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A detailed risk assessment of shale gas development on headwater streams in the Pennsylvania portion of the Upper Susquehanna River Basin, U.S.A.

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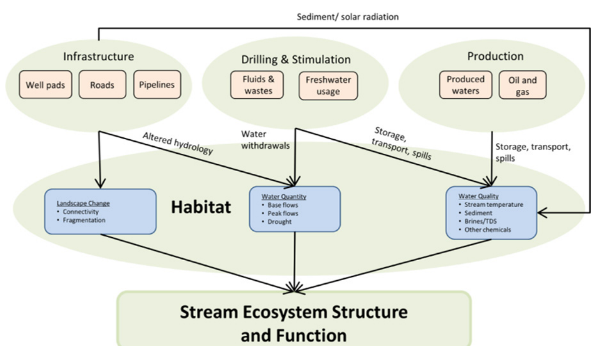
HIGHLIGHTS

- Infrastructure, water withdrawals, and spills from UOG cumulatively affect ecosystems.
- A disturbance intensity index was developed that captured all these potential effects.
- Well density correlated with well pads and production metrics but not other measures.
- Some catchments and high quality streams were in medium-high disturbed areas.
- A large proportion of catchments and streams were at high risk to future development.

GRAPHICAL ABSTRACT



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ABSTRACT

The development of unconventional oil and gas (UOG) involves infrastructure development (well pads, roads and pipelines), well drilling and stimulation (hydraulic fracturing), and production; all of which have the potential to affect stream ecosystems. Here, we developed a fine-scaled (1:24,000) catchment-level disturbance intensity index (DII) that included 17 measures of UOG capturing all steps in the development process (infrastructure, water withdrawals, probabilistic spills) that could affect headwater streams (<200 km^2 in upstream catchment) in the Upper Susquehanna River Basin in Pennsylvania, U.S.A. The DII ranged from 0 (no UOG disturbance) to 100 (the catchment with the highest UOG disturbance in the study area) and it was most sensitive to removal of pipeline cover, road cover and well pad cover metrics. We related this DII to three measures of high quality streams: Pennsylvania State Exceptional Value (EV) streams, Class A brook trout streams and Eastern Brook Trout Joint Venture brook trout patches. Overall only 3.8% of all catchments and 2.7% of EV stream length, 1.9% of Class A streams and 1.2% of patches were classified as having medium to high level DII scores (>50). Well density, often used as a proxy for development, only correlated strongly with well pad coverage and produced materials, and therefore may miss potential effects associated with roads and pipelines, water withdrawals and spills. When analyzed with a future development scenario, 91.1% of EV stream length, 68.7% of Class A streams and 80.0% of patches were in catchments with a moderate to high probability of development. Our method incorporated the

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cumulative effects of UOG on streams and can be used to identify catchments and reaches at risk to existing stressors or future development.

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1. Introduction

Oil and gas production from unconventional sources (unconventional oil and gas, UOG) has dramatically increased in the U.S.A. over the past 10 years. Annual production of natural gas from shale within the U.S.A. has increased almost 12 fold from 2007 (1.3 trillion cubic feet, TCF) to 2015 (15.2 TCF) and daily production of tight oil (oil found in impermeable rock that requires stimulation for production) has increased from <1 million barrels in 2000 to over 4 million barrels in 2016; production from both are projected to further increase over the next few decades (USEIA, 2017a, 2017b). The world's tight oil production also is predicted to more than double from 2015 to 2040 (USEIA, 2016). Such rapid increase in development and future potential of development has led to an increased concern over the potential effects on associated ecosystems (Gottschalk et al., 2013; Kiviat, 2013; Brittingham et al., 2014; Jackson et al., 2014; Souther et al., 2014; Habicht et al., 2015; Macuda and Konieczyńska, 2015; Werner et al., 2015).

Stream ecosystems may be particularly vulnerable to shale gas and tight oil development because streams are strongly dependent on and influenced by upstream catchment conditions (Hynes, 1975). Recent reviews have identified three aspects of the shale gas and tight oil process that could affect streams: infrastructure, water withdrawals, and spills (Entrekin et al., 2011; Weltman-Fahs and Taylor, 2013; Souther et al., 2014). Infrastructure, including well pads, access roads and pipelines, alters the landscape by exposing soil to runoff during construction, thereby increasing erosion and sedimentation to receiving streams (Williams et al., 2008), although use of appropriate best management practices can reduce these loads (Wachal et al., 2009). Road and stream crossings not only serve as conduits for increased runoff, but also can fragment the stream network acting as barriers to fish movement (Warren and Pardew, 1998). Where crossings result in riparian removal, they may alter the stream's natural thermal regime (Moore et al., 2005). Alteration to the natural flow regime of streams from water withdrawals also has been postulated, especially in arid areas or during low flow periods (Vengosh et al., 2014), and headwater streams were found to be at higher risk from withdrawals than larger systems (Shank and Stauffer, 2014). Spills and releases of raw chemicals, oil and gas, and waste materials can occur in proximity to streams or conduits to streams (Maloney et al., 2017), can reach surface and ground waters (USEPA, 2015), and can affect associated stream fauna (Papoulias and Velasco, 2013; Patnode et al., 2015; Akob et al., 2016; Cozzarelli et al., 2017). Such evidence on potential effects of infrastructure, withdrawals, and spills suggests a complete assessment of UOG development on streams must be cumulative and incorporate data on all three aspects (Smith et al., 2012; Souther et al., 2014).

Limited data availability on infrastructure, water withdrawals and spills/releases has forced many recent assessments to base their analyses largely on well information such as well density, age, and proximity to streams (Entrekin et al., 2015; Meng, 2015; Preston and Chesley-Preston, 2015) or to use probability based analyses (Rozell and Reaven, 2012). These analyses have greatly advanced our understanding of potential issues related to UOG development but they could be improved upon by incorporating data for each of the three main pathways. Here, we focused our study on the Pennsylvania portion of the Upper Susquehanna River Basin (PAUSRB), U.S.A, an area with ample data on infrastructure, water withdrawals, and spills/releases in an effort to provide a more holistic assessment of UOG development on streams. Our study had two main objectives: 1) to calculate a UOG development intensity index based on existing measures and use this index to identify high-quality streams at risk to such development and 2) to assess future risk of these high-quality streams to projected UOG development. For the first objective, we calculated a development intensity index based on existing UOG development for all headwater catchments (<200 km^2) in the PAUSRB. This index was derived from a set of 17 UOG-related potential stressors encompassing all aspects of the development process. We identified the most at risk highest quality and brook trout streams by relating these catchment-scale indices to the state's highest quality streams (Exceptional Value, EV) and two estimates of brook trout, *Salvelinus fontinalis*, population status. Brook trout are a key species of concern for this region, support an important recreational fishery industry, and serve as a sentinel species for the overall health of cold-water streams (EBTJV, 2006). However, across its southern historic range (Pennsylvania to Georgia) only 52% of watersheds (HUC10), 32% of subwatersheds (HUC12) and 14% of catchments (HUC14) were predicted occupied and, across all scales, <10% were predicted occupied exclusively by native brook trout (Hudy et al., 2013a). Because of these noted declines, efforts are underway to conserve and restore this species (EBTJV, 2005; Chesapeake Bay Program, 2014). However, much of the existing occupied habitat for the Chesapeake Bay Watershed is underlain by UOG resources with development potential, which may hamper ongoing and future restoration goals. In order to assess future risk of streams in this area to projected UOG development, we related the EV streams and two estimates of brook trout population status to a published estimate of future shale gas build out for the Appalachian Basin (Dunscomb et al., 2014). Our inference for both analyses was at the reach scale, a scale finer than previous studies and more relevant to species conservation and management efforts.

2. Methods

2.1. Study site

The Susquehanna River basin encompasses an area of 71,251 km^2 and is the largest tributary that drains into the Chesapeake Bay (~166,500 km^2 drainage area, Fig. 1). Our study focused on the PAUSRB (drainage area = 31,352 km^2), which includes the West Branch Susquehanna and Middle Susquehanna sub-basins and portions of the Chemung and Upper Susquehanna sub-basins.

The area is largely in forest cover (69.2%, 2011 National Land Cover Data, NLCD, Homer et al., 2015), followed by agriculture (18.9%). Developed land only covers 6.3% of the region. Although encompassing only 26.7% of Pennsylvania (117,328 km^2), catchments within this region harbor over 55.6% of the State's high quality, Class A, trout streams (defined as unstocked streams that support a population of wild trout, brook trout, brown trout, and rainbow trout, of sufficient size to support a long-term and rewarding sport fishery, PAFBC, 2016). The study area also contains 73.6% of the state's intact brook trout populations as defined by the Eastern Brook Trout Joint Venture at the sub-catchment scale (Coombs and Nislow, 2015) (Fig. A.1).

A large portion of the study region is underlain by the Marcellus and Utica Shale plays (Fig. 1). Over the past 10 years, this area has experienced a dramatic increase in gas development from shale resources (Fig. A.2).

2.2. UOG stressor data sets

To assess overall risk of headwater, brook trout streams to UOG development, we collated data on a suite of potential stressors from the