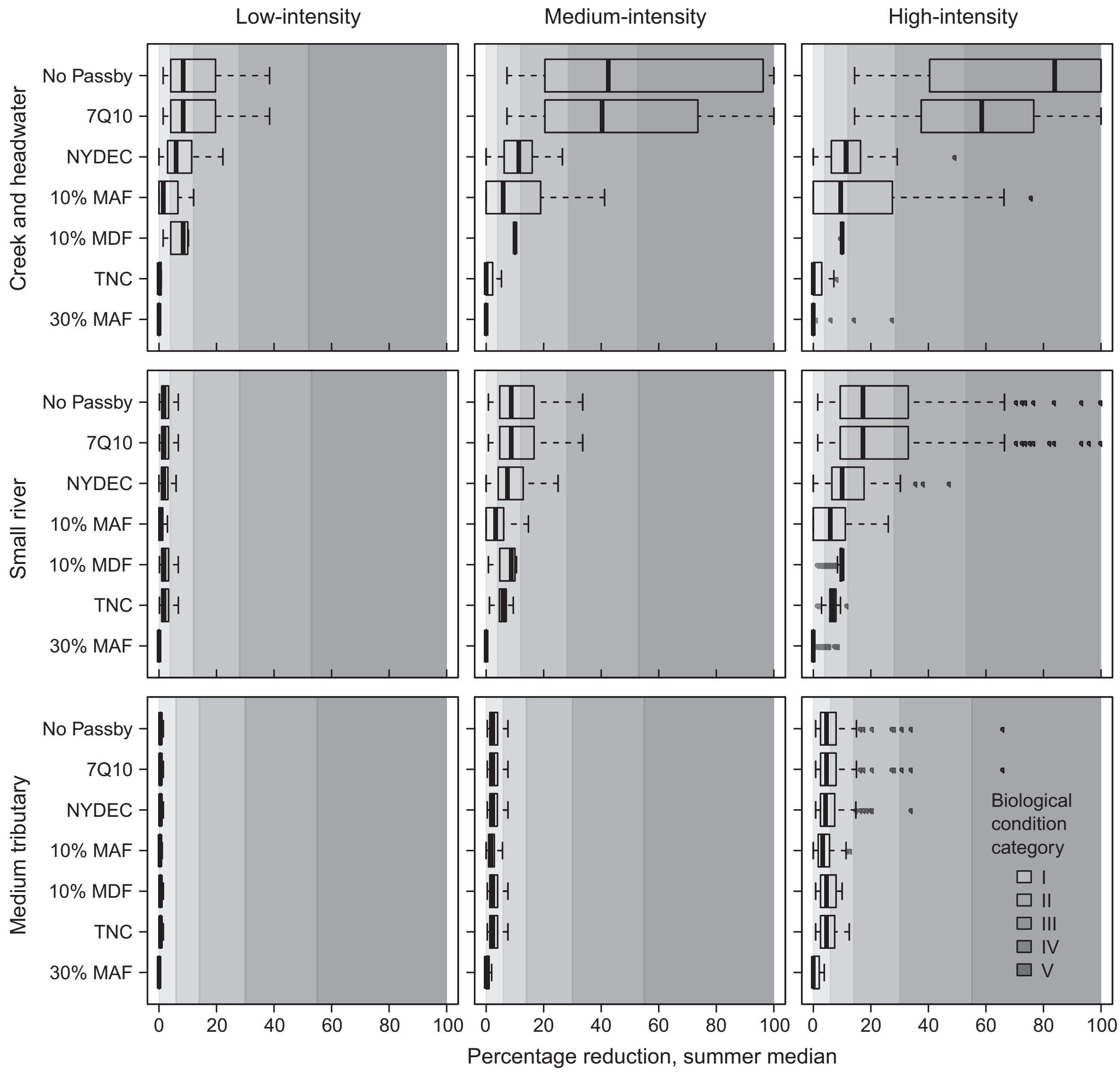

Fig. 9. Boxplots of the percent reduction in summer median-flow for a random subsample of the 378 nonreference gages distinguished by drainage area (headwater/creek ≤99 km^2, n = 34; small river = 100–517 km^2, n = 139; medium tributary = 518–2,500 km^2, n = 125) under increasing intensity of withdrawal in combination with environmental flow standards. See *methods* and Fig. 8 caption for additional details.

toward reduced high-flows, elevated low-flows, and dampened variability, effects typical of dams and reservoirs that store peak discharge for later, gradual release (Magilligan and Nislow 2005, Fitzhugh and Vogel 2011, Homa et al. 2013). Although this pattern of flow alteration did not reflect the presumptive effects of water withdrawal, the region-wide observations were sufficient to establish relevant flow–ecology relationships Assessing withdrawal scenarios relative to these relationships, we found little effect from the lowest intensity withdrawals but substantial fish species loss and community change under the higher demand scenarios, particularly in small streams. The available empirical data indicate a clear risk that flow alteration due to shale gas development may impair stream ecosystems, yet the concentration of impacts within smaller reaches and the protections afforded by some environmental flow standards also reveal prospects for management that effectively navigates divergent priorities for freshwater resources.

Flow–ecology relationships

We predicted the loss of 7–8 species from MSR streams, depending on basin size, following a 25% reduction in summer median-flow (Table 3, Fig. 4). Reduced aquatic biodiversity is consistent with previous studies documenting fish species loss, reduced abundance, increased habitat generalists, and declines in benthic invertivores in

Table 4. Hypothetical biological condition categories based on loss of species richness.

Percent reduction, August median flow for mid-sized streams in each category			Change in species richness	Biological condition category
Headwaters and creeks (50 km²)	Small rivers (300 km²)	Medium tributaries (1,750 km²)		
≤4	≤4	≤6	<5% (healthy level of biodiversity)	I
4.1–12	4.1–12	6.1–14	5–15% (reductions in sensitive species)	II
12.1–28	12.1–28	14.1–30	15–35% (moderate loss of sensitive species)	III
28.1–52	28.1–53	30.1–55	35–65% (severe loss of sensitive species)	IV
≥52.1	≥53.1	≥55.1	>65% (substantial overall reduction in biodiversity)	V

Note: The percent reduction in summer median for each biological condition category was computed using the slope of the 90th quantile regression of species richness against summer median flow.

response to even modest summer reductions in flow (8–25%; Freeman and Marcinek 2006, Kanno and Vokoun 2010, Armstrong et al. 2011, Zorn et al. 2012). Lower summer median-flows degrade habitat quality by reducing dissolved oxygen, increasing water temperature and contaminant concentrations, and leading to larger diel swings in pH that can increase the bioavailability and toxicity of contaminants to aquatic organisms (Valenti et al. 2011, Rolls et al. 2012). These changes potentially harm fish that utilize riffle, run, and pool habitats (Schlosser and Toth 1984, Bain and Finn 1988, Kessler et al. 1995, Travnichec et al. 1995, Stauffer et al. 1996, Bowen et al. 1998, Freeman et al. 2001, McCargo and Peterson 2010, Armstrong et al. 2011). Armstrong et al. (2011) observed a less dramatic loss of approximately two fluvial species with each 25% decline in summer median flow for streams in Massachusetts (USA; also calculated at the 90th quantile). The lower rate of species loss observed in Armstrong et al.'s study may be related to the fact that (1) streamflow alterations resulted from groundwater as opposed to surface water withdrawals and/or (2) there may be substantial differences in regional species pools.

Fish categorized as intolerant of disturbance to stream habitat or water quality may also be especially vulnerable to such hydrologic alteration, and quantile regressions significant at $\alpha = 0.1$ showed that a 25% reduction of baseflow was associated with a roughly 30% decrease in the abundance of these taxa (calculated from regression weights assuming 100 km^2 basin; Appendix S3). Lower abundance of intolerant fish in the MSR was also significantly related to decreased winter high-flows and increased fall rates, perhaps due to reliance on lost life history cues, flushing flows, or other fluvial geomorphic dynamics that maintain critical in-channel habitat. Reduced fall high-flows, reduced winter low-flows, and diminished annual runoff were also associated with declines in the abundance of fish in the nest-building, riffle-obligate, and riffle-associate guilds (Fig. 5; Appendix S3). These guilds require sufficient flow volume and stability to maintain spawning and rearing habitat, refugia and passage corridors, and adequate dissolved oxygen levels, and are highly sensitive to reductions in stream flow that disproportionately affect shallow, fast-flowing riffle habitats (Nehring 1979, Freeman and Marcinek 2006, Kanno and Vokoun 2010). This may explain the relatively large effect size (regression slopes; Table 3) of riffle-obligates and -associates in response to depleted annual discharge and winter low-flows. Our results indicate the link between fish recruitment and fall and winter flows throughout the

Table 5. Regional hydrological impacts of withdrawal and environmental flow scenarios presented as the median alteration for reference headwater and creek reaches due to the high pumping scenario.

	Median change (%)												
	Low-flows				Median-flows				High-flows				Annual flows
Passby flow	Wnt	Spr	Sum	Fall	Wnt	Spr	Sum	Fall	Wnt	Spr	Sum	Fall	Annual runoff
No passby	54	34	100	100	28	15	100	100	5	3	37	20	14.9
7Q10	54	34	64	78	28	15	82	81	5	3	37	20	14.4
10% MAF	45	34	0	0	28	15	11	27	5	3	34	20	12.6
30% MAF	10	23	0	0	25	15	0	0	5	3	21	15	9.7
NYDEC	0	0	0	0	16	12	18	21	5	3	37	20	8.3
10% MDF	10	10	10	10	10	10	10	10	5	3	10	10	7
TNC	0	0	0	0	8	8	0	0	1	2	1	1	3.1

Note: Passby flows are presented in descending order of the median percent change to annual runoff.

Table 6. Mean number of days (%) over entire period of record that water extraction was allowed under various passby flow standards.

	Mean days pumping allowed (%)			Mean water needed for hydraulic fracturing per pumping scenario (%)								
				Headwaters and creeks			Small rivers			Medium tributaries		
Passby Flow	Headwater and creeks	Small rivers	Medium tributaries	L	M	H	L	M	H	L	M	H
Reference												
10% MDF	100	100	100	95	85	77	98	89	80	100	98	95
7Q10	99	99	100	99	99	98	99	99	98	99	99	99
10% MAF	86	87	90	87	87	87	86	85	85	89	89	89
TNC	65	79	79	71	62	56	76	66	56	78	77	76
NYDEC	62	71	73	68	67	66	69	68	67	71	71	70
30% MAF	65	66	68	65	65	65	64	64	64	66	66	66
Nonreference												
10% MDF	100	100	100	89	60	44	99	91	82	100	98	96
7Q10	99	99	99	98	96	94	99	99	98	99	99	99
10% MAF	85	85	93	84	81	80	84	84	83	93	93	93
TNC	64	79	79	56	34	22	77	68	59	78	77	76
NYDEC	61	71	72	58	54	52	69	68	67	71	71	70
30% MAF	54	59	78	51	49	48	57	56	56	77	77	76

Notes: The average percent of water needs for hydraulic fracturing met by each passby standard is also provided. L, M, and H represent low-, medium-, and high-intensity pumping scenarios.

MSR, supporting previous regional studies that proposed the need to protect distinct flow patterns year-round (DePhilip and Moberg 2010, Taylor et al. 2013).

It is crucial to recognize that water demands from HVHF (or other forms of energy development and land use change) will affect freshwater ecosystems already subject to other stressors. Indeed, according to the unbiased variable importance rankings in the conditional inference random forest model for summer median discharge, the number of dams was the most influential explanatory variable among the anthropogenic predictors. While the artificially augmented summer low-flows below some dams might be viewed as cause to permit greater withdrawal (i.e., to correct an unnaturally elevated low), such an interpretation requires the utmost caution. Nonreference streams are, by definition, more likely to experience anthropogenic disturbance, such as water quality impairment, threats from non-native species, or other factors that render them especially vulnerable to further degradation from flow alteration. These circumstances reinforce the importance of considering cumulative, possibly multiplicative impacts during management decisions.

A persistent challenge facing environmental flow assessment methods, such as ELOHA, is the development of flow–ecology relationships that are specific to particular stream classes or ecoregions. Stream classifications have been proposed as a means to help control correlations among landscape features that may structure ecological responses to flow attributes (King et al. 2005, Poff et al. 2010). Our examination of streamflow classes and spatial patterns in the distribution of flow alteration (Appendices S4 and S5) did not suggest that strong spatial gradients were apparent in these data or that classification would offer additional explanatory power over quantile regression on sites pooled regionally. Other studies have also been unable to establish stream class-specific flow–ecology curves due to inadequate sample size and/or the inability of stream classes to describe variation in biological communities (e.g., Buchanan et al. 2013, NCEFSAB 2013). Nonetheless, the theory and practice of environmental flow assessment stands to benefit considerably from future research that applies hierarchical mixed-effect models or similar strategies to explicitly account for spatial autocorrelations in existing observations that may violate the assumptions of traditional quantile regression. Furthermore, the inherent uncertainty in predicted natural flow metrics, the observation error in both fish and flow records, the low sample sizes of some flow–ecology relationships, and the limited number of sites with reduced low-flows all justify revisiting regionally derived relationships where and whenever additional site-specific data are available.

Finally, we note that this analysis emphasized flow–ecology relationships construed as a continuous ecological response over a smooth gradient of flow alteration (as well as the press disturbance of continuously applied withdrawal pressure). Such assumptions may not always hold true, especially in cases where rapidly varied withdrawal rates coincide with factors such as drought to produce sudden pulse shifts in hydrologic regime. In more extreme cases, such alterations could even produce transitions from perennial to intermittent flows, thereby degrading water quality, altering energy dynamics, reducing connectivity, and perhaps pushing stream ecosystems outside of the historically observed range of variation (Auerbach et al. 2012, Rolls et al. 2012). These sharp hydrologic transitions can hinder dispersal and recolonization in addition to causing habitat loss, with rapid and profound effects on aquatic ecosystem structure and biodiversity, even to the point of extirpation of endemic species (e.g., Lake 2003, Jaeger et al. 2014, Ruhi et al. 2015).

Implications for HVHF withdrawals and environmental flow standards

Withdrawal scenarios were imposed under the expectation that permitting would involve absolute volumes (i.e., 1,210–12,269 m^3/d). The greatest impacts from consumptive water extraction were therefore concentrated on the smallest streams (basin area ≤99 km^2), with many small rivers and most medium tributaries (100–2,500 km^2) insensitive to pumping at these rates. These results are congruent with past empirical studies reporting less severe impacts to fish and mussel communities following reduced low-flows in larger rivers and streams (Johnson et al. 2001, Haag and Warren 2008, McCargo and Peterson 2010, Shea et al. 2013). However, the protective standards were calculated and implemented as various percentages of flow metrics, demonstrating how regulations and voluntary conservation initiatives can scale the allowable streamflow deviation with drainage area. The simple measure of limiting or preventing withdrawals from reaches with characteristically smaller discharges appears necessary to prevent deleterious impacts to freshwater biodiversity in the MSR.

Flow regulations for surface water withdrawals must balance the often conflicting considerations of ecological protection, economic concerns, computational complexity and accuracy, and permitting compliance and enforcement. In our analysis, relatively simple fixed standards based on 10% and 30% of mean annual flow resulted in a highly variable degree of flow protection, with winter/spring experiencing substantially more alteration than summer/fall for low and median flows. Yet the observed flow–ecology relationships indicate that protections should not be limited solely to summer low-flow periods. For example, the large change in winter low-flows allowed by 10% MAF could adversely affect the relative abundance of riffle-obligate species within the MSR. Our results bolster prior claims that the commonly used 7Q10 standard, originally intended to protect water quality under the Clean Water Act of 1972, would provide very little flow protection across the majority of stream sizes and pumping scenarios (Freeman and Marcinek 2006, Richter et al. 2012).

The 30% MAF standard provided greater protection, but such fixed standards may do little to protect flow regime attributes other than minimum discharge, indeed this was a major motivation for the development of environmental flows rather than minimum flows (Poff et al. 1997, Arthington 2012). Moreover, this standard resulted in the largest reduction in the number of days allowed for withdrawals and the least total amount of water available for withdrawal. Beyond direct effects on shale gas development, this constraint could negatively affect other sectors depending on surface water withdrawal. During periods when discharge approaches the passby flow threshold, a fixed withdrawal limit may also result in unnaturally low day-to-day flow variation (e.g., Fig. 7). The lack of sufficient sub-daily data prevented a regional study of such dynamics but may be a worthwhile subject of further research.

In general, standards based on monthly flow quantiles, scaled to drainage area (i.e., the TNC and NYDEC rules) offered adequate ecohydrological protection across most seasons and flow components. They also allowed an intermediate level of water withdrawal, perhaps striking a suitable balance between ecological conservation and energy development. However, we note that the NYDEC standard did allow considerable alteration to fall high-flows, perhaps with negative impacts on nest builder species in the MSR. Additionally, the relative complexity of the NYDEC and TNC may be viewed as a drawback that limits compliance and enforcement.

The 10% MDF rule represents a compromise between the fixed minimum and variable standards in that it provides a conservative level of ecohydrological protection across seasons and flow components, while making more water available for withdrawal over a greater number of days. It would require an estimate of the instantaneous flow from either the stream of interest or from a nearby index gage. The 10% MDF approximates the presumptive standard proposed by Richter et al. (2012), which was intended to protect streamflow in the absence of more rigorous, but also more resource intensive environmental flow analyses. The 10% MDF offers an advantage over the presumptive standard in that, because it is computed from the previous day's flow, it does not require sophisticated process-based or statistically based hydrological models in order to estimate natural flows on a daily time-step. However, this standard may inadequately protect certain stream types, such as flashy or intermittent streams with substantial short-term flow variability.

Finally, we note that the utility of an environmental flow rule also depends on the feasibility of estimation (Richter et al. 2012). Mitchell et al. (2013) concluded that a minimum of 20–30 years of discharge record are required for accurate estimates of monthly passby flow standards, whereas mean annual passby flow statistics (e.g., 30% MAF) could be accurately computed from as little as five years of flow record. They also suggested that annual measures calculated from shorter periods of record were much less likely than monthly passby standards to result in ecologically meaningful low-flow shortages. Thus, flow standards such as 20–30% MAF or 10% MDF may be more appropriate in data-scarce regions, while more rigorous standards such as TNC may be better suited to data-rich areas such as the MSR.

Conclusions

Water resources and rainfall in the Marcellus Shale region are abundant and the total amount of water required for gas development is small relative to the overall regional water demand. However, our results demonstrate that surface water withdrawals at the scale of individual streams, especially headwaters and creeks, can have significant ecological consequences and must be appropriately managed to ensure that human water needs are well balanced with those of riverine ecosystems. This study found five measures of fish community health and integrity were significantly reduced by alteration in a suite of seasonal, low-, median-, and high-flow hydrologic metrics across the Marcellus Shale region. An evaluation of consumptive water use scenarios indicated that withdrawals for shale gas development have the potential to substantially alter natural flow regimes, especially streams draining small watersheds (<100 km^2) during low-flow periods. However, seasonally variable flow standards resulted in substantial eco-hydrological protection across low-, median-, and high-flows, while providing for considerable human water use.

These findings can help inform regional water resource decisions and facilitate development of a coherent set of evidence-based flow recommendations for the Marcellus Shale region. Our results and analysis framework may also be useful in environmental flow assessments in other regions and are relevant to non-HVHF water withdrawals. However, managers and policy makers should recognize that this study is based on limited available regional data, and additional analyses are warranted for specific local applications. Policy decisions based on these findings should occur as part of an adaptive process, wherein flow provisions are designed and implemented as experiments with appropriate monitoring and feedback. This ensures that efforts to optimize water resource conservation and exploitation are continually refined through the closing of knowledge gaps, as well as improvements to regional ecohydrological relationships that underpin environmental flow standards.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1425/full

Data Availability

Data associated with this paper are available in figshare: 10.6084/m9.figshare.3459581