Environmental Science & Technology

Policy Analysis

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Surface Water Withdrawals for Marcellus Shale Gas Development: Performance of Alternative Regulatory Approaches in the Upper Ohio River Basin

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Ⓢ *Supporting Information*

ABSTRACT: Almost all of the water used for developing Marcellus Shale gas is withdrawn from surface water sources. State environmental and interstate water authorities take different approaches to managing these withdrawals. In the Upper Ohio River Basin, which covers the western third of Pennsylvania, the Pennsylvania Department of Environmental Protection requires that all water sources used for development have an approved water management plan. For surface water sources the plans stipulate the amount and timing of withdrawals from each source as a function of annual streamflow statistics. Neighboring regulatory authorities and some environmental groups now favor the use of monthly streamflow statistics to establish the conditions for water withdrawals. Our analysis indicates that, given the state of flow measurement data in the Upper Ohio River Basin, the annual streamflow statistics are more likely to prevent water withdrawals during the driest times of the year when aquatic ecosystems are most stressed, and to result in fewer and smaller occurrences of computed low-flow ecodeficits.

■ INTRODUCTION

The Marcellus Shale discovery well was drilled in 2005,[1] and today there are more than 5700 wells drilled and nearly 3600 producing Marcellus Shale gas wells in Pennsylvania.[2,3] The current core areas of development are in northwest West Virginia and southwest and northeast Pennsylvania. Estimates vary, but tens of thousands of additional wells may be drilled and hydraulically fractured in the coming decades.

There are numerous concerns about the impacts to regional water resources from developing the Marcellus Shale, including surface run and sedimentation from land disturbance;[4−6] groundwater contamination from drilling operations and gas migration;[7−16] and impacts from improperly managed and incompletely treated wastewater return flows.[5,7,8,17−25] This paper focuses on the environmental impacts of water withdrawals for shale gas development and what is being done to manage them. Reductions to instream flows can adversely affect aquatic, riparian, and floodplain habitats and the biota dependent on them. Water withdrawals during low flow and drought conditions carry the most risk, but maintaining the stream's natural seasonal variability is also important for healthy aquatic ecosystems.[26−28] Potential effects include the disruption of important stream features such as pools and riffles and diminished connectivity within basins. Withdrawal-induced temperature changes can also alter water quality and chemistry.[26,27,29−31] Water withdrawals from degraded sources may be beneficial to water quality downstream,[32,33] but withdrawals from high quality surface waters can cause downstream functions to be impaired by reducing dilution capacity.[34]

The regulatory framework for water withdrawals is different in each of Pennsylvania's four major river basins. The Pennsylvania Department of Environmental Protection (PADEP) has sole authority over water withdrawals in Pennsylvania's portion of the Upper Ohio River Basin (ORB).[35] The ORB covers most of western Pennsylvania except for the northwest corner near Lake Erie, which is part of the Great Lakes Basin Compact. The Delaware River Basin Commission and Susquehanna River Basin Commission (SRBC) have authority to regulate water withdrawals in the eastern two-thirds of the Commonwealth.

This study evaluates the impacts of different water withdrawal management options in the ORB, a watershed that covers 40 500 km^2 in western Pennsylvania, contains 22 000 km of second-order and larger streams, and four major rivers (Allegheny, Monongahela, Youghiogheny, and Beaver).[36]

Received: August 13, 2013
Revised: October 10, 2013
Accepted: October 14, 2013
Published: October 14, 2013

Table 1. Characteristics of Water Use by Well Type, Both Vertical and Horizontal, And Estimated Annual Water Use in the Pennsylvania Portion of the Upper Ohio River Basin (ORB) for Hydraulic Fracturing (Supporting Information, A)

	vertical wells				horizontal wells				
year	no. of well records[a]	(% of total)	avg. water use (m^3)	WUI (m^3/m)	no. of well records[a]	(% of total)	avg. water use (m^3)	WUI[b] (m^3/m)	estimated water use in ORB for hydraulic fracturing (m^3)
2008	141	(42%)	3900	144	35	(71%)	11 000	28	930 000
2009	155	(63%)	5000	164	114	(83%)	12 300	32	2 200 000
2010	107	(54%)	4400	115	274	(73%)	17 000	16	5 100 000
2011	54	(13%)	8700	62	612	(56%)	17 500	14	11 200 000
2012	42		1500		579		16 400		9 600 000

[a]Estimated number of wells (by type) hydraulically fractured each year and percent of wells for which water use data were reported, as of March 2013. [b]Water use intensity (WUI) is calculated from statewide hydraulic fracturing water use data.

■ BACKGROUND

In 2008, the PADEP began requiring shale gas drilling operators to submit water management plans (WMP) for each hydraulic fracturing water source. Water use data were assembled from 233 well record and completion reports from early 2011 (all of those available as of March 2013).[37] More than 70% of the water used for hydraulic fracturing of these wells was taken by operators directly from surface waters in Pennsylvania. For the first half of 2011, the SRBC reported that 75% of water withdrawals for unconventional gas development were coming directly from surface water sources in their basin.[38] Water purchased from public and bulk water suppliers was the second largest source. Since these entities obtain the majority of their water from river and reservoir intakes,[39] it is likely that more than 85% of the shale gas industry's water use was taken directly or indirectly from surface water sources. The third largest source was reused water, known as "produced water" (waste brine) that returns to the surface within a few weeks after a well has been completed (hydraulically fractured). Reused water constituted an average of about 12% of the water used for hydraulic fracturing according to the well record and completion reports; on a per-well basis, some reported 25% reused water use and others reported zero.

Table 1 shows that the average water use for horizontal wells approximately doubled from 2008 to 2011, due primarily to the increased measured depth of wells (which includes the vertical and horizontal sections). However, the water-use intensity (WUI)[40] for both vertical and horizontal wells decreased over the same period from 32 to 14 m^3 of water per meter of hydraulically fractured formation, possibly indicating more efficient use of water during the hydraulic fracturing process.

In 2011, approximately 11.2 million m^3 of water was used for hydraulic fracturing in Pennsylvania's ORB, which represents an 11-fold increase since 2008. Despite this dramatic growth, water use for natural gas development in Pennsylvania constitutes only a very small fraction of surface water withdrawals within Pennsylvania's ORB (Supporting Information (SI), B). Basin-wide comparisons, however, do not address the potential for water withdrawals to have localized impacts on water quantity and quality.

Where to source water can be a complex decision for operators in the Marcellus Shale. Consideration is given to the consistency and chemistry of the supply, regulatory aspects, potential environmental impacts, and cost.[41] There is no fee or charge for taking water from rivers or streams in the Upper Ohio River Basin, but costs are incurred in transporting water.[17,42,43] This incentive to source locally means that small rivers, streams, and creeks are an important part of the industry's freshwater portfolio in the ORB. Of all surface water sources covered by WMPs on file with the PADEP as of July 2012, approximately 60% of withdrawal sites have upstream drainage areas smaller than 518 km^2 (200 mi^2), while 40% are smaller than 259 km^2 (100 mi^2).[44] Besides being a convenient source for the industry, small streams are often essential to greater watershed and ecological health, and are important to regional tourism and recreation.[45]

Current Approaches for Managing Surface Water Withdrawals. The Q_{7-10} is a statistical estimate of the average minimum streamflow that can be expected for seven consecutive days once every 10 years.[46,47] The PADEP considers basin-wide water withdrawals summing to less than 10% of the Q_{7-10} flow to be *de minimis,* which means that withdrawals up to this amount could occur on a daily basis, including during declared droughts, presumably without significant ecological effects.[48,49] In intermediate and large streams and rivers (drainage areas >500 km^2) in western Pennsylvania, 10% Q_{7-10} typically exceeds what a single operator would propose to withdraw on a daily basis (SI, C).

When the volume of the proposed withdrawal (plus other known upstream withdrawals) exceeds 10% Q_{7-10}, withdrawals are still possible, but are subjected to a "passby flow" condition, which means that they may only occur on days when the instantaneous flow exceeds the passby flow at the withdrawal location. In other words, the passby flow defines a minimum flow that must be maintained in the stream for ecological purposes.[29,50,51] For compliance with the passby flow, the PADEP requires entities withdrawing water to verify (by measurement) that the (instantaneous) flow is greater prior to commencing withdrawals.

PADEP varies the passby flow definition with the quality and designated uses of the source water. For exceptional value and high quality streams[52] the passby flow is set to 25% of the average daily flow (ADF). This means that water withdrawals are prohibited when the instantaneous flow is below 25% of the ADF at the withdrawal site. The passby flow for degraded streams, such as those impacted by acid mine drainage, is set at 15% ADF.[48,53]

In contrast to the PADEP, the New York State Department of Environmental Conservation's (NYSDEC) Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program (SGEIS) and the SRBC's new low-flow protection policy rely on monthly flow duration curves (FDCs) to calculate different passby flows for each month. This approach reflects the desire to preserve the natural flow regimes with respect to magnitude and variability, which shape ecological patterns and lifecycles.[26] The NYSDEC's

dx.doi.org/10.1021/es403537z | Environ. Sci. Technol. 2013, 47, 12669−12678

SGEIS proposes setting the passby flow to a value that is exceeded 60% of the time (the Q60) in each of the driest months (July, August, September). For all other months the passby flow is set to the Q75. For drainage areas smaller than 129 km^2 (50 mi^2), the Q60 is recommended for all months.[34] The SRBC passby flow rules allow withdrawals 70−95% of the time depending on the size, quality, and other features of the watershed.[54] A monthly Q70, the most protective passby flow employed by the SRBC, is reserved for small, high-value streams. The SRBC reserves some flexibility in implementation at sensitive locations.

Figure 1 contrasts a 25% ADF passby flow to a "monthly Q75/60" passby flow for two years of streamflow recorded by the U.S. Geological Survey (USGS) streamgage on Laurel Hill Creek at Ursina, PA, a high quality tributary of the Youghiogheny River used for fishing and recreation.[55] Under the 25% ADF passby flow, withdrawals can occur more frequently during high seasonal flows (winter to spring) but are more restricted during low seasonal flows (summer to fall). With the monthly Q75/60, water withdrawals are allowed more consistently throughout the year. Though different in how withdrawals are distributed, both passby flows would allow water withdrawals approximately the same number of days in a typical year at Laurel Hill Creek.

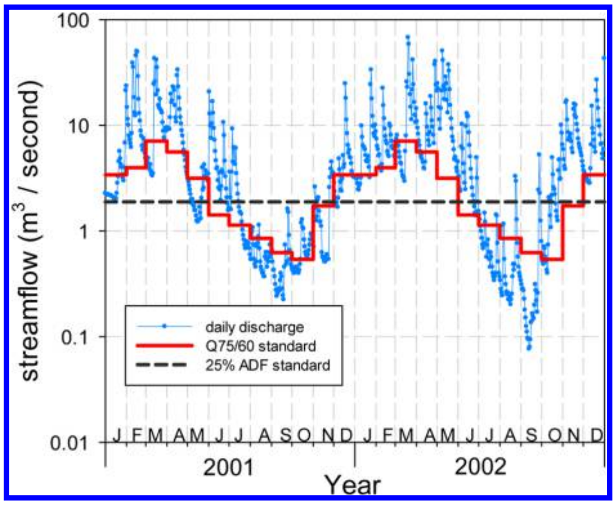

Figure 1. Passby flow standards—the 25% average daily flow (ADF) (dashed line) and monthly Q75/60 (solid line)—compared to the daily discharge values for Laurel Hill Creek (USGS 0308000) at Ursina, Pennsylvania between 1/1/2001 and 12/31/2002. Both passby flow standards were calculated from the discharge data between climate year 1942 and 2002. Passby flow equal to 25% ADF prohibits more withdrawals during periods of low flow and allows more withdrawals during periods of high flow than does the monthly Q75/60 standard.

Estimating Stream Statistics at Ungaged Withdrawal Locations. Companies seeking to withdraw water from rivers and streams in Pennsylvania's ORB have flexibility in how they estimate Q_{7-10} or ADF in their WMPs when the proposed withdrawal location is ungaged. They may use values determined from flow records at a more-distant streamgage, scaled by drainage area, to estimate a Q_{7-10} or ADF statistic, provided that the following are true: (1) the upstream drainage areas of the index streamgage and the withdrawal point are within a factor of 3 of each other, (2) the two drainage areas share similar geomorphic and climatic traits, and (3) both flow regimes are minimally altered by upstream withdrawals, diversions, and mining.[48,56] Scaling flow statistics from an index gage by applying the drainage area ratio is the simplest approach to estimating statistics on an ungaged stream.[57] A study of streamgages in Pennsylvania found that this method of estimating Q_{7-10} resulted in errors on the order of ±33% or less in 80% of the gage-to-gage comparisons examined.[58] The accuracy of the index gage approach could be improved using transformation techniques, such as base-flow correlation[59] or maintenance of variation extension.[60] However, these methods require a sufficient number of overlapping discharge measurements at the withdrawal location and in the index gage's discharge record. Eng et al. (2011) compare the bias in these transformation methods, and found less bias when the overlapping discharge measurements include a larger range of flows.[61] The additional data requirement may explain why these methods are not being used in practice.

The most common method for estimating Q_{7-10} and ADF absent an appropriate index gage is use of a web application hosted by the USGS (PA StreamStats). This application allows users to estimate Q_{7-10} or ADF at any point along any perennial stream in Pennsylvania[44] using a set of regression models that predict flow statistics from basin characteristics.[62] ADF is predicted using weighted least-squares from the input variables drainage area, mean elevation, annual precipitation, percent forested area, and percent urban area. The estimated standard error of ADF predictions is 12%.

Separate generalized least-squares regressions were employed to predict Q_{7-10} in five low-flow regions (LFRs) in Pennsylvania.[63] The ORB in Pennsylvania occupies LFR3 and LFR4 (SI, E). The LFR3 model uses the variables, drainage area, mean elevation, and precipitation. The LFR4 model only uses drainage area and precipitation. The standard errors for the Q_{7-10} prediction for LFR3 and LFR4 are, 54% and 66%, respectively.[62]

Streamgage Data Requirements for USGS StreamStats Regression Models. Only continuous record streamgages in which the flow regime has been minimally altered by human activities (including underground mining, surface development, significant withdrawals, or significant upstream diversions or impoundments) are acceptable for use in the USGS regression models.[47,62] The flow records produced from such streamgages are assumed to be representative of a "natural" flow regime. The 2006 USGS regression models for Q_{7-10} and ADF employed historical average daily discharge records from 63 continuous record streamgages in or near the Pennsylvania portion of the ORB, all of which contained at least nine years of average daily discharge records.[62] Figure 2 shows the sites of these 63 streamgages (24 of which are currently active) and surface water sources (withdrawal locations) named in Marcellus Shale WMPs on file with the PADEP as of July 2012.[62,64] The flow records from 33 of the streamgages contain no "natural" streamflow data more recent than 1983 (SI, F).

Because the USGS regression models are calibrated using the flow records of streamgages that were considered minimally altered by human activities, these models should only be used to predict flows for other locations that are *also* minimally altered (without extensive mining or and little to no upstream regulation). In western Pennsylvania, whether this condition is satisfied may be difficult to determine. For example, Pennsylvania only requires reporting of withdrawals exceeding 38 m^3 per day on average (10 000 gallons per day).[66] If there

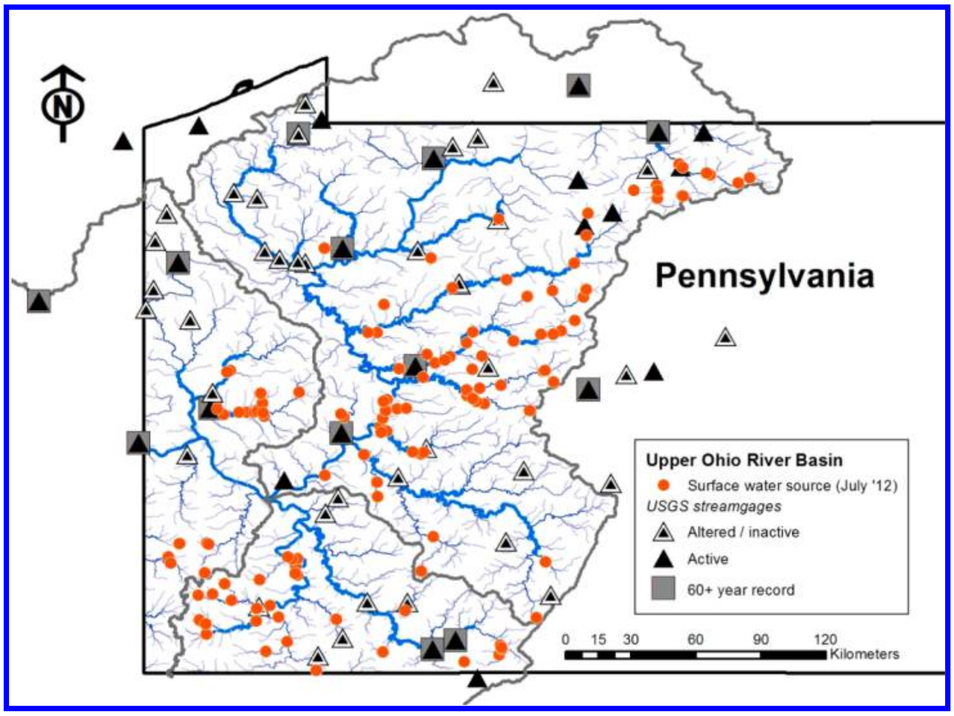

Figure 2. Locations of the 63 continuous record streamgages used by USGS StreamStats and approved surface water sources for hydraulic fracturing as of July 2012.[65] The 14 streamgages with 60 or more years of continuous flow record between 1900 and 2002 are indicated. Most of the hydraulic fracturing withdrawals occur at ungaged surface water locations.

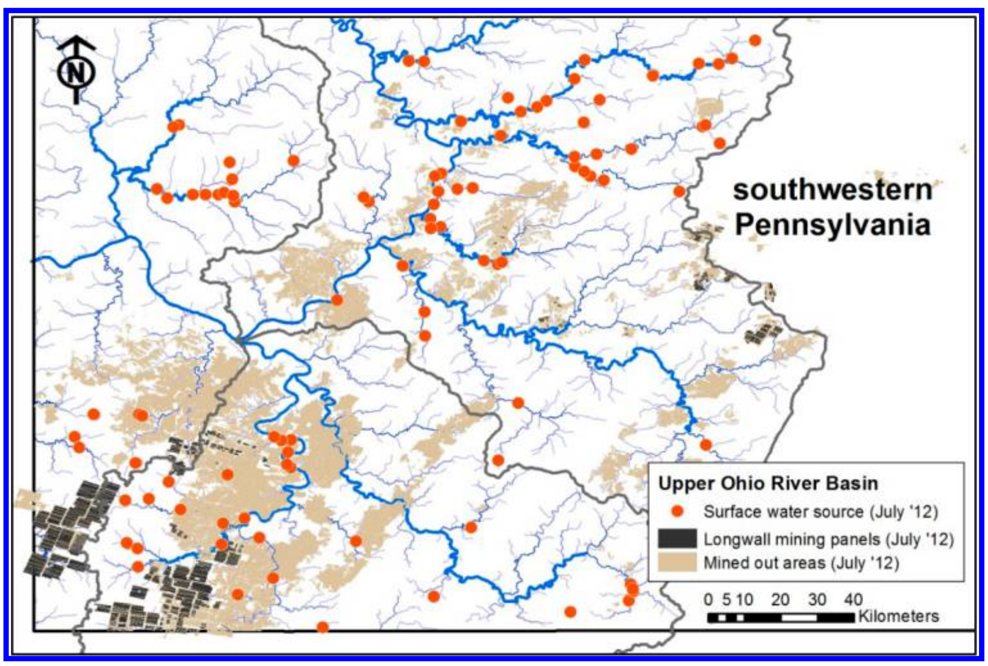

Figure 3. Water Management Plan surface water sources as of July 2012[65] from the Ohio River Basin[70] in southwestern Pennsylvania. Mined out coal areas and longwall mining panels are indicated.[71,72]

are many small, undocumented withdrawals, less water might be available than predicted. The existence of "natural" flow conditions might also be difficult to establish given the widespread topographic, geologic, and other physiographic changes from past subsurface mining and surface development in the ORB. The effects of mining on groundwater flow are long-lasting, difficult to predict,[47] may vary over time,[67,68] and are particularly impactful to the groundwater-dominated flows characteristic of smaller streams in dry months.[69] Figure 3 shows the extent of past subsurface mining in southwestern Pennsylvania.

Neither the index gage method nor the USGS regressions are appropriate for estimating flow statistics at withdrawal locations with significantly altered flow. Unfortunately, this has not prevented their use in WMPs. Altered streams require case-by-case assessments, but the methods for establishing the appropriate withdrawal conditions are beyond the scope of this analysis.

■ ANALYSIS

Sensitivity of 10% Q_{7-10} Estimates to Number of Years in the Flow Record. In this section bootstrap resampling[73] is employed to show how Q_{7-10} estimates derived from the log-Pearson type III distribution are sensitive to the number of years in the flow record.[46,74] For each of the 63 ORB streamgages with ≥9 years of continuous flow data, the lowest 7 day average flow was calculated for every climate year in the flow record. From the set of the lowest 7 day flows, random samples were drawn (with replacement) to generate 1000 new sets of 7 day flows for each streamgage. The log-Pearson type-III distribution was fit to each of the generated sets of 7 day flows, and 1000 estimates for Q_{7-10} were obtained for each streamgage.[46] The means and standard deviations of the resultant Q_{7-10}'s were used to calculate the coefficient of variation (CV) of the Q_{7-10} for each streamgage, which are shown in Figure 4 as a function of the number of years in the original flow record for all 63 streamgages.

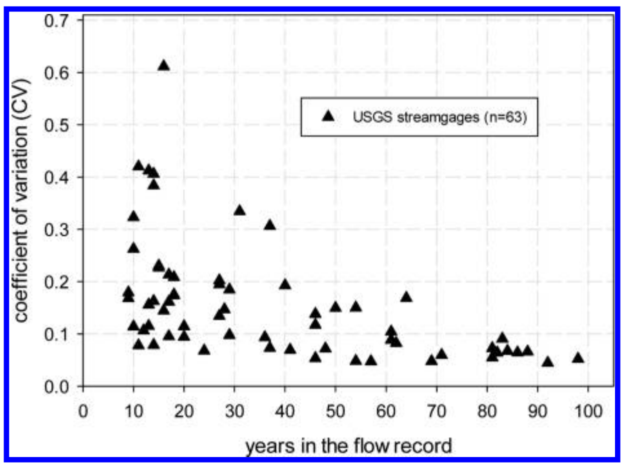

Figure 4. Uncertainty in estimated Q_{7-10} statistics as measured by the bootstrap coefficient of variation, as a function of the number of years in the flow record. Each triangle corresponds to one of the 63 USGS streamgages used in the StreamStats regressions.

The Q_{7-10} CV's tend to decrease as the number of years in the flow record increases. Thus longer flow records result in more confident Q_{7-10} estimates. The CV's for some streamgages with short flow records were comparable. In these instances the lowest average 7 day flows may not have varied much over the time interval considered, but it does not mean that the Q_{7-10} estimates from short flow records are accurate or precise.

Sensitivity of Passby Flow to Number of Years in the Flow Record. In this section the passby flow is calculated by the two competing methods (25%ADF and monthly Q75/60) with streamflow records of varying length, and their performance is evaluated.

There are 14 streamgages with at least 60 years of uninterrupted flow record among the 63 streamgages. These are located on small and large rivers: four had upstream drainage areas under 388 km^2 (150 mi^2), the largest drainage area was 4165 km^2 (1608 mi^2), and the average was 1023 km^2 (395 mi^2). (SI, F)

The data from the 14 streamgages with at least 60 years of uninterrupted flow record were divided into segments ranging in length from 1 to 35 consecutive years. The passby flow statistics were calculated from all such segments, resulting in a collection of sample passby flow statistics, whose biases were determined by comparison to the full (60 year) flow record. The fraction of days in each month of the 60 year flow record above each sample passby flow statistic was computed for all 14 gaged streams. The computed fractions were sorted by flow record length (1−35 years) and fit to a beta distribution. The mean and 90% confidence interval (CI) of the fitted fractions were multiplied by days in the month to estimate the "days withdrawal is allowed." The averages of these values across all 14 streamgages are reported in Figure 5.

In Figure 5 (a) the width of the 90% confidence interval in most months is small, even when fewer than 10 years of data are used to calculate 25% ADF. One explanation for this is that daily streamflow in the highest (November to May) and lowest (August and September) flow months is typically well above or below 25% ADF, respectively.

The number of days withdrawal is allowed under a monthly Q75/60 passby flow (Figure 5 (b)) is more uncertain than corresponding estimates for 25% ADF. For example, the July passby flow of Q60 is intended to allow water withdrawals 19 days out of 31 (60%), but the 90% CI ranges from 12 to 25 days when Q60 is calculated from 10 year flow records (a typical regulatory minimum). In months with higher average flows (January to May) the monthly Q75/60 could limit withdrawals to less than 60% of the days at the 90% CI. The wider confidence intervals with the monthly Q75/60 passby flow are due simply to the fact that approximately $^1/_{12}$ as many daily flow records are used to calculate individual passby flows compared to passby flow based on ADF, which uses all of the flow data in a year.

Ecodeficit from Underestimated Passby Flows. From the biologist's perspective, this uncertainty is important if it results in the approval of water withdrawals that might actually harm aquatic ecosystems and water quality as a result of data scarcity. In this section, how monthly low flows could be altered by allowing water withdrawals to occur on more days than intended is investigated. This involves using the concept of a computed "ecodeficit," which is a dimensionless metric used to provide a quantitative basis for assessing the effects of removing water from a stream.[75−77] (SI, G) It is recommended and used to analyze water withdrawal scenarios.[26,28,54]

Reported water use data from hydraulic fracturing operations in 2011 in the Upper ORB[37,78] served as the basis for three hypothetical monthly water demand scenarios (SI, D): (1) 150 m^3/km^2, which represents the average of the maximum monthly demand rate for all sub-basins with at least one hydraulically fractured well in 2011; (2) 1000 m^3/km^2, representing the highest rate among sub-basins in 2011 (931 m^3/km^2); and (3) 2000 m^3/km^2, a high estimate, compensating for incomplete water use records and other unknowns.

To simultaneously contrast yearly versus monthly passby flow standards and show the effects of streamgage record length, three examples of underestimated passby flows for each of the 14 gages were selected, (1) the fifth percentile of all possible 25% ADFs calculated from only 5 years of data, (2) the fifth percentiles of the 12 monthly Q75/60 passby flows calculated from all subsets of 10 years of data, and (3) the fifth percentiles of the 12 monthly Q75/60 passby flows calculated from all subsets of 25 years of continuous record.

For each streamgage, altered flow records were generated for every pairing of the three monthly water demand scenarios with the underestimated passby flows. From these altered flow records the average low-flow monthly ecodeficit was calculated

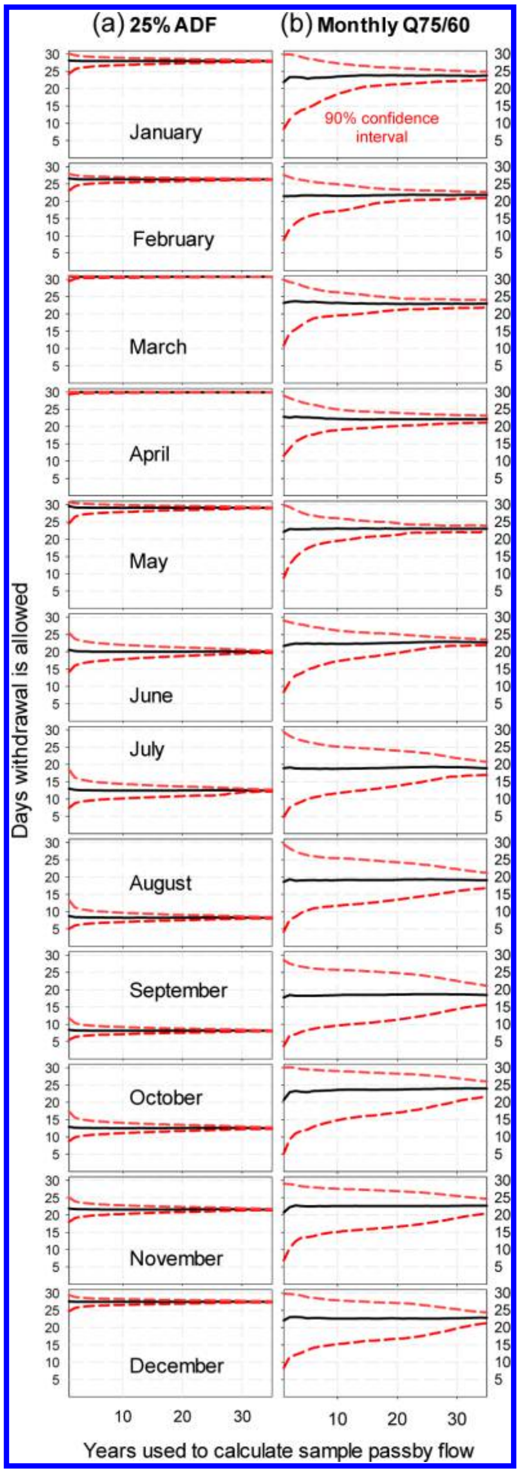

Figure 5. The sensitivity of passby flows to of the number of years in the flow record length. The solid line shows the average number of days that withdrawal is allowed for (a) 25% average daily flow and (b) monthly Q75/60 passby flows, and the dashed lines indicate the 90% confidence intervals.

(Figure 6). The Nature Conservancy recommends that for basins larger than 130 km^2 (50 mi^2), the low flow ecodeficit should not exceed 10% (0.1).[26,28] Typical flow ecodeficits were also calculated for the 14 USGS streamgages (SI, G).

The fifth percentile represents a *grossly* underestimated passby flow and is not a likely outcome, but, for the purposes of this study, it is useful bound to show the potential significance of this problem. Figure 6 demonstrates that underestimating passby flow is unlikely to be a problem for monthly water demand equal to 150 m^3/km^2 because the ecodeficits are not close to the 10% threshold. However, in areas where development activities are concentrated, this rate of withdrawal will be easily surpassed. To illustrate, a monthly water demand of 150 m^3/km^2 upstream of the Laurel Hill Creek streamgage (drainage area of 313 km^2) would provide enough water to hydraulically fracture three average Marcellus Shale wells (fewer than half the number of wells that might be located on a single well pad).

Passby flow equal to 25% ADF is most protective of monthly low flows in summer and fall, even when calculated from only five years of data. The monthly Q75/60 passby flow is the least protective if calculated with only 10 years of flow data. Even when monthly Q75/60 passby flow is calculated from 20 years of data, two of the withdrawal scenarios produced large ecodeficits in October and November, which are not protected to the same level as other dry months in NYSDEC's SGEIS.

■ DISCUSSION

In this analysis the focus has been on a set of regulatory standards applied to water withdrawals for unconventional gas development, and the circumstances that might lead to their miscalculation and the subsequent degradation of ecosystems and water quality in the streams to which the standards are applied. The finding that only five years of continuous discharge data are necessary to successfully implement a passby flow standard based on the average daily flow is important because it is less than the typical regulatory minimum of 10 years. The recommendation that Q_{7-10} should be derived from a minimum of 20 years of discharge data is not new.[79−81] Neither is the finding that 30−35 years of flow record are needed to for reliable statistics based on the flow duration curve,[80,81] though the Nature Conservancy recommends a minimum of only 20 years.[26]

The USGS regression model (PA StreamStats) is not a better option to estimate Q_{7-10} and ADF for WMPs. Potential errors from the use (and misuse) of these models can be significant. The error in Q_{7-10} predictions in western Pennsylvania is large (>50%) and whether WMPs based on StreamStats information provide adequate low-flow protections is unknown. Furthermore, instantaneous flow data are required for implementation of a passby flow standards in the field. The current approaches to obtain these data introduce an additional element of uncertainty, particularly when they involve observing water depth from a "staff gage" (SI, H).

The potential uncertainties presented in this study are not currently incorporated into the approval process for water management plans. Ignoring this uncertainty might result in miscalculations that allow environmentally damaging water withdrawals to occur. The flip-side of this situation occurs when the errors are in the opposite direction. Such errors could prevent companies from taking water at times when they would not harm the environment. Thus, both industry and regulators have a stake in determining appropriate and reliable regulatory controls.

The preceding analysis led to the following conclusions. (1) Given the large coefficients of variation for estimating Q_{7-10} from short flow records, a minimum of 20 years of record is recommended for calculating this statistic. A third of the available flow records in western Pennsylvania do not meet this recommendation. (2) The current passby flow statistic used by

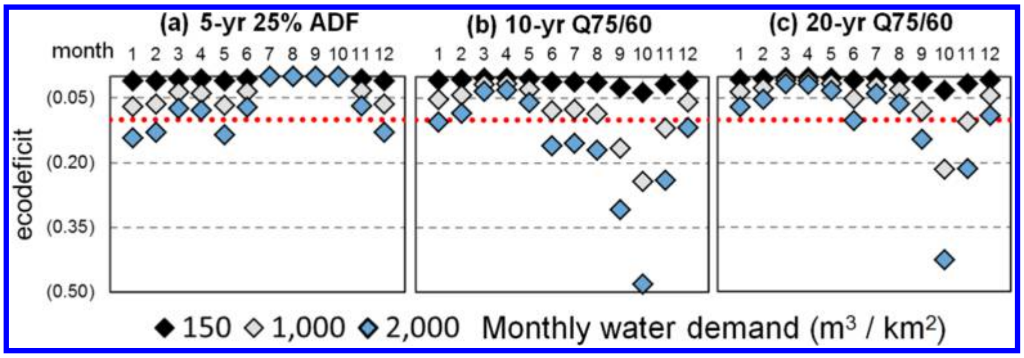

Figure 6. The average monthly low flow ecodeficits estimated for the 14 USGS streamgages for hypothetical monthly water demands of 150, 1000, and 2000 m^3/km^2 subject to underestimated (fifth percentile) values of (a) the 5 year 25% average daily flow (ADF), (b) the 10 year Q75/60, and (c) the 20 year Q75/60. The Nature Conservancy threshold of 0.10 is indicated by the red-dashed line. Low flow ecodeficits plotting below this line are considered unacceptable. The passby flow equal to 25% ADF (a) provided the most protection for low flows (June to October) even though only five years of flow data were used in its calculation.

the PADEP (15−25% average daily flow) can be reliably estimated with as few as five years of flow record because it is not as sensitive to the potential biases of short flow records. (3) Severely under- or overestimated monthly Q75/60 passby flows may result from using fewer than 20 years of flow record, but 30 or more years may be necessary to achieve a level of confidence comparable to that of the 5 year ADF. There are only 24 active streamgages with 20 or more years of minimally altered ("natural") flow record to cover 22 000 km of streams in Pennsylvania's portion of the ORB. (4) When calculated from short streamflow records, passby flow standards derived from the 25% ADF are less likely to result in large low-flow ecodeficits in dry months than those based on Q75/60.

The main justification for monthly passby flow standards is to prevent water consumers from dampening seasonal flow variability. Aggregate water demands of the gas industry are typically a small fraction of streamflow during wet months, raising the question of whether PADEP would have anything to gain from switching to a more complex monthly standard, as have neighboring water authorities. Our findings are relevant to other entities developing water withdrawal policies for the shale gas industry. Where flow records are short, the annual passby statistic is preferable to the monthly.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

A, Water use data and estimation methods. B, Surface water withdrawals in the Ohio River Basin. C, WMP surface water sources. D, Water demand for HF in the ORB. E, Low-flow regions in Pennsylvania. F, Streamgages in this study. G, Ecodeficit calculations. H, Instantaneous flow measurement errors. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We express our thanks to Jeanne VanBriesen for her insightful feedback throughout the drafting of this paper. We appreciate the help of Brian Dillemuth and Derek Smith, formerly of the Pennsylvania Department of Environmental Protection, for their assistance collecting WMP data, and thank Kristin Carter (Pennsylvania Department of Conservation and Natural Resources) for assistance obtaining well record and completion reports and Mohan Jiang (CMU) and Stacie Lackler (CMU) for helping to digitize them. Thanks also to Anthony Spehar and Clinton Hittle of the U.S. Geological Survey for their explanations of the science and art of their work. This research was made possible through support from the Climate and Energy Decision Making Center (CEDM) located in the Department of Engineering and Public Policy. This Center has been created through a cooperative agreement between the National Science Foundation (SES-0345798) and Carnegie Mellon University. Additional support is from Gordon and Betty Moore Foundation and the John and Claire Bertucci Fellowship.

■ ABBREVIATIONS

Q_{7-10}, 7 day, 10 year low flow
Q60, flow exceeded 60% of the time
Q75, flow exceeded 75% of the time
ADF, average daily flow
API, American Petroleum Institute
CI, confidence Interval
CV, coefficient of variation
DRBC, Delaware River Basin Commission
FDC, folw duration curve
HUC, hydrologic unit code
LFR, low flow region
NYSDEC, New York State Department of Environmental Conservation
ORB, Ohio River Basin
PADEP, Pennsylvania Department of Environmental Protection

SGEIS, supplemental generic environmental impact statement
SRBC, Susquehanna River Basin Commission
USGS, U.S. Geological Survey
WMP, water management plan
WUI, water-use intensity

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