Hydraulic Fracturing and Brook Trout Habitat in the Marcellus Shale Region: Potential Impacts and Research Needs

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ABSTRACT: *Expansion of natural gas drilling into the Marcellus Shale formation is an emerging threat to the conservation and restoration of native brook trout (*Salvelinus fontinalis*) populations. Improved drilling and extraction technologies (horizontal drilling and hydraulic fracturing) have led to rapid and extensive natural gas development in areas overlying the Marcellus Shale. The expansion of hydraulic fracturing poses multiple threats to surface waters, which can be tied to key ecological attributes that limit brook trout populations. Here, we expand current conceptual models to identify three potential pathways of risk between surface water threats associated with increased natural gas development and life history attributes of brook trout: hydrological, physical, and chemical. Our goal is to highlight research needs for fisheries scientists and work in conjunction with resource managers to influence the development of strategies that will preserve brook trout habitat and address Marcellus Shale gas development threats to eastern North America's only native stream salmonid.*

Ruptura hidráulica y el hábitat de la trucha de arrollo en la región de Marcellus Shale: impactos potenciales y necesidades de investigación

RESUMEN: El crecimiento de las actividades de perforación de gas natural en la formación Marcellus Shale es una amenaza emergente para la conservación y restauración de las poblaciones nativas de la trucha de arroyo (*Salvelinus fontinalis*). La perforación más eficiente y las tecnologías de extracción (perforación horizontal y ruptura hidráulica) han facilitado el rápido y extensivo desarrollo de esta industria a las áreas que comprende la región Marcellus Shale. La expansión de las rupturas hidráulicas representa múltiples amenazas a las aguas superficiales, que pueden estar asociadas a atributos ecológicos clave que limitan las poblaciones de la trucha de arroyo. En la presente contribución se expanden los modelos conceptuales actuales que sirven para identificar tres fuentes potenciales de riesgo entre las amenazas a las aguas superficiales asociadas al creciente desarrollo del gas natural y los atributos de la historia de vida de la trucha de arroyo; atributos hidrológicos, físicos y químicos. El objetivo de este trabajo es hacer notar las necesidades de investigación para los científicos pesqueros y trabajar junto con los manejadores de recursos para influir en el desarrollo de estrategias tendientes a preservar el hábitat de la trucha de arroyo; así mismo se atienden las amenazas que representa el desarrollo de la industria del gas natural para el único salmónido nativo de América del norte.

INTRODUCTION

Hydraulic Fracturing in the Marcellus Shale

Natural gas extraction from subterranean gas-rich shale deposits has been underway in the northeastern United States for almost 200 years but has expanded rapidly over the past decade within the Devonian Marcellus Shale formation (P. Williams 2008). This expansion has largely been driven by the development and refinement of the horizontal hydraulic fracturing process (United States Energy Information Administration 2011a). Horizontal gas drilling differs from the more traditional vertical drilling process because the well is drilled to the depth of the shale stratum and then redirected laterally, allowing for access to a larger area of subterranean shale (Figure 1). Drilling is followed by the hydraulic fracturing process, which involves injecting a chemically treated water-based fluid into the rock formation at high pressure to cause fissures in the shale and permit the retrieval of gas held within the pore space of the shale. The fissures are kept open by sand and other proppants, which allow gas to be extracted (Soeder and Kappel 2009; Kargbo et al. 2010). The hydraulic fracturing process was granted exemptions to the Clean Water and the Safe Drinking Water Acts under the Energy Policy Act of 2005. Drilling has since expanded rapidly in the Marcellus Shale deposit in portions of West Virginia and Pennsylvania (Figure 2), is expected to continue into Ohio and New York, and will likely continue to expand within these states to include the gas-bearing Utica Shale formation.

Brook Trout Status within the Marcellus Shale

Eastern brook trout are native to the Eastern United States, with a historic range extending from the southern Appalachians in Georgia north to Maine (MacCrimmon and Campbell 1969; Figure 2). Brook trout require clean, cold water (optimal tem-

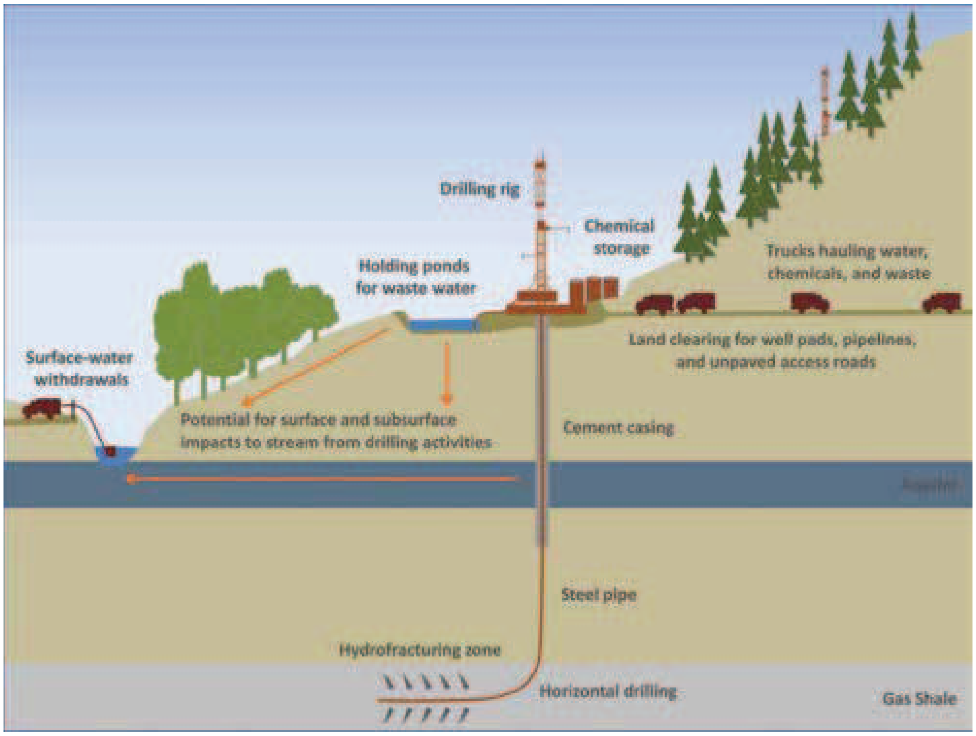

Figure 1. Conceptual diagram depicting the hydraulic fracturing process. A rig drills down into the gas-bearing rock and the well is lined with steel pipe. The well is sealed with cement to a depth of 1,000 ft. to prevent groundwater contamination. The well is extended horizontally 1,000 ft. or more into the gas-bearing shale where holes are blasted through the steel casing and into the surrounding rock. Sand, water, and chemicals are pumped into the shale to further fracture the rock and gas escapes through fissures propped open by sand particles and back through the well up to the surface. Supporting activities include land clearing for well pads and supporting infrastructure, including pipelines and access roads. Trucks use roads to haul in water extracted from local surface waters, chemicals, and sand. Recovered water is stored in shallow holding ponds until it can be transported by truck to treatment facilities or recycled to fracture another well. These activities may impact nearby streams through surface and subsurface pathways.

perature = 10–19°C), intact habitat, and supporting food webs to maintain healthy populations, making them excellent indictors of anthropogenic disturbance (Hokanson et al. 1973; Lyons et al. 1996; Marschall and Crowder 1996). Only 31% of subwatersheds (sixth level, 12-digit hydrological units [HUC12], as defined by the Watershed Boundary Dataset; U.S. Department of Agriculture, Natural Resources Conservation Service 2012) within the historic range of brook trout are currently expected to support intact populations (self-sustaining populations greater than 50% of the historical population; Hudy et al. 2008). Substantial loss of brook trout populations within their native range is due to anthropogenic impacts that have resulted in habitat fragmentation and reduction, water quality and temperature changes, and alteration of the biological environment through introduction and removal of interacting species (Hudy et al. 2008). Conservation efforts, including formation of the Eastern Brook Trout Venture (Eastern Brook Trout Joint Venture [EBTJV] 2007, 2011) and a shift by organizations such as Trout Unlimited (TU) to policies that oppose the stocking of nonnative hatchery-produced salmonids in native trout streams (TU 2011), are focused on maintaining and restoring brook trout populations in their native range. With these growing concerns about the future of native brook trout populations, natural gas well development within the Marcellus Shale region presents another potential threat to native brook trout populations.

Twenty-six percent of the historic distribution of brook trout habitat overlaps with the Marcellus Shale (Figure 2). The Pennsylvania portion of the Marcellus Shale has experienced the largest increase in natural gas development (Figure 2). Between January 1, 2005, and May 31, 2012, the cumulative number of Marcellus Shale well permits issued in Pennsylvania increased from 17 to 11,784 (Pennsylvania Department of Environmental Protection [PADEP] 2012a). Of these permitted wells, 5,514 were drilled during the same time period (PADEP 2012b; Figure 3A). Trends in drilled well densities among subwatersheds during the rapid expansion of drilling activity suggest that there have not been any extra protections granted during the well permitting process for subwatersheds that are expected to support intact brook trout populations (Figure 3B). Fifty-four of the 134 subwatersheds categorized as having intact brook trout populations within the Marcellus Shale region have already experienced drilling activity (Hudy et al. 2008). Overall, Marcellus drilling activity has expanded to 377 subwatersheds (mean area = 94.8 ± 1.9 km^2) in Pennsylvania (Figure 4).Within these 377 subwatersheds, patterns in well density over time show similar trends among subwatersheds varying in their current brook trout population status (Figure 3B). Though there is a significant difference in current well densities among the three subwatershed types (one-way analysis of variance [Type II], $F_{2,292} = 4.14$, $P = 0.02$), mean well density does not differ between subwatersheds where brook trout are extirpated/unknown and those with intact brook trout populations (Tukey's multiple comparison test, $\alpha = 0.05$; Figure 3B). In fact, the two highest drilling densities include an extirpated/unknown subwatershed (16.7 wells/10 km^2) and a subwatershed expected to support intact brook trout populations (15.1 wells/10 km^2; Figure 4). These trends highlight that increasing hydraulic fracturing development is occurring not only in degraded subwatersheds but also in those that support an already vulnerable native species and valuable sport fish. This trend should be of concern to fisheries scientists, managers, and conservationists who work to maintain and improve the current status of this natural heritage species.

Linking Marcellus Shale Drilling Impacts to Brook Trout Population Health

Recent efforts to conceptualize horizontal hydraulic fracturing impacts have focused on stream ecosystems and regional

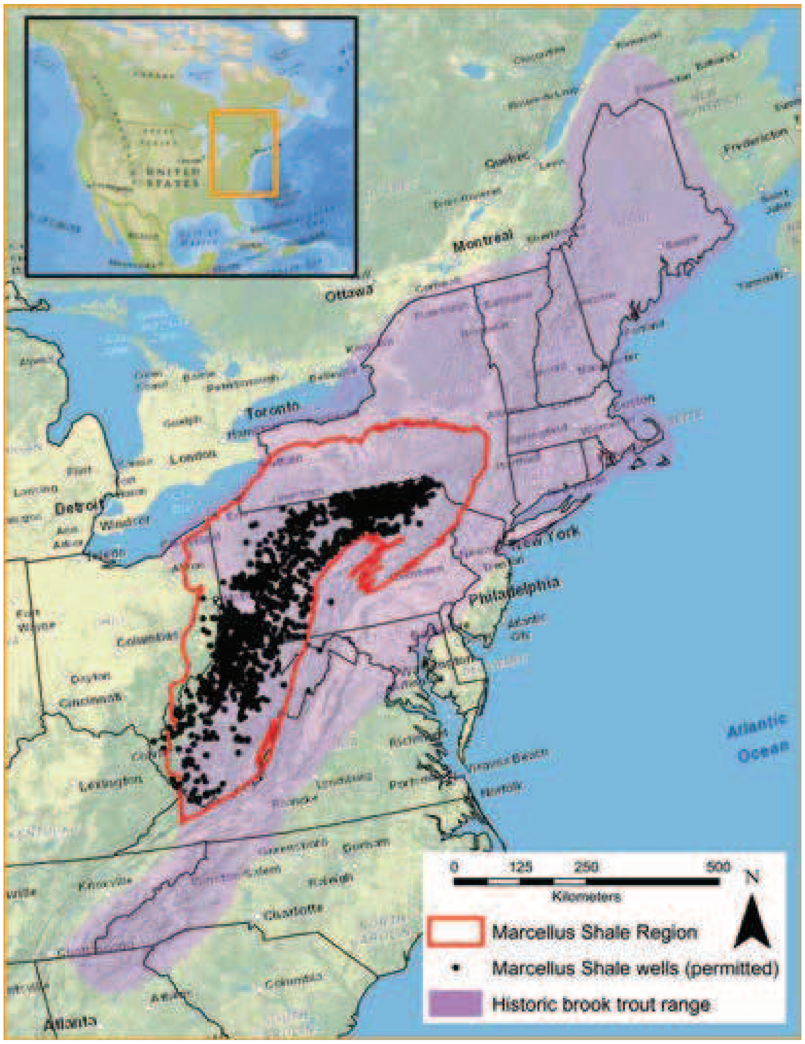

Figure 2. Overlay of the Marcellus Shale region of the Eastern United States (U.S. Geological Survey [USGS] 2011) and the historic distribution of eastern brook trout (Hudy et al. 2008) with permitted Marcellus Shale well locations, 2001–2011 (Ohio Department of Natural Resources 2011; West Virginia Geological and Economic Survey 2011; PADEP 2012a).

water supplies but not on potential pathways to particular target organisms. Herein, we integrate two existing conceptual models of potential natural gas development impacts to surface waters and link them to different brook trout life history attributes (Entrekin et al. 2011; Rahm and Riha 2012). Entrekin et al.'s (2011) conceptual model establishes connections between hydraulic fracturing activities and the ecological endpoint of stream ecosystem structure and function by way of potential environmental stressors from drilling activity sources. These stressors to stream ecosystems can be planned activities that must necessarily occur in the hydraulic fracturing process (deterministic events) or those that may occur unexpectedly (probabilistic events; Rahm and Riha 2012). Brook trout have different environmental requirements at the various stages of their life cycle and may be sensitive to potential impacts associated with the current expansion of hydraulic fracturing; thus, understanding the environmental stressors associated with hydraulic fracturing has implications for fisheries conservation, including maintenance and/or enhancement of native brook trout populations.

We delineated relationships between various stream ecosystem attributes that are potentially impacted by increased drilling activities and different aspects of the brook trout life cycle (Figure 5). A review of extant literature on the activities associated with natural gas drilling and other extractive industries and of the environmental changes known to directly influence brook trout at one or more of their life stages identified three primary pathways by which increased drilling will likely impact brook trout populations. The primary pathways include (1) changes in hydrology associated with water withdrawals; (2) elevated sediment inputs and loss of connectivity associated with supporting infrastructure; and (3) water contamination from introduced chemicals or wastewater (Entrekin et al. 2011; Rahm and Riha 2012). These three pathways may be considered natural gas drilling threats to brook trout populations that require study and monitoring to fully understand, minimize, and abate potential impacts.

PATHWAY #1: WITHDRAWALS → HYDROLOGY → BROOK TROUT

Two to seven million gallons of water are needed per hydraulic fracturing stimulation event; a single natural gas well can be fractured several times over its lifespan, and a well pad site can host multiple wells (Soeder and Kappel 2009; Kargbo et al. 2010). This large volume of water needed per well, multiplied by the distributed nature of development across the region, suggests that hydraulic fracturing techniques for natural gas development can put substantial strain on regional water supplies. This level of water consumption has sparked concern among hydrologists and aquatic biologists about the sourcing of the water, as well as the implications for available habitat and other hydrologically influenced processes in adjacent freshwater ecosystems (Entrekin et al. 2011; Gregory et al. 2011; Baccante 2012; Rahm and Riha 2012; Figure 5). Surface water is the primary source for hydraulic fracturing–related water withdrawals in at least one major basin intersecting the Marcellus Shale region (Susquehanna River Basin Commission [SRBC] 2010), but groundwater has been a major water source in other natural gas deposits such as the Barnett Shale region in Texas (Soeder and Kappel 2009). The cumulative effects of multiple surface and/or groundwater withdrawals throughout a watershed have the potential to effect downstream hydrology and connectivity of brook trout habitats (Rahm and Riha 2012; Petty et al. 2012).

Aquatic habitat is particularly limited by low-flow periods during the summer for fish and other aquatic organisms (Figure 6). Changes in temperature and habitat volume during summer low-flow periods are primary factors limiting brook trout populations (Barton et al. 1985; Wehrly et al. 2007; Xu et al. 2010). Brook trout rely on localized groundwater discharge areas within pools and tributary confluences to lower body temperature below that of the ambient stream temperature during warm periods, and groundwater withdrawals can alter these temperature refugia. Additionally, access to thermal refugia may be limited by loss of connectivity associated with reduced flows between temperature refugia (headwater streams, seeps, tributary confluences, groundwater upwellings) and larger stream habitats (Petty et al. 2012). Reduced flows, particularly coldwater inputs, may inhibit growth rates by reducing feeding activity of both juveniles and adults or inducing sublethal heat shock at temperatures above 23°C and lethal effects at 24–25°C (7-day upper lethal temperature limit; Cherry et al. 1977; Tangiguchi et al. 1998; Baird and Krueger 2003; Lund et al. 2003; Wehrly et al. 2007). Recovery from thermal stress responses (heat shock) can be prolonged (24–48 h) even if exposure to high stream temperatures is relatively short (1 h) but may be more than 144 h when exposed to high temperatures for multiple days (Lund et al. 2003). Adult abundance and biomass of brook trout in run habitats declines with flow reduction and carrying capacity is likely limited by available pool area during low-flow periods (Kraft 1972; Hakala and Hartman 2004; Walters and Post 2008).

Reduction in surface water discharge during summer months may also indirectly impact brook trout growth by decreasing macroinvertebrate prey densities (Walters and Post 2011) in small streams and lowering macroinvertebrate drift encounter rates for drift-feeding salmonids (Cada et al. 1987; Nislow et al. 2004; Sotiropoulos et al. 2006; Figure 5). Other indirect effects may include increasing interspecific competition through habitat crowding, especially with more tolerant competitor species such as brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*), due to decreased habitat availability and increased temperature during low-flow periods. Introduced brown trout tend to out-compete brook trout for resources and have higher growth rates in all but the smallest, coldest headwater streams (Carlson et al. 2007; Öhlund et al. 2008; Figure 5). Additionally, salmonids may be more susceptible to disease or infestation of parasites when the temperature of their environment is not consistent and adequately cool (Cairns et al. 2005), a problem that could be exacerbated by the crowding in pool habitats that can occur as a result of flow reductions (Figure 5). Sediment accrual in redds can limit recruitment (Alexander and Hansen 1986; Argent and Flebbe 1999), and adequate summer base flows coupled with occasional high flow pulses are important for preparing sediment free spawning redds (Hakala and Hartman 2004). DePhilip and Moberg (2010) demonstrated that the magnitude of withdrawals proposed by drilling companies in the Susquehanna River basin has the potential to impact summer and fall low flows, and in some cases, high-flow events (Q_{10}) in small streams.

Water withdrawals may also impact brook trout spawning activities and recruitment during higher flow periods (Figures 5 and 6). Brook trout peak spawning activity typically occurs at the beginning of November in gravel substrates immediately downstream from springs or in places where groundwater seepage enters through the gravel (Hazzard 1932). Withdrawals during the fall may dewater and reduce available spawning habitat, particularly during low-flow years. Additionally, stable base flows after spawning are necessary for maintaining redds during egg incubation throughout winter (Figure 6). Maintaining base flow in trout spawning habitats throughout the incubation period maintains shallow groundwater pathways, chemistry, and flow potentials in redds (Curry et al. 1994, 1995), which protect developing eggs from sedimentation (Waters 1995; Curry and MacNeill 2004) and freezing (Curry et al. 1995; J. S. Baxter and McPhail 1999). Thus, insuring that water withdrawals required for hydraulic fracturing do not interrupt stable winter base flows in small coldwater streams is an important consideration in protecting brook trout recruitment in the Marcellus Shale region (Figures 5 and 6).

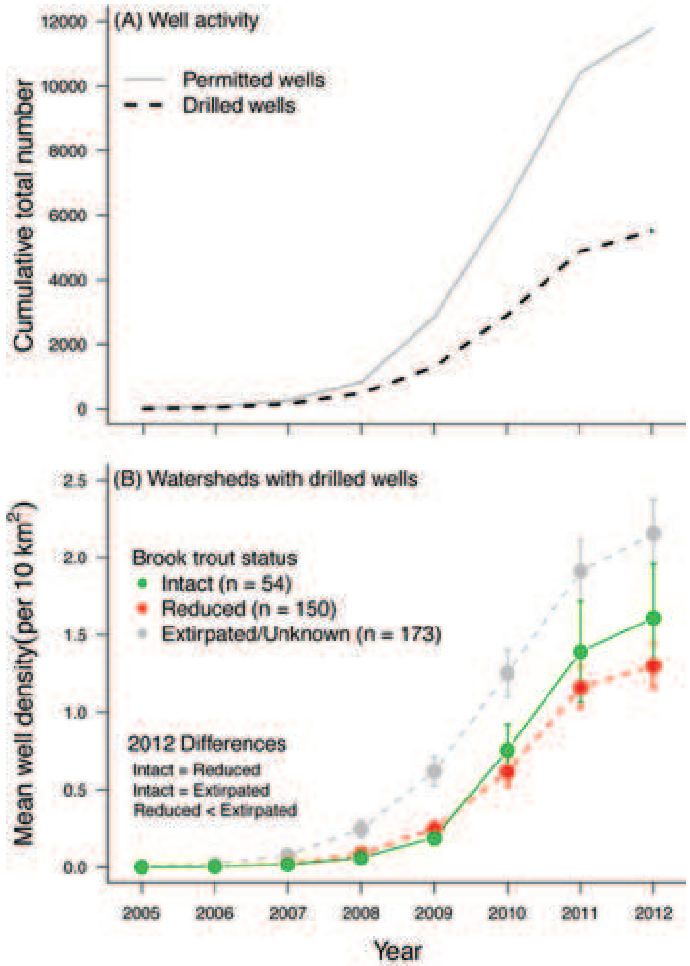

Figure 3. Well permitting and drilling in the Pennsylvania portion of Marcellus Shale from January 1, 2005, through May 31, 2012. (A) Cumulative number of permitted and drilled wells over time. (B) Mean well density (wells per 10 km²) over time for 377 actively drilled HUC12 subwatersheds, grouped by status of brook trout population (Hudy et al. 2008). Permitted and drilled Marcellus well data are from PADEP (2012a, 2012b), respectively.

PATHWAY #2: INFRASTRUCTURE → PHYSICAL HABITAT → BROOK TROUT

Natural gas extraction requires development of well pad sites and infrastructure for transportation and gas conveyance, which involves a set of activities that will likely have impacts on water quality and habitat quality for brook trout unless proper precautions and planning are implemented. These activities

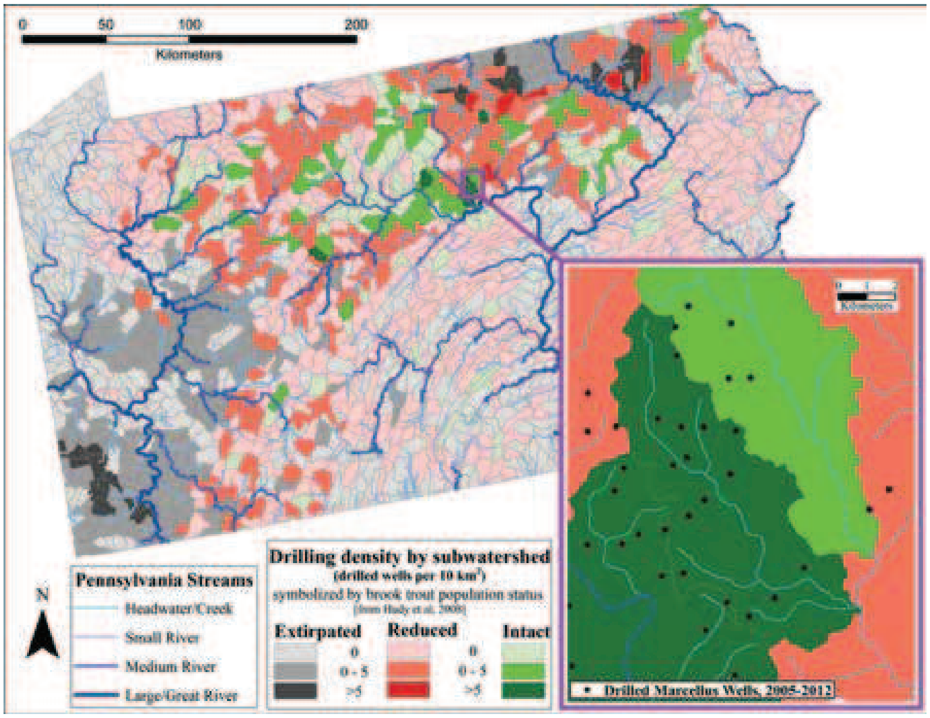

Figure 4. Density of wells drilled in the Pennsylvania portion of the Marcellus Shale by HUC12 subwatershed (well drilling locations from PADEP 2012b; 12-digit HUC subwatershed boundaries and areas from USGS Watershed Boundary Dataset; U.S. Department of Agriculture, Natural Resources Conservation Service 2012), symbolized by status of current brook trout population (Hudy et al. 2008). Inset: A subwatershed expected to support an intact brook trout population that currently has the second highest well density (15.1 wells/10 km2) of all drilled subwatersheds.

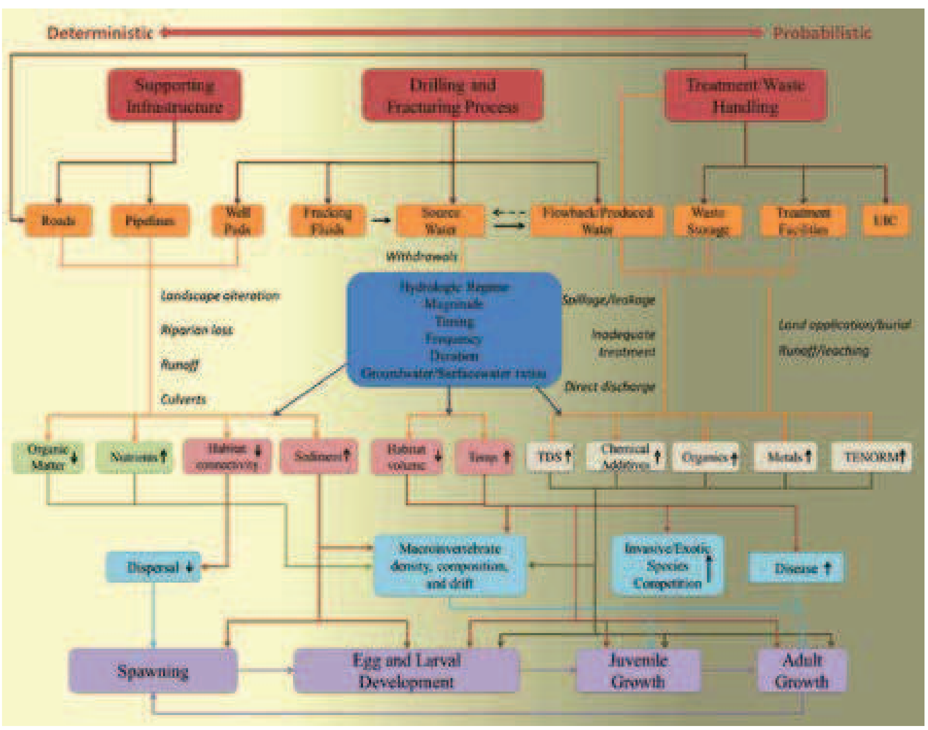

Figure 5. Conceptual model of relationships between hydraulic fracturing drilling activities and the life cycle of eastern brook trout (modified from conceptual models based on Entrekin et al. [2011] and Rahm and Riha [2012]).

include, but are not limited to, construction of well pads, roadways, stream crossings, and pipelines; increased use of existing rural roadways for transportation of equipment, source water, recycled flow-back, and wastes associated with hydraulic fracturing activities; and storage of these same materials (Figure 1). Increased sediment loads and loss of stream connectivity are some of the stream impacts associated with these deterministic activities, which could reduce habitat quality and quantity needed for brook trout spawning success, egg development, larval emergence, and juvenile and adult growth and survival (Figure 5).

Brook trout are particularly sensitive to the size and amount of sediment in streams, with coarse gravel providing a more suitable substrate than fine particles (Witzel and MacCrimmon 1983; Marschall and Crowder 1996). Well pad site, access road, and pipeline corridor construction require land clearing, which can mobilize from tens to hundreds of metric tons of soil per hectare (H. Williams et al. 2008; Adams et al. 2011). Pipeline construction (Reid et al. 2004) and unpaved rural roadways (Witmer et al. 2009) crossing streams can trigger additional sediment inputs to streams. Road and well pad densities have been found to be positively correlated with fine sediment accumulation in streams (Opperman et al. 2005; Entrekin et al. 2011), which disrupts fish reproduction and can lead to mortality (Taylor et al. 2006). Overall, trout populations have been found to decline in abundance, even with small increases in stream sediment loads (Alexander and Hansen 1983, 1986). Sediment can impact all stages of trout life cycles, because turbidity reduces foraging success for adults and juveniles (Sweka and Hartman 2001), and sediment accumulation can cause oxygen deprivation in salmonid redds and reduce successful emergence of larvae from eggs (Witzel and MacCrimmon 1983; Waters 1995; Argent and Flebbe 1999; Curry and MacNeill 2004; Figure 5).

The spatial and temporal extent of sediment impacts to streams is linked to the scale and persistence of mobilizing activities. For example, localized events, such as construction of culverts

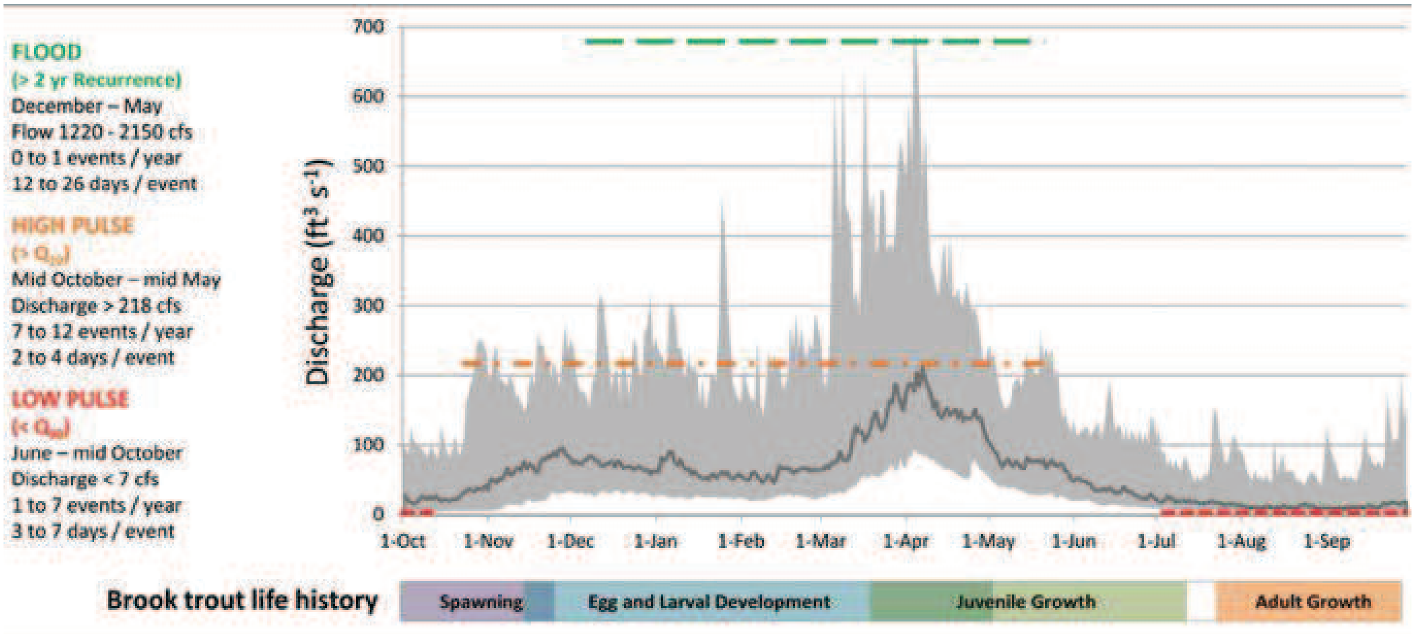

Figure 6. Hydrologic patterns for a trout supporting stream with relatively unaltered hydrology (Little Delaware River, USGS Gage 01422500, watershed area = 129 km2) in relation to timing of brook trout life history periods. Median (dark line), bounded by 10th and 90th percentile daily flows (grey) for 47 years of discharge data. Important flood, high-, and low-flow components were computed and described using Indicators of Hydrologic Alteration (The Nature Conservancy 2009).

at stream road crossings can increase sediment loads for up to 200 m downstream of the culvert over a 2- to 3-year period (Lachance et al. 2008). Conversely, the sediment loads associated with more diffuse land clearing activities and frequent and sustained access into rural areas by large vehicles can contribute to reductions in brook trout biomass and densities and shifts in macroinvertebrate communities that last approximately 10 years (VanDusen et al. 2005).

Sedimentation from drilling infrastructure development can further impact brook trout indirectly by reducing the availability of prey (Figure 5): high sediment levels reduce species richness and abundance of some aquatic macroinvertebrates (Waters 1995; Wohl and Carline 1996; VanDusen et al. 2005; Larsen et al. 2009), with high sediment environments generally experiencing a shift from communities rich in mayflies (Ephemoptera), stoneflies (Plectoptera), and caddisflies (Trichoptera) to those dominated by segmented worms (Oligochaeta) and burrowing midges (Diptera: Chironmidae; Waters 1995). Riparian clearing can also diminish food sources for brook trout populations, which tend to depend heavily on terrestrial macroinvertebrates (Allan 1981; Utz and Hartman 2007). However, shifts in the prey base from shredder-dominated communities that support higher brook trout abundance to grazer-dominated communities have been observed in recently logged watersheds due to higher primary productivity associated with increased sunlight from sparser canopy cover (Nislow and Lowe 2006). Consequently, land clearing and infrastructure development will likely increase sediment loads, culminating in changes in composition and productivity of the invertebrate prey base for brook trout, although not all of these changes will necessarily be negative for brook trout (Figure 5).

Conveyance of hydraulic fracturing equipment and fluids, and the extracted natural gas, into and out of well pad sites often necessitates crossing streams with trucks and pipelines. Culvert construction for roadway and pipeline stream crossings, if not properly designed, can create physical barriers that fragment brook trout habitat and disrupt their life cycle by preventing movement of adult fish into upstream tributaries for spawning and repopulation of downstream habitat by new juveniles (Wofford et al. 2005; Letcher et al. 2007; Poplar-Jeffers et al. 2009; Figure 5). Barriers to connectivity negatively impact fish species richness (Nislow et al. 2011), and habitat fragmentation without repopulation can cause local population extinction (Wofford et al. 2005; Letcher et al. 2007). Additionally, connectivity between larger stream reaches that provide food resources during growth periods and small headwater streams that may serve as temperature refugia during warmer months is important for overall population health (Utz and Hartman 2006; Petty et al. 2012). For these reasons, land clearing activities, road densities, and culvert densities can have a negative impact on trout reproductive activity and overall population size (Eaglin and Hubert 1993; C. V. Baxter et al. 1999).

PATHWAY #3: CHEMICAL WASTE → WATER QUALITY→ BROOK TROUT

Probabilistic events during the drilling process such as runoff from well pads, leaching of wastewater from holding ponds, or spills of hydraulic fracturing fluids during transportation to processing sites can affect the chemical composition of streams (Rahm and Riha 2012). Although the specific chemical composition of fracturing fluids is typically proprietary information, voluntary reporting of the content of fracturing fluids to the FracFocus Chemical Disclosure Registry (a partnership between the Ground Water Protection Council [GWPC] and Interstate Oil and Gas Compact Commission [IOGCC], supported the U.S. Department of Energy [USDOE]) has become more common (USDOE 2011). Fracturing fluids are generally a mix of water and sand, with a range of additives that perform particular roles in the fracturing process, including friction reducers, acids, biocides, corrosion inhibitors, iron controls, cross-linkers, breakers, pH-adjusting agents, scale inhibitors, gelling agents, and surfactants (GWPC and IOGCC 2012). The wastewater resulting from the hydraulic fracturing process is high in total dissolved solids (TDS), metals, technologically enhanced naturally occurring radioactive materials (TENORM), and fracturing fluid additives (U.S. Environmental Protection Agency [USEPA] 2012). Increased metals and elevated TDS from probabilistic spill events, or deterministic events including direct discharge of treated flow-back water into streams, will likely have negative effects on stream ecosystems that support brook trout populations (Figure 5).

Elevated concentration of metals causes decreased growth, fecundity, and survival in brook trout. In particular, aluminum has been shown to cause growth retardation and persistent mortality across life stages (Cleveland et al. 1991; Gagen et al. 1993; Baldigo et al. 2007), chromium reduces successful emergence of larvae and growth of juveniles (Benoit 1976), and cadmium can diminish reproductive success by causing death of adult trout prior to successful spawning (Benoit et al. 1976; Harper et al. 2008). Trout normally exhibit avoidance behaviors to escape stream reaches that are overly contaminated with heavy metals; however, because brook trout are so heavily reliant on low-temperature environs, they seek out refugia of cold groundwater outflow even if the water quality is prohibitively low (Harper et al. 2009). Thus, if groundwater is contaminated and the groundwater-fed portions of a stream are receiving a significant contaminant load, brook trout might be recipients of high concentrations of those contaminants.

Total dissolved solids represent an integrative measure of common ions or inorganic salts (sodium, potassium, calcium, magnesium, chloride, sulfate, and bicarbonate) that are common components of effluent in freshwaters (Chapman et al. 2000). Elevated TDS and salinity may have negative effects on spawning and recruitment of salmonids by decreasing egg fertilization rates and embryo water absorption, altering osmoregulation capacity, and increasing posthatch mortality (Shen and Leatherland 1978; Li et al. 1989; Morgan et al. 1992; Stekoll et al. 2009; Brix et al. 2010). There is also evidence from western U.S. lakes with increasing TDS concentrations that growth and survival of later life stages may be negatively impacted as well (Dickerson and Vinyard 1999). Elevated salinities can lower salmonid resistance to thermal stress (Craigie 1963; Vigg and Koch 1980), which may influence competition between brook trout and more tolerant brown trout (Öhlund et al. 2008). There is a growing body of evidence supporting associations between declines in macroinvertebrate abundance, particularly mayflies, and increased TDS or surrogate specific conductivity related to mining activities within the Marcellus Shale region (Kennedy et al. 2004; Hartman et al. 2005; Pond et al. 2008; Pond 2010; Bernhardt and Palmer 2011). Overall, changes in TDS associated with improper handling or discharge of flow-back water will likely impact brook trout through direct and indirect pathways including changes in macroinvertebrate communities that serve as the prey base and/or the alteration of environmental conditions to those more favorable for harmful invasive species (i.e., Golden algae; Renner 2009; Figure 5).

A FRAMEWORK FOR ADDRESSING RESEARCH NEEDS

Our examination of potential impacts of hydraulic fracturing for natural gas extraction in the Marcellus Shale on brook trout populations reveals three key pathways of influence: hydrological, physical, and chemical. These pathways originate from the various activities associated with the hydraulic fracturing method of natural gas extraction and may affect brook trout at one or more stages of their life cycle through direct and indirect mechanisms (Figure 5). The hydrological pathway is the broadest in that it is influenced by events at both the surface and groundwater levels and, subsequently, it influences brook trout both directly through flow regimes and indirectly by also influencing physical and chemical pathways. The primary drilling activity driving the hydrological pathway is the need for source water for the hydraulic fracturing process. The physical habitat pathway originates from the infrastructural requirements of the natural gas extraction industry, which can be expected to increase stream sedimentation and impede brook trout at all life phases. The consequences of infrastructural development further impact brook trout populations if road-building activities and poorly designed road-crossing culverts reduce connectivity between spawning areas, temperature refugia, and downstream habitats. Finally, the chemical pathway addresses the potential for contamination of streams by the hydraulic fracturing fluids and wastewater. This contamination can have direct consequences for brook trout and their food resources. The hydrological and physical pathways are expected to result from planned (deterministic) hydraulic fracturing activities, and the chemical pathway may be triggered by both unplanned spill and leak (probabilistic) events, as well as planned discharge of treated wastewater into streams or spreading of brines on roadways.

The delineation of these pathways identifies an array of immediate research priorities. The potential relationships identified in the conceptual model (Figure 5) provide a framework of empirical relationships between Marcellus Shale drilling activities, deterministic pathways, and brook trout populations that need to be tested and verified. There is currently variation in hydraulic fracturing density within the Marcellus Shale, ranging from extensive operations in Pennsylvania and West Virginia to a moratorium on the process in New York. Opportunities exist for researchers to develop studies that verify potential relationships between drilling activities and brook trout populations, such as examining sediment impacts and brook trout responses across watersheds representing a range of well densities (Entrekin et al. 2011) or over time in watersheds with increasing levels of drilling activity. Correlative studies should also be confirmed through experimental approaches that take advantage of paired watershed or before–after control-impact (Downes et al. 2002) designs. Tiered spatial analysis techniques can be used to assess the cumulative impacts of persistent drilling activity within nested drainage areas at a range of spatial scales (Bolstad and Swank 1997; MacDonald 2000; Strager et al. 2009). Additionally, risk assessment analyses based on biological endpoints are needed to characterize impacts of probabilistic events such as chemical spills and leaks (USEPA 1998; Karr and Chu 1997).

MOVING FROM RESEARCH TO MANAGEMENT AND CONSERVATION POLICY

Management of hydraulic fracturing activities in the Marcellus Shale is the responsibility of various permitting regulatory agencies with various scales of influence, including statewide (departments of environmental conservation/protection, departments of transportation, fish and game commissions, etc.) and regional (conservation districts, river basin commissions, etc.) entities. Though the individual policies are too numerous to describe in depth here, it is apparent that policies can be developed and refined with the support of research and monitoring programs that provide crucial data, such as a geographically finer scale understanding of brook trout distribution and population status, seasonal flow requirements for brook trout at their various life stages (Figure 6), identification and prioritization of high-quality habitat, and verification of the potential drilling impacts within the Marcellus Shale. These types of data are necessary for revising existing policies and developing new policies that are protective of brook trout populations and the stream ecosystems that support them in the face of increased Marcellus Shale drilling activities.

An example of science influencing policy that is protective of brook trout habitat is the current and proposed water withdrawal policies for the Susquehanna River Basin. The SRBC governs water withdrawal permitting for the Susquehanna River Basin region, and its policies have the potential to influence the degree to which hydrologic impacts of Marcellus Shale drilling may influence brook trout populations (SRBC 2002). The SRBC currently enforces minimum flow criteria for water withdrawals for hydraulic fracturing in coldwater trout streams to prevent low-flow impacts (Rahm and Riha 2012). The SRBC requires that water withdrawals must stop when stream flow at withdrawal sites falls below predetermined passby flows and cease until acceptable flow returns for 48 h. For small streams (<100 mile^2), passby flows are determined based on instream flow models (Denslinger et al. 1998) and are designed to prevent more than 5% to 15% change in trout habitat, depending on the amount of trout biomass the stream supports. A more general 25% average daily flow requirement is used as the passby flow for larger coldwater trout streams (SRBC 2002). This policy is expected to prevent water withdrawals from impacting habitats during low flows in summer. However, analyses of hypothetical withdrawals within the range of proposed water withdrawal permits suggest that water needs associated with Marcellus Shale drilling will impact seasonal flow needs (not just summer low flow) of small streams likely to support brook trout (DePhilip and Moberg 2010; Rahm and Riha 2012). Additionally, multiple upstream withdrawal events occurring on the same day within the same catchment may culminate in stream flows falling below the passby flow requirement. Though there is considerable uncertainty around water withdrawal estimates, accounting for cumulative withdrawal-induced low-flow effects can increase the number of days that are expected to fall below passby requirements for smaller streams by as much as approximately 100 days within an average year (Rahm and Riha 2012). Consequently, the SRBC has released new proposed low-flow protection regulations for public comment (SRBC 2012b, 2012c), based primarily on recommendations from a cooperative project between The Nature Conservancy, staff from the SRBC, and its member jurisdictions (DePhillip and Moberg 2010). The proposed SRBC flow policy uses a tiered approach to flow protection that prevents withdrawals or puts more stringent requirements in extremely sensitive or exceptional quality streams such as small headwater streams that support reproducing brook trout populations (SRBC 2012b, 2012c). This proposed policy would also provide significant flow protection for trout streams by incorporating seasonal or monthly flow variability into passby flow criteria rather than based on a single average daily flow criterion (Richter et al. 2011; Figure 6) and assessing proposed withdrawal impacts within the context of cumulative flow reductions associated with existing upstream withdrawals (Rahm and Riha 2012). However, the SRBC's proposed policy has received considerable critique from stakeholders, including the natural gas industry (SRBC 2012a). It is unclear what protections a revised water withdrawal policy will provide to streams that support brook trout habitat.

The SRBC policy is only one example of a regulatory body using scientific data to improve and refine a management policy that directly relates to potential drilling impacts on trout populations. It is crucial that policies governing hydraulic fracturing activities be likewise dynamic and subject to adaptation based on updated scientific knowledge. For example, the Pennsylvania *Oil and Gas Operators Manual* provides technical guidance for infrastructure development by identifying best management practices for sediment and erosion control and well pad, road, pipeline, and stream-crossing designs and delineates preventative waste-handling procedures to avoid unexpected probabilistic events like spills and runoff (PADEP 2001). These practices should be amended and updated as new studies refine methods to minimize impacts (e.g., Reid et al. 2004) and strategically protect or restore habitat quality or connectivity (e.g., Poplar-Jeffers et al. 2009). Furthermore, water quality data from monitoring efforts, like TU's Coldwater Conservation Corps (one of many stream survey programs that train and equip volunteers to conduct water quality testing in local streams; TU 2012) can alert regulatory agencies to failures in the probabilistic event prevention strategies that may help better characterize risks and improve waste transport and disposal procedures. For expansion of drilling in new areas, such as into New York State, regulatory agencies including the New York State Department of Environmental Conservation (NYSDEC), which is currently evaluating potential impacts of hydrologic fracturing activities and developing a corresponding set of proposed regulations (NYSDEC 2011), should utilize the most up-to-date and complete scientific data possible from active monitoring efforts to develop best management practices that are optimally protective of natural flow regimes, habitat conditions, and water quality in high-quality streams.

Spatial analysis and visualization of well density (Figure 4) can be combined with refined understanding of brook trout habitat and population status from stream surveys and groundtruthing to prioritize and geographically focus conservation efforts. Currently the Pennsylvania Fish and Boat Commission's Unassessed Waters Program in conjunction with Trout Unlimited and other partner organizations is conducting intensive assessments of streams with unknown brook trout status: to date, this program has identified an additional 99 streams that support wild populations (Weisberg 2011). Similar efforts are being spearheaded in New York by the NYSDEC and TU (2011). Furthermore, the efficacy of regulatory policy can be bolstered by data from monitoring and research efforts that define highest priority watersheds for conservation of brook trout. Various trout-focused organizations have identified key watersheds for protection and restoration. Trout Unlimited has updated their existing Conservation Success Index (J. E. Williams et al. 2007) with a targeted analysis for Pennsylvania to integrate new data on brook trout streams and natural gas drilling threats (TU 2011b). Likewise, the EBTJV has identified an extensive set of action strategies that identify priorities on a state-by-state basis (EBTJV 2011). Results from these types of analyses can be used to identify and direct conservation efforts to key areas where Marcellus Shale drilling activities are likely to have the greatest impacts by disturbing habitat for the highest quality remaining brook trout populations.

In summary, expedient efforts to develop strategies that minimize negative impacts of Marcellus Shale drilling activities on brook trout habitat are needed. Horizontal drilling and hydraulic fracturing for natural gas extraction is likely to increase and expand from Pennsylvania and West Virginia into unexploited areas with growing pressure related to economic incentives from the oil and gas industry and the need for cheap domestic energy sources. Natural gas drilling is expected to persist in the region for several decades due to the extent of the Marcellus Shale natural gas resource and the presence of the gas-rich Utica Shale below it (P. Williams 2008). Consequently, development of adequate management and conservation strategies based on science and enforcement of policies that conserve and protect stream ecosystems supporting brook trout populations and other aquatic organisms are needed to balance energy needs and economic incentives with environmental and brook trout conservation concerns.

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