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# Case Study Analysis of the Impacts of Water Acquisition for Hydraulic Fracturing on Local Water Availablility

**Office of Research and Development**
*National Exposure Research Laboratory*

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U.S. Environmental Protection Agency
Office of Research and Development
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# Disclaimer

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# List of Abbreviations

| | |
|---|---|
| ac-ft | Acre-feet |
| ASL | Above sea level |
| BLM | Bureau of Land Management (United States Department of the Interior) |
| CDF | Cumulative distribution function |
| CFS | Cubic feet per second |
| CMS | Cubic meters per second |
| CODWR | Colorado Department of Water Resources |
| COGCC | Colorado Oil and Gas Conservation Commission |
| CWCB | Colorado Water Conservation Board |
| EIA | United States Energy Information Administration |
| EPA | United States Environmental Protection Agency |
| FEMA | Federal Emergency Management Agency |
| ft | Foot |
| $ft^3$ | Cubic foot |
| GIS | Geographic information system |
| GUI | Groundwater use intensity index |
| gal | Gallon |
| HSPF | Hydrologic Simulation Program—Fortran |
| HUC | Hydrologic unit code |
| $m^3$ | Cubic meter |
| MG | Million gallons |
| MGD | Million gallons per day |
| MGY | Million gallons per year |
| mi | Mile |
| $mi^2$ | Square mile |
| NCDC | National Climatic Data Center |
| NLCD | National Land Cover Data Set |
| O&G | Oil and gas |
| NS | Nash-Sutcliffe efficiency score |
| PADEP | Pennsylvania Department of Environmental Protection |
| PADCNR | Pennsylvania Department of Conservation and Natural Resources |
| PAGWIS | Pennsylvania Groundwater Information System |
| PEST | Parameter estimation tool |
| PWS | Public water system |
| $Q_{7,2}$ | The lowest seven-day average flow that occurs once every two years at a river gage |
| $Q_{7,10}$ | The lowest seven-day average flow that occurs once every 10 years at a river gage |
| $Q_{mean}$ | Mean annual flow |
| RMSE | Root mean squared error |
| SRB | Susquehanna River Basin |
| SRBC | Susquehanna River Basin Commission |
| STATSGO | State Soil Geographic Database |
| SUI | Surface water use intensity index |
| UCRB | Upper Colorado River Basin |
| USDA | United States Department of Agriculture |
| USFWS | United States Fish and Wildlife Service |
| USGS | United States Geological Survey |
| WCD | West Conservancy District |
| WNS | Weighted Nash-Sutcliffe efficiency score |

# Units and Conversions

## Length

| To<br>From | Mi | km | ft |
|---|---|---|---|
| **mi** | 1 | 1.609 | 5,280 |
| **km** | 0.621 | 1 | 3,281 |
| **ft** | 0.0001894 | 0.0003048 | 1 |

## Area

| To<br>From | mi$^2$ | km$^2$ | acre | ha |
|---|---|---|---|---|
| **mi$^2$** | 1 | 2.590 | 640 | 259.0 |
| **km$^2$** | 0.386 | 1 | 247.1 | 100 |
| **acre** | 0.001563 | 0.004047 | 1 | 0.408 |
| **ha** | 0.003861 | 0.01 | 2.471 | 1 |

## Volume

| To<br>From | ft$^3$ | m$^3$ | gal | ac-ft |
|---|---|---|---|---|
| **ft$^3$** | 1 | 0.02832 | 7.481 | 0.00002296 |
| **m$^3$** | 35.315 | 1 | 264.2 | 0.0008107 |
| **gal** | 0.134 | 0.003785 | 1 | 0.000003069 |
| **Mgal** | 133,681 | 3785 | 1,000000 | 3.069 |
| **ac-ft** | 43560 | 1,233 | 325,848 | 1 |

## Flow Rate

| To<br>From | CFS | CMS | MGD | ac-ft/year |
|---|---|---|---|---|
| **CFS** | 1 | 0.02832 | 0.646 | 724.97 |
| **CMS** | 35.315 | 1 | 22.825 | 25,567 |
| **MGD** | 1.547 | 0.044 | 1 | 1,120 |
| **ac-ft/year** | 0.00138 | 0.00003911 | 0.0008927 | 1 |

# Preface

The U.S. Environmental Protection Agency (EPA) is conducting a study of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources. This study was initiated in Fiscal Year 2010 when Congress urged the EPA to examine the relationship between hydraulic fracturing and drinking water resources in the United States. In response, EPA developed a research plan (*Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources*) that was reviewed by the Agency's Science Advisory Board (SAB) and issued in 2011. A progress report on the study (*Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report)*, detailing the EPA's research approaches and next steps, was released in late 2012 and was followed by a consultation with individual experts convened under the auspices of the SAB.

The EPA's study includes the development of several research projects, extensive review of the literature and technical input from state, industry, and non-governmental organizations as well as the public and other stakeholders. A series of technical roundtables and in-depth technical workshops were held to help address specific research questions and to inform the work of the study. The study is designed to address research questions posed for each stage of the hydraulic fracturing water cycle:

- Water Acquisition: What are the possible impacts of large volume water withdrawals from ground and surface waters on drinking water resources?
- Chemical Mixing: What are the possible impacts of surface spills of hydraulic fracturing fluid on or near well pads on drinking water resources?
- Well Injection: What are the possible impacts of the injection and fracturing process on drinking water resources?
- Flowback and Produced Water: What are the possible impacts of surface spills of flowback and produced water on or near well pads on drinking water resources?
- Wastewater Treatment and Waste Disposal: What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources?

This report, Case Study Analysis of the Impacts of Water Acquisition for Hydraulic Fracturing on Local Water Availability, is the product of one of the research projects conducted as part of the EPA's study. It has undergone independent, external peer review in accordance with Agency policy and all of the peer review comments received were considered in the report's development.

The EPA's study will contribute to the understanding of the potential impacts of hydraulic fracturing activities for oil and gas on drinking water resources and the factors that may influence those impacts. The study will help facilitate and inform dialogue among interested stakeholders, including Congress, other Federal agencies, states, tribal government, the international community, industry, non-governmental organizations, academia, and the general public.

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# 1. EXECUTIVE SUMMARY

Hydraulic fracturing and its associated technologies have made vast reserves of oil and gas (O&G) economically recoverable in the United States, which has resulted in a surge of natural gas and oil production. Approximately 0.8 to 5 million gallons of water are typically used to complete each O&G well on average. As the number of hydraulic fractured wells increases across the United States, the need for water increases. Local water acquisition for hydraulic fracturing use has the potential to impact the quantity and quality of drinking water resources. The local consequences of water demand and acquisition on water quantity and quality are a function of water sources, users, permitting, and hydraulic fracturing technology dictated by geologic characteristics.

At the O&G well site, water is used during well construction and during the reservoir stimulation process. The hydraulic fracturing fluid is used to initiate and/or extend fractures and carry proppant into the fractures to hold them open. Water is the most commonly used base fluid for hydraulic fracturing. Injection volumes vary widely, with an average of 4 million gallons per well in the Marcellus Shale and 2.3 to 2.9 million gallons in the Piceance Basin, although how much of this is freshwater versus reused hydraulic fracturing wastewater depends on local conditions.

This study explored the impact of hydraulic fracturing water demand in two U.S. river basins where hydraulic fracturing operations have been widely implemented: the Susquehanna River Basin (SRB) in Pennsylvania (in the humid east) and the Upper Colorado River Basin of Colorado (UCRB) (in the semi-arid west). These two large river basins were chosen because they are naturally, economically, and socially important; and because they are focal points for natural gas extraction using hydraulic fracturing technology. The goal of this project was to investigate the water needs and sources to support hydraulic fracturing operations at the river basin, county, and local spatial scales and to place these demands in a watershed context in terms of annual and daily water availability. Through these analyses, the study confirmed that, at larger drainage areas in these two systems, hydraulic fracturing water demand has minimal impact on water availability and water quality. As spatial and temporal scale decreased, the potential for impact on water quality and quantity increased. However, water management strategies at the two study areas reduce the chance for realization of impact.

- A combination of factors determine whether hydraulic fracturing introduces imbalance in the relationship between water supply and demand in a region, including drinking water resources. These factors include available water resources and their capacity to yield water, industry needs influenced by geologic characteristics of rocks in each play, other user demands, and permitting or allocation controls.

- Minimal impacts to past or present drinking water supplies or other water users resulting from hydraulic fracturing water acquisition were found in either study basin due to unique combinations of these factors in each area.

- In the Susquehanna River Basin in Pennsylvania (SRB), there is little use of public water supplies (currently <8%) because water resources are well distributed and available year round and hydraulic fracturing operators have been able to develop unallocated sources. In SRB, there are times or locations when water sources can be stressed, but water is managed to prevent overuse and minimize risk at individual sources.

- Water in the Upper Colorado River Basin in Colorado (UCRB) is strongly seasonal and over-allocated, but unconventional gas production requires little freshwater as the industry is able to reuse large volumes of flowback and produced water instead. No municipal drinking water supplies are used for hydraulic fracturing in the areas studied within the UCRB.

Withdrawal impacts were quantified using a ratio between water use and available water volume: the water use intensity index, ranging between 0 and 1. Higher values indicate higher vulnerability to water withdrawal. The water use intensity indices were implemented for surface water (the SUI, or surface water use intensity index) and groundwater (the GUI, or groundwater water use intensity index). Water use data were gathered from publicly available databases from state, federal, and private sources. Surface water and groundwater volumes available for consumptive use were calculated using observations at U.S. Geological Survey (USGS) gage stations where available, or predicted from empirical areal-weighting techniques and Hydrologic Simulation Program Fortran Model (HSPF) stream flow simulations. Groundwater availability was associated with pump ratings at well fields and geohydrologic modeling. Analyses included use intensity calculations using actual observed hydraulic fracturing withdrawals, and hydraulic fracturing withdrawals at current and projected drilling rates.

The Marcellus Shale covers 95,000 $mi^2$ spanning Ohio, New York, West Virginia, Pennsylvania, and Maryland. It is currently the largest producing shale gas play in the United States. Its most productive dry gas portion underlies the Susquehanna River Basin (SRB), spanning Pennsylvania, New York and Maryland. As of 2014, water from rivers and streams withdrawn from water sources by operators (self-supplied) is the dominant source of water used for hydraulic fracturing activities, with public supplies currently providing approximately 8% of water. The Susquehanna River Basin Commission (SRBC) regulates water acquisition and issues permits to operators for individual withdrawal sites. Permits constrain the volume, rate, and timing of withdrawals. Permits assign daily withdrawal and pumping rate limits, and set river passby flow thresholds that halt withdrawals during low flows.

The water use intensity quantification approach based on the SUI index demonstrated that the relative effects of hydraulic fracturing withdrawals from streams were dependent on their size, defined by contributing basin area. Small streams that supply water to hydraulic fracturing operators had the potential for SUI of 0.4 or higher (withdrawal of 40% or more of available water) during all or most of the year. Based on measured flow records throughout the SRB, there was an increased probability of higher SUI at average daily withdrawal volumes in watersheds less than 10 $mi^2$. Watersheds up to 600 $mi^2$ had some increased level of vulnerability at maximum withdrawal volumes during infrequent droughts.

The water management system operated by SRBC is applied with the objective to provide water for all users while protecting ecological values. The system is effective in maintaining low use intensity at virtually all sites across a range of flow volumes. Water management in the SRB demonstrated that large withdrawals can be managed with hydrological predictive measures and data made available by USGS. Hydraulic fracturing operations do not currently provide a significant challenge to public water supplies at a regional, county or local scale in the SRB due in part to use of different water sources and in part to oversight that controls the large-volume withdrawals and industry use patterns that have distributed self-supplied water sources throughout a wide geographic area.

In the SRB, groundwater meets about 20% of the freshwater demand from the O&G industry, with a mixture of public and private self-suppliers. Given the higher yields and higher permeability required, these groundwater wellfields are located in the glacially deposited valley fill and alluvium of large rivers, like the Susquehanna River, and its smaller tributaries. The potential for cumulative impact on regional aquifers was shown to be unlikely. However, we examined the potential for local impact due to well drawdown and baseflow depletion at a representative public water supply in Bradford County and a private wellfield in Wyoming County. We did not find any observed or reported impact from hydraulic fracturing water acquisition on local domestic wells. Baseflow depletion was less than 10% under average flow conditions. The SRBC manages drawdown and baseflow depletion through its permitting process.

Based on use intensity expressed as the proportion of water source volume withdrawn, a concentration magnification approach was used to evaluate impacts on water quality in the SRB. This approach assumed that removing water for hydraulic fracturing upstream of pollutant discharge locations would concentrate pollutants. Results showed that for watersheds larger than 200 $mi^2$, pollutant concentrations would increase 10% or less and usually 1% or less due to reduced water volume. Water quality in watersheds smaller than 20 $mi^2$ was more vulnerable to withdrawal, with potential concentration magnification 2–10 times (although these smaller streams may be less likely to be permitted for effluent discharges). The vast majority of observed SUI values in the SRB were less than 0.02 (2%), suggesting that water withdrawal for hydraulic fracturing would have minimal impact on water quality.

The Piceance Basin (~7,250 $mi^2$) in western Colorado has a large volume of recoverable natural gas in low-permeability reservoirs within the Mesaverde formation. The Piceance contains one of the richest known oil shale deposits (not to be confused with shale oil or shale gas) in the world and is the focus of most ongoing oil shale research and development extraction in the United States, with an estimated 64 trillion gallons of in-place oil shale resources. According to the water use records maintained by the Colorado Department of Water Resources (CODWR), freshwater obtained for hydraulic fracturing is self-supplied with a mix of surface water and groundwater resources. Irrigated agriculture is the largest user of water in the Upper Colorado River Basin (UCRB). Water acquired for hydraulic fracturing in this region is highly concentrated within the tributary watershed of Parachute Creek located in the vicinity of the Parachute gas field (198 $mi^2$). Tributary streams and groundwater wells provide about 50% of hydraulic fracturing water demand in the area.

CODWR manages water in Colorado using a system of water rights, where water is allocated based on prior appropriations. The volume of water allocated exceeds available supplies in some locations at some times creating localized shortages. In the 1970s, O&G companies collectively acquired significant water allocations in the Piceance structural basin in anticipation of the need for very large volumes of water for extraction of hydrocarbons from oil shale with current technologies. A very small portion of these allocations are currently used for hydraulic fracturing for gas.

In the UCRB, hydraulic fracturing operators report a very high flowback volume of fluid returning to the surface following the hydraulic fracturing process and during production. The Piceance tight sands have natural water content, and produced water continues flowing from each well at a rate of approximately 140,000 gallons per well per year. Hydraulic fracturing operators collect and treat the high volume of flowback and produced water and reuse it for fracturing almost all new wells. Although the volume of fluid used per well is similar between the SRB and the UCRB, the high water recycling rate observed in the tight sands of the Piceance results in use of much smaller volumes of freshwater in this semi-arid region.

In Parachute Creek, a tributary to the Colorado River, hydraulic fracturing operators obtain water from small reservoirs and a groundwater well field. The impact of cumulative daily withdrawals in Parachute Creek, primarily by irrigators, generally had higher SUI than observed in the SRB. Many days (45%) had more than 10% of the available water withdrawn, and 16% of the days had more than 40% removed. The percent of water removed daily from small reservoirs within the watershed averaged 1 to 20%. The SUI values did not show a marked decrease with increasing basin area as observed in the SRB. This is because withdrawal rights tend to allocate more water in the lower portions of the watershed where irrigated agriculture occurs and water withdrawal volumes tend to increase faster moving downstream than streamflow accumulates, resulting in higher SUI values in some larger basins.

Scenario analyses in the Parachute and Roan Creek watersheds were performed in a complementary manner to that applied in the SRB, but with different hydraulic fracturing assumptions reflecting differences in freshwater use. Without the influence of irrigation, there was a strong pattern of increasing potential impact of water removal (higher SUI) with decreasing watershed size. The runoff rate in the semi-arid west is one-third that of the humid east, meaning UCRB watersheds must be larger than in the SRB to meet the same SUI thresholds. SUI dropped below 0.4 under current directional drilling rates when watersheds were larger than 30 $mi^2$; with horizontal wells drilled at current rates, the median 0.4 SUI threshold increased to a basin area of approximately 100 $mi^2$.

Demand scenarios were simulated in Parachute Creek using precipitation and streamflow from a historically dry year, 2012, and a historically wet year, 2011. In the wet year, median historical demand including water used for hydraulic fracturing, was generally met without issue. However, in the dry year, median historical demand throughout the basin could not be satisfied, and large federal reservoirs were called on to augment supplies, as they were designed to do.

In the UCRB, groundwater meets a small percentage of the freshwater demand from the O&G industry. We investigated one of the few private wellfields in Garfield County and explored the potential for local impact due to drawdown and baseflow depletion at this site. There were no known domestic water wells within the maximum predicted cone of depression of this wellfield. Baseflow depletion was less than 10% under average flow conditions. Colorado state appropriation law manages alluvial wellfield acquisition as tributary flow.

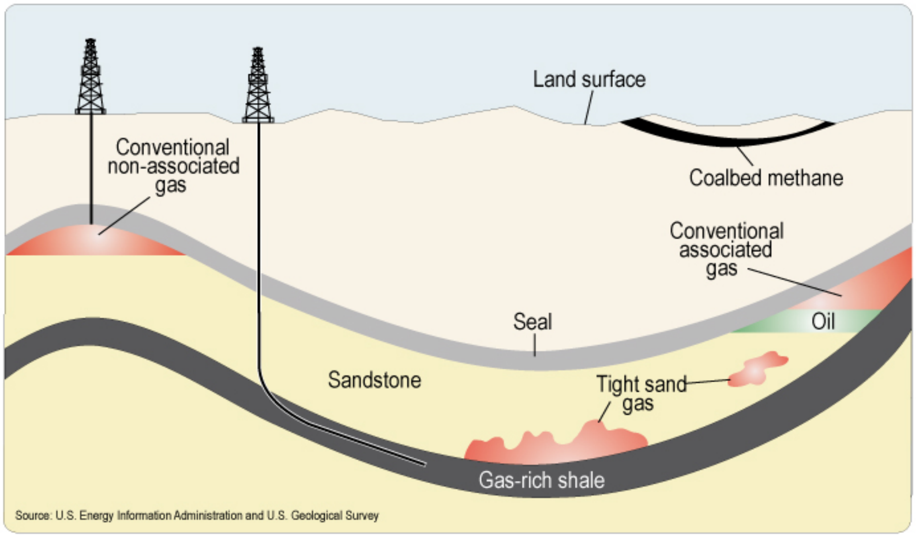
In summary, the potential for higher intensity use locally due to water acquisition for hydraulic fracturing was related to watershed size in both UCRB and SRB. Higher vulnerability (higher SUI values) was demonstrated in small streams ($\leq 10$ $mi^2$) during most of the year and in larger watersheds ($<600$ $mi^2$) during low flow periods. Higher use intensity calculated from observed hydraulic fracturing withdrawals, however, occurred only at a few sites on smaller streams in both basins, and localized high use intensity was found at only a few withdrawal locations. These results were similar, not because the required water volumes for hydraulic fracturing were minimal, but rather because emergent local consumptive factors limited the need for freshwater while management and hydraulic fracturing technology influenced withdrawal practices.

Water demands on limited water resources create potential for higher intensity use in the semi-arid Colorado River basin. However, the geology of this play results in large return volumes of hydraulic fracturing fluids that can be recycled and reused. Recycling rates of 100% are reported. A different story unfolds in the SRB, where surface water and groundwater reserves have not approached depletion, with less demands among users and withdrawals managed with daily and low flow restrictions.

A mosaic of factors that contributed to the outcome in each basin included water sources, users, permitting controls, and hydraulic fracturing technology dictated by geologic characteristics. These factors should be thoroughly understood to assess potential local impacts of hydraulic fracturing on water resources in other regions and for future hydraulic fracturing development in these same areas—results from one area do not readily transfer to another. However, the approach outlined in this report provides a methodology for assessing how water acquisition for hydraulic fracturing might impact water quantity and quality in other regions. These findings provide information to states, Tribes, communities, and industry to help understand the potential impacts of hydraulic fracturing on drinking water supplies, and the protection of those resources for the future.

# 2. INTRODUCTION

Shale and tight sand sedimentary deposits contain significant quantities of natural gas and oil that until recently were considered unrecoverable because of very low rock permeability, depth below surface, and thickness of geologic formations (Aydemir 2012; Cueto-Felgueroso and Juanes 2013). Recent advances in technologies have allowed economically viable gas and oil production from so-called "unconventional" deposits (Montgomery and Smith 2010; Clark *et al.* 2012) (Fig.2-1). Horizontal and directional drilling techniques steer the drill head to the thin layers of shale, coal bed, or tight sand deposits deep below surface, while hydraulic fracturing allows gas to flow by improving rock permeability. Together, these technologies have enabled a tenfold increase in natural gas production from shale and tight sand deposits in the United States since 2000 (U.S. EIA 2013a).



Source: U.S. Energy Information Administration and U.S. Geological Survey

**Figure 2-1. The technologies of deep horizontal and directional drilling that target resource rich sedimentary strata and hydraulic fracturing that increases permeability of the rock allow recovery of natural gas from unconventional shale and tight sand formations. (Source: U.S. EIA 2011a.)**

**The Process of Hydraulic Fracturing.** Wells are typically directionally bored, often thousands of feet, to tap the targeted gas-bearing formation. Rather than strictly drilling in a vertical direction, directional drilling deviates the wellbore along a planned path to a target located a given lateral distance and direction from vertical (Schlumberger 2014). Horizontal drilling is any wellbore that exceeds 80 degrees. During well construction, water is used in drilling fluids to maintain downhole hydrostatic pressure, cool the drill head, and remove drill cuttings (Clark *et al.* 2013). Once drilled, wells are cased with steel and cement and the producing intervals are then "stimulated" to release the gas or oil tightly held within the fine-grained matrices of the rock. The major need for water comes during the typically week-long stimulation phase, when large quantities of the base fluid (typically water) are mixed with a proppant and various chemicals are injected under high pressure to induce and maintain fracture openings (Clark *et al.* 2012; Soeder and Kappel 2009). The proppant is an inert material such as sand or ceramics that props the fissures and cracks open, allowing the hydrocarbons to migrate into the wellbore. The chemical mixture introduces friction reducers, scale inhibitors, and biocides into the well to maintain well functionality (Gregory *et al.* 2011). Some wells produce just gas or liquids, but a significant portion produce a combination of gas and liquids (U.S. EIA 2013a).

After the hydraulic fracturing procedure is completed and pressure is released, the direction of fluid flow reverses, and a portion of the water and excess proppant flow back through the wellbore to the surface, referred to as "flowback." Water may also continue to flow to the surface—along with the natural gas—for the life of the well. Some of this "produced water" is returned fracturing fluid and some is natural formation water. The returned fluid is of poor quality and is returned in volumes that can be substantial over time (Gregory *et al.* 2011; Maloney and Yoxtheimer 2012;

Wilson and VanBriesen 2012). We refer to both flowback and produced water as "hydraulic fracturing wastewater" in this report. How much hydraulic fracturing wastewater returns is highly variable among plays.

Well operations are centered at "well pads" where water is stored, chemicals are mixed, and flowback and produced water is collected and possibly treated for reuse (Fig. 2-2). Water is delivered to each well pad where it is stored in temporary reservoirs or tanks to be ready for hydraulic fracturing stimulation. Flowback water is collected and trucked away or reintroduced into other hydraulic fracturing wells. Operators can typically drill numerous horizontal wells radiating outward from one pad, reducing the construction footprint of pads and access roads on the landscape.

A significant portion of the United States has potentially recoverable dry natural gas or liquids within unconventional shale and tight sand formations (Fig. 2-3). Natural gas and oil production using hydraulic fracturing technologies is in the early phases of a decades-long build-out of a network of wells that will tap the 29 known commercially viable unconventional natural gas and oil reserves. These reserves (also termed "plays") underlie as many as 32 states in the United States (Entrekin *et al.* 2011; U.S. EIA 2011b) but do not follow state boundaries. The annual pace of well drilling and production has increased exponentially from 0.3 to 8.6 trillion cubic feet per year in the past 10 years and is expected to continue to increase in the coming decades (U.S. EIA 2013a).

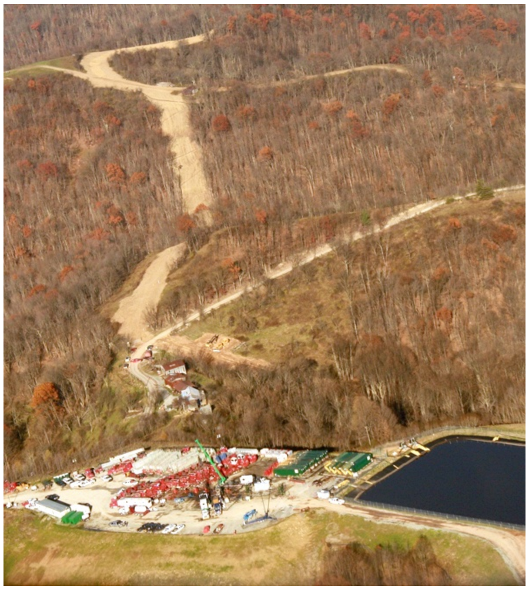


**Figure 2-2. Hydraulic fracturing well pad. (Photo by SkyTruth: aerial overflight provided by LightHawk.)**

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

**Figure 2-3. Location of unconventional shale gas plays in North America. There are also some gas fields in northern Alaska not shown on the map. (Map obtained from U.S. EIA 2011b.)**

**Figure 2-4. Left is a photograph of mature wellfield in the Uinta Basin, Utah. Well pads are 2 acres in size with a density (visible as small white squares) of 1 per 11 acres within this area. Large dark shapes are storage reservoirs of hydraulic fracturing wastewater. Right is a close-up of image on the left. (Images from Google Earth, Landsat.)**

Gas production at individual wells declines with time as the area around the wellbore is slowly drained. An individual well may yield gas for 20 or more years, though production lifetime of hydraulic fracturing wells and the need for re-fracturing is not fully established (Clark *et al*. 2012; Cueto-Felgueroso and Juanes 2013). To develop a play, O&G companies must drill the wells and link them to distant refining and distribution hubs through transmission lines, a sort of natural gas highway typically buried below ground that maintains the flow of gas to markets. To ensure a flow of gas from the play that meets customer demand, new wells must be drilled as older wells decline. This means that an area will experience episodic drilling and hydraulic fracturing to keep gas flowing, often infilling between existing wells. Oil and natural gas producers adjust their formation targeting in response to changes in the market value of natural gas and liquid hydrocarbons in an attempt to focus on the more profitable products in response to markets (U.S. EIA 2014a).

The final well density below ground is dependent on the characteristics of the rock formation. Projected below-ground well density in the Marcellus Shale in Pennsylvania is one well per 132 acres (U.S. EIA 2012). The directionally drilled wellfield in the Uinta Basin in Utah shown in Fig. 2-4 illustrates well pads spaced approximately 700 feet apart, yielding a surface and below ground density of one well per 11 acres, with apparently one pad supporting one well. A dense network of wells far below ground and well pads on the Earth's surface increasingly characterizes the landscape in these regions as build-out proceeds. Fig. 2-5 shows multiple directionally drilled wellbores below ground within the formation radiating outward from one well pad.

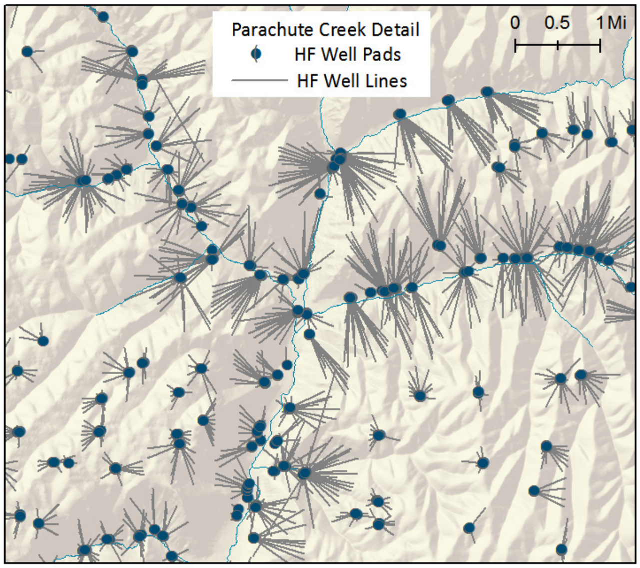


**Figure 2-5. Example of multiple subsurface directionally drilled wellbores radiating from each well pad. (Data source: COGCC 2013.)**

**How Much Water Is Needed for Hydraulic Fracturing?** The amount of water injected into wells for hydraulic fracturing varies significantly between areas, depending on the permeability of the rock formation and well design including length and depth of the wellbore (Gregory *et al.* 2011; GWPC 2009; Kargbo *et al.* 2010; Soeder and Kappel 2009). The amount of water consumed at individual wells also can vary widely between wells within each play. Hydraulic fracturing injection volume in the Marcellus Shale has averaged 4 million gallons per well but varies from 2 to 13 million gallons (Clark *et al.* 2012; Gregory *et al.* 2011; Nicot *et al.* 2014; Vengosh *et al.* 2014). This average per well volume is relatively similar among shale plays (Vengosh *et al.* 2014). It appears that relatively little additional freshwater is required during the life of the producing well, although this is not well established.

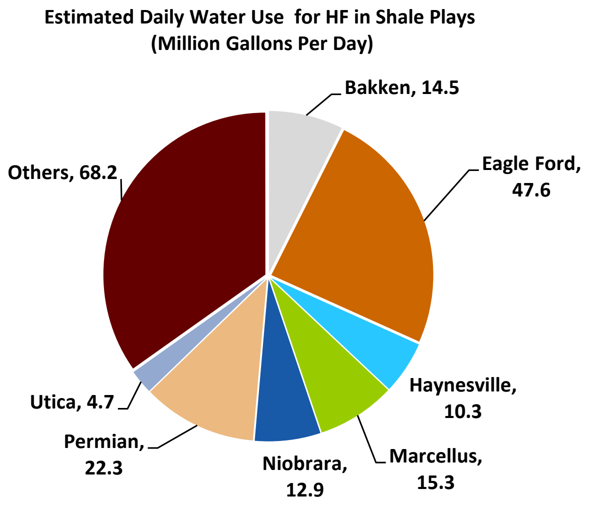


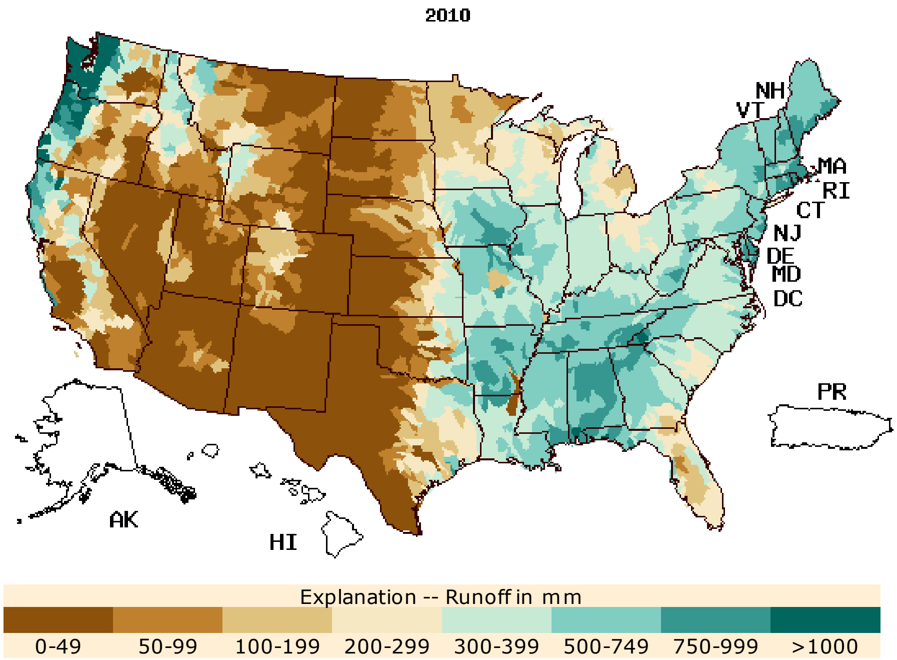
**Figure 2-6. Estimated daily water used for hydraulic fracturing in natural gas shale plays. Estimates are based on drilling rig counts. (July 2014: U.S. EIA 2014a.)**

At the play level, water use can be roughly estimated from drilling rig counts that drive the pace of hydraulic fracturing along with assumptions of drilling speed and injection volume. Annual water use in seven major plays and all others combined was computed assuming that each hydraulic fracturing well requires the average volume of water per well determined from the FracFocus national well registry (U.S. EPA 2015b), minus 8% reused wastewater. Well numbers were estimated from the distribution of drilling rigs in July 2014 (U.S. EIA 2014a) assuming that each rig drills between 1 and 1.5 wells per month. Water use estimates are very approximate, as the time required to drill a well and the needed water volume can vary significantly depending on rock material and length of the wellbore. Results expressed in million gallons per day (MGD) are shown in Fig. 2-6.

According to these assumptions, approximately 50 to 72 billion gallons of water are needed each year nationally to supply about 27,000 wells developed with hydraulic fracturing technology, with play-level demand ranging from 2 to 17 billion gallons. Nationwide, hydraulic fracturing uses 173 million gallons of water per day. Daily use varies from 5 to 48 million gallons per day (MGD) among plays with the most water use in the Eagle Ford play in Texas.

**Water Sources.** Hydraulic fracturing operators must obtain water from sources available in each area. Intrinsic water availability is highly variable at national, regional, and local scales. The physiographic setting of landforms, underlying geologic structure, climate, vegetation, and hydrography—coupled with societal investment in water storage and delivery infrastructure—create a varied array of potential water sources (Padowski and Jawitz 2012). These factors control the nature and extent of surface and groundwater resources available for use. Surface water resources far exceed current allocations in the humid eastern states but constrained in the semi-arid/arid southwest, which has less than a third of the annual runoff (Fig. 2-7A) and lower groundwater recharge rates. Many of the drier regions rely on large regional aquifers that have accumulated water over long time periods (Fig. 2-7B). Region-scale aquifers, such as the High Plains aquifer that underlies 173,000 $\text{mi}^2$ from Texas to South Dakota, are important water sources for agricultural and drinking water supplies in these regions (Reilly *et al*. 2008). Overexploitation of surface water and groundwater supplies is a concern for all users in water-scarce regions (GAO 2003), including areas with hydraulic fracturing (Nicot and Scanlon 2012). If the pace of hydraulic fracturing development continues or increases, there is potential for increased intensity of use of available water resources and competition for available supplies among users. Just as intrinsic water availability is not uniform spatially, water imbalance issues are not generally uniform within states or physiographic areas or over time (GAO 2003; Roy *et al*. 2005). Water imbalance is particularly disruptive in dry regions where water supplies are insufficient to meet demand (Bureau of Reclamation 2005, 2012) and where populations are large or increasing (CWCB 2011; GAO 2003). Periodic droughts draw attention to the limits of local and regional water supplies (Bureau of Reclamation 2005, 2012; GAO 2003, 2014; Kenny *et al*. 2009).

A) Surface Water Runoff



B) Groundwater Aquifers

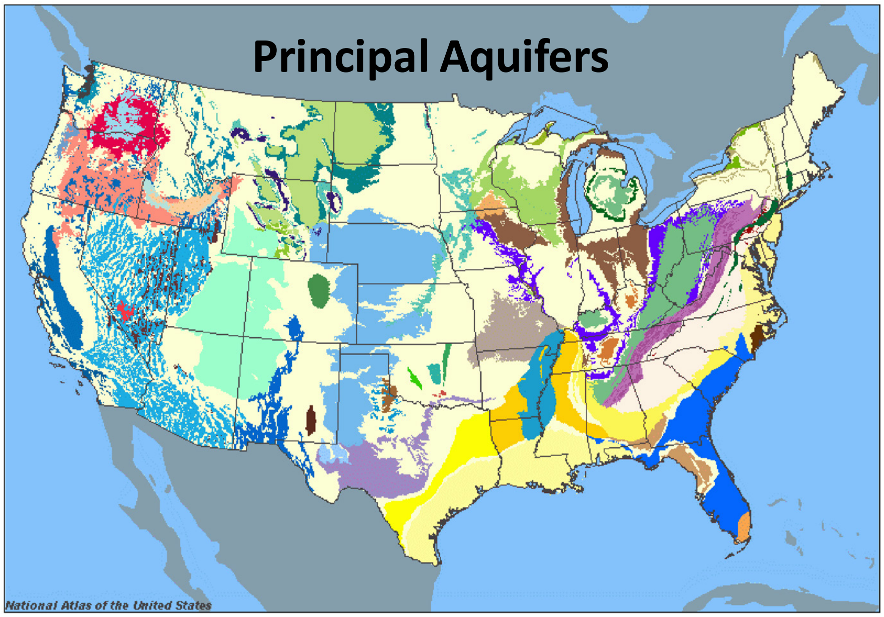


**Figure 2-7. Intrinsic variability of water resources within the United States. A) Estimated annual surface water runoff for October 1, 2009, through September 30, 2010 computed for each of the eight-digit hydrologic unit code cataloging units in the United States (Map source: USGS 2014c). B) Major groundwater aquifers of the United States (Map source: USGS 2003). Annual runoff is three to four times greater in the humid east relative to the semi-arid west. Regional aquifers are important water sources, especially in more arid regions, and vary in location, extent, and water quality.**

Hydraulic fracturing operators are likely to acquire water in the same places other users do. Water use statistics for 15 states with ongoing hydraulic fracturing development activity are shown in Figs. 2-8 and 2-9, with data taken from the U.S. Geological Survey (USGS) 2010 water census (Maupin *et al.* 2014). This group of states includes most of the hydraulic fracturing activity in shale gas and tight sands plays and have varying climate, water sources, and populations. Most water in these states, as elsewhere throughout the United States, is acquired for all uses from surface water sources, although some states, such as Texas and Arkansas, rely more heavily on groundwater (Fig. 2-8).

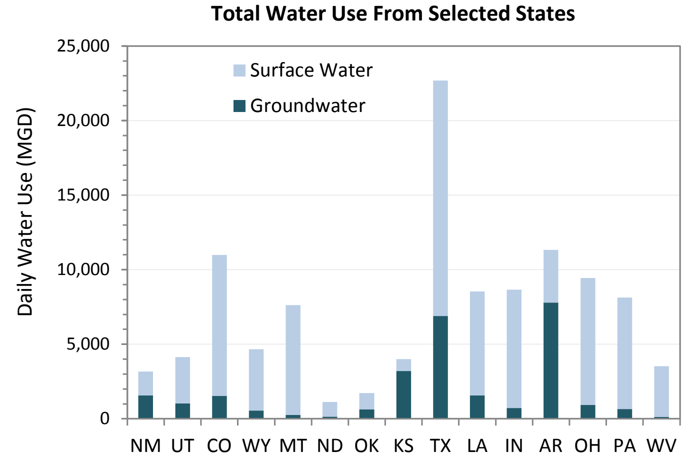


**Figure 2-8. Daily surface and groundwater usage by all user sectors in 15 states with unconventional oil and gas reserves in the 2005 USGS water census. States were selected as examples of varying climate, water sources, and population. (Data source: USGS data in Maupin *et al*. 2014).**

Because water quality is a less significant concern for hydraulic fracturing, lower quality water than that used for human consumption can be used (Vengosh *et al.* 2014). The need for freshwater can be partially mitigated by use of non-potable, brackish, or chemically contaminated water. Hydraulic fracturing wastewater can be used in other wells within the limits of the hydraulic fracturing technology. Hydraulic fracturing wastewater reuse is increasing, but availability varies between plays, reflecting the volume of flowback and produced water that returns to the surface, treatment and transportation costs, and availability of less-expensive water sources. This volume varies from as little as 5% of water injected into shales to as much as 80% injected into tight sands (Clark *et al*. 2012). Despite increased reuse, freshwater remains the dominant source of water for well stimulation in most plays (Nicot *et al*. 2014; Vengosh *et al.* 2014).

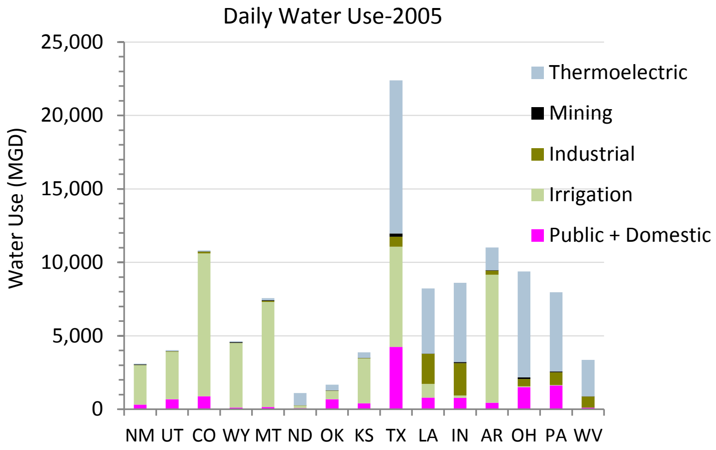


**Figure 2-9. Daily water use (surface and groundwater combined) by major sectors in selected group of states with unconventional gas reserves in 2005 water census. States are sorted from driest to wettest from left to right. Hydraulic fracturing water use is included in mining. (Data source: USGS water census data in Maupin *et al.* 2014.)**

### Water Use

Every region has its own portfolio of water in surface water and groundwater resources shared among users that have evolved over time, including drinking water supply, agriculture, industries, and power generation (Davis 2012; Kargbo *et al*. 2010; Kenny *et al*. 2009; Tidwell *et al*. 2012). Increasingly there is demand to provide water to support the viability of endangered species and aquatic and terrestrial ecosystems (GAO 2003; Roy *et al*. 2005).

Fig. 2-9 shows daily water usage by major user sectors in the 15 exemplar states. The combined water use for public and domestic water supplies is a relatively small portion of water consumption, but it is higher in states with larger populations. More than 86% of the U.S. population relies on public water supplies for household use, with that proportion increasing over time. As many as 43 million people, most living in rural areas, supply their own water from groundwater wells (Maupin *et al*. 2014). The majority of water in these states and others is used to produce food and electricity. Irrigation is the largest user in the drier western states, while thermoelectric power generation is the dominant user in the more populous eastern states (Kenny *et al*. 2009). The USGS includes any hydraulic fracturing water use in the mining user category. This category is such a small proportion of use in each state that it can barely be seen in the bars in Fig. 2-9.

When comparing play-level hydraulic fracturing water demand (Fig. 2-6) and state-level water use (Figs. 2-8 or 2-9), it is clear that hydraulic fracturing consumes a small fraction of water resources at this scale of assessment. Individual state-level water consumption for mining in the 15 exemplar states ranges from 1,300 to 23,000 MGD, hundreds of times greater than the hydraulic fracturing daily water use by play, which may span several states. Others have independently compared hydraulic fracturing to total state water use and arrived at a similar conclusion: hydraulic fracturing water use makes up less than 1% of state water use generally as documented in Texas (Nicot *et al*. 2014), Oklahoma (Murray 2013), and Pennsylvania (Arthur *et al*. 2010). Even if hydraulic fracturing drilling rates continue to increase, hydraulic fracturing water use is not likely to be a large component of any state's total water use.

**Hydraulic Fracturing Water Acquisition Is Unique.** While hydraulic fracturing water acquisition is not likely to affect the balance between water supply and demand at the national, state, or large river basin scale, it can have local impacts where the water is obtained (Nicot and Scanlon 2012; Nicot *et al*. 2014). Hydraulic fracturing has different water use requirements than most other industries. Operators need large quantities of water episodically in many different places spread over large areas. Water acquisition is spatially and temporally dynamic. The need for water is short-lived at individual well pads and regionally dependent on drilling rig activity. Within a play, there are typically multiple independent operators developing numerous wells at any time in widely dispersed areas with uncoordinated demands (Entrekin *et al*. 2011; Nicot *et al*. 2014).

The hydraulic fracturing industry acquires water differently than most other users. Most water is trucked from source to well, giving the industry high mobility and flexibility to acquire supplies close to where they will be used. Water is tapped at locations that are accessible with proper permissions, and supplies need only be sufficient to complete as few as one well at a time. The high cost of trucking water (as much as one-third to one-half of well drilling costs) encourages the industry to obtain water as close to hydraulic fracturing wells as possible (Arthur *et al.* 2010; Kargbo *et al*. 2010; Nicot *et al.* 2014).

Hydraulic fracturing operators are capable of withdrawing water from a variety of sources including rivers, streams, farm ponds, lakes, municipal hydrants, groundwater wells, and wastewater treatment plants (Brantley *et al.* 2014; Mitchell *et al.* 2013; Nicot *et al.* 2014). Stress on water supplies is more likely to arise locally than regionally because of this flexibility (Davis 2012; Entrekin *et al*. 2011; Freyman 2014; Nicot *et al*. 2014).

Where and how water is acquired is governed by state or regional authority (GAO 2003; Richardson *et al.* 2013). The doctrinary basis of many state laws (riparian vs. prior appropriation) varies in approach, regarding how water is allocated There are a variety of water laws and regulations overseeing water use, including allocation rules, management and technology requirements, reporting, and enforcement (Entrekin *et al*. 2011; GWPC 2009; Murray 2013; Nicot and Scanlon 2012; Richardson *et al*. 2013). This gives rise to variability in how the states manage water (GAO 2003).

**Figure 2-10. Most water is trucked from source to well pad in Bradford County, Pennsylvania.**

**Concerns About Increased Water Use to Supply Water for Hydraulic Fracturing.** Water use imbalance arises at the local level when the demand for water exceeds what is available in streams or groundwater aquifers within the time span of natural replenishment. Water use imbalance is less likely when there is larger volume at the source, or when the volume is withdrawn over a longer period. Water storage within the system alleviates short-term pressures during high-use or lower-flow periods, and some areas of the county have water delivery systems in places for storage and transfer of water to where it is needed. Use imbalance can be more consequential when water demands are higher, as when irrigation is active and surface water flow is naturally lower.

Locally, hydraulic fracturing operators can rapidly withdraw the necessary volumes of water from available surface or groundwater supplies. High use intensity resulting from these withdrawals is most likely in situations involving extraction from smaller volume sources such as headwater streams, small ponds, or domestic water supplies (Clark *et al*. 2012; Kargbo *et al*. 2010); cumulative withdrawals from proximal users (Dunlap 2011; Rahm and Riha 2012); withdrawals during episodic shortages, such as low flows or droughts (Arthur *et al*. 2010; Brantley *et al*. 2014; Mitchell *et al*. 2013); or withdrawal from sources that replenish slowly (GAO 2003).

Options for acquiring water depend upon volume and water quality requirements for each play, physical availability, competing uses, and water management. Not all options are available to hydraulic fracturing operators in all situations (API 2010), and there is likely to be considerable variability from state to state and play to play. Important factors that influence the potential impacts of hydraulic fracturing on water resources are climate as it determines available water sources, the portfolio of users, state and regional policies that oversee allocation and use, and the characteristics of the geologic plays that determine the hydraulic fracturing engineering practices deployed by the industry. State spatial scales do not provide sufficient granularity to detect effects given volume of use relative to state level use. County or finer levels may be more informative (Freyman 2014). Ultimately, the most useful assessments will match the scale of impact analyses to the water bodies where the water is taken.

**Research Needs.** While there is potential for local impacts with hydraulic fracturing water acquisition, there has been little study to verify whether impacts occur (Brantley *et al.* 2014). Nicot and colleagues (Nicot and Scanlon 2012; Nicot *et al.* 2014) have reported on hydraulic fracturing water use in the Barnett, Haynesville and Eagle Ford Shale plays in Texas, including water acquisition in the heavily populated Dallas-Fort Worth area. In Texas, water for hydraulic fracturing has been obtained from the same surface and groundwater sources relied on by most other users, including municipal supplies. The industry reduces some reliance on commonly shared freshwater sources by utilizing some brackish groundwater and hydraulic fracturing wastewater. At the county scale, water supplies for a few rural counties with small populations were considered most at risk, while depletion of important groundwater aquifers was considered a more widespread potential problem (Nicot *et al*. 2014). Hydraulic fracturing operators draw water from regional aquifers that are important sources of freshwater for municipal supplies and are considered depleted (Nicot *et al*. 2014). Localized analysis is hindered by difficulties obtaining necessary data at fine spatial resolution or specific to hydraulic fracturing activity relative to broader industrial use in many agency databases (Brantley *et al.* 2014; Hansen et al. 2013; Nicot *et al*. 2014; Perrone *et al.* 2011).

## 3. RESEARCH OBJECTIVES AND APPROACH

**Goals and Objectives.** The goal of this project was to investigate the water needs and sources to support hydraulic fracturing operations at the river basin, county, and site spatial scales, and to place this demand in the context of annual and daily water availability at water sources. Potential effects on water quality were estimated in the context of changes to water volumes. Recognizing the unique geography and geology of unconventional oil and gas (O&G) resources, the project adopted a case study approach within natural river basins.

**Study Areas.** The project was conducted in two study areas to explore and identify potential differences related to water acquisition: the Susquehanna River Basin (SRB), located in the eastern United States (humid climate) and overlying the Marcellus Shale gas reservoir, and the Upper Colorado River Basin (UCRB), located in the western United States (semi-arid climate), overlying the Piceance structural basin and tight gas reservoir (Fig. 3-1). These two river basins were among those studied for future climate change impacts on streamflow by the U.S. EPA (2013a).

The two study areas are similar in several ways. Both river basins are large (20,000+ $mi^2$) and important to the natural, economic, and social fabric of their regions. Each has considerable hydrocarbon reserves, an active oil and gas industry using hydraulic fracturing technologies, and productive natural gas wells with long term development prospects. Each has been targeted as a potential area of concern for hydraulic fracturing water acquisition in nationwide analyses (e.g., Freyman 2014). There are also many differences in factors that could influence the extent of hydraulic fracturing impact on water supplies. These include water management methods, existing water users, inherent water availability, and hydraulic fracturing technology required by the geologic formations.

The objective of the project was to understand and quantify the effects of water acquisition, with emphasis on drinking water supplies. Understanding drinking water supply impacts requires consideration of other water users as they can have a strong influence on the availability of water when they compete. Ecological water use is both affected by human water use and can limit supplies when ecological protection measures are invoked.

**Overview of Approach.** A basic premise of the project was that the water acquired for hydraulic fracturing would be insignificant at either the state or large basin scale relative to other existing uses. The working hypothesis was that impacts from hydraulic fracturing withdrawals are most likely to occur at the local sources where the water is acquired. Considerable project effort was applied to quantify how the oil and gas industry obtains water in each study area: How much water was withdrawn? Where and how often did this happen? How significant was the withdrawal relative to the volume at the source?

**Terminology.** We use the term “water use” to refer to water that is withdrawn for a specific purpose, such as for public supply, domestic use, irrigation, thermoelectric power cooling, mining, or industrial processing (Kenny *et al.* 2009). “Water withdrawal” or “acquisition” refers to water removed from the ground or diverted from a surface water source for use. This is the total amount of water removed from the water source, regardless of how much of that total is “consumptively” used, meaning not returned to the water resource system. For many uses, some fraction of the total withdrawal will be returned to the same or a different water source after use or treatment, and is then available for other withdrawals (Kenny *et al.* 2009). This project generally disregarded the consumptive use distinction by assuming that all freshwater used for hydraulic fracturing was 100% consumed. We use the term “freshwater” to refer to any water taken from water bodies, regardless of its water quality. Use of the term does not imply specific standards or drinking water quality. Our primary distinction in water sources based on water quality is between freshwater and hydraulic fracturing wastewater.

**Data Acquisition.** Two primary questions guided data collection:

- How much water was acquired from what sources for hydraulic fracturing?
- How much water was available at the sources where it was acquired?

The project gathered information on where and how much water was acquired in each study basin by querying publicly available databases from state, regional government, and federal data sources, augmented by databases maintained by private or nonprofit organizations. In characterizing water use, we emphasized direct monitoring of usage and minimally relied on county-scale water census data provided by the U.S. Geological Survey (USGS) that is not specific to hydraulic fracturing water use to understand other sector usage. In each area, we were able to develop good-quality information on local sourcing of water by hydraulic fracturing operators from agency records that likely included most if not all known withdrawal sites in the regulatory system.

Data acquired from state/regional/federal sources were used as obtained. We occasionally found what appeared to be data errors. Obvious mistakes were repaired, or the agency was consulted to verify or correct. Members of the project team visited each basin to familiarize researchers with the watersheds and to meet with representatives from government and industry, who provided insight to how hydraulic fracturing water acquisition works at the field level in each area. This included visits to acquisition sites, as well as some subsequent interaction to guide understanding of the data systems.

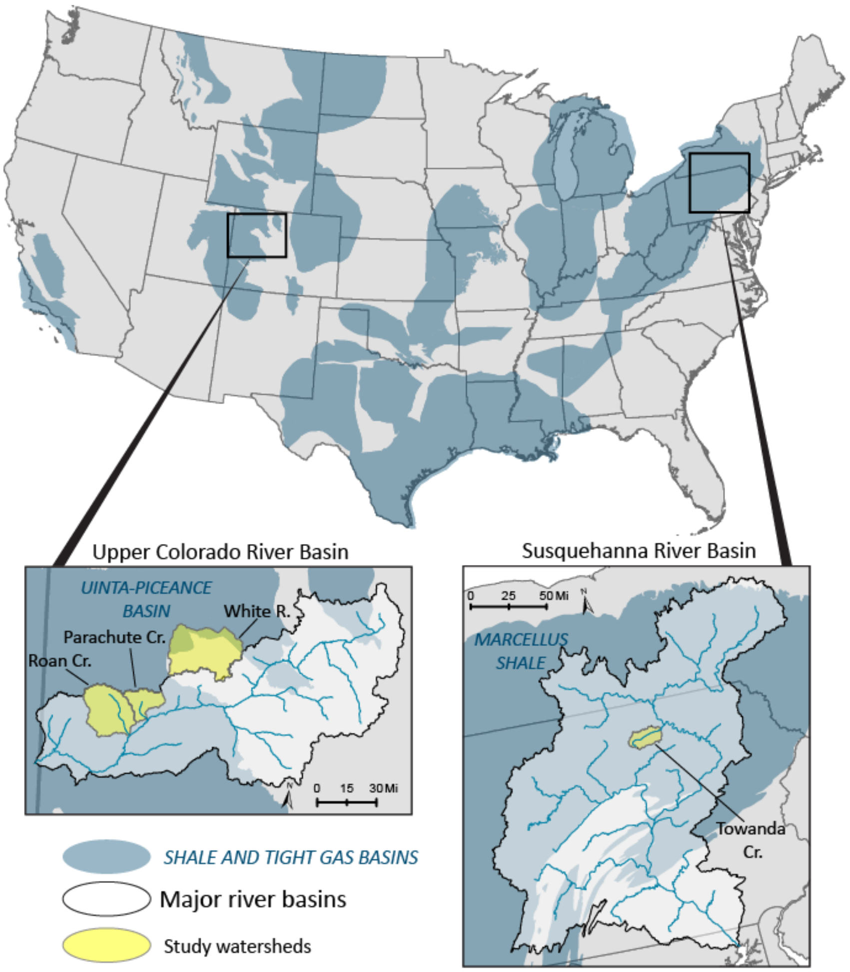


**Figure 3-1. Case study area location map. Major shale gas plays are shaded in blue. River basins include the Susquehanna River Basin (SRB) in the Marcellus Shale region and the Upper Colorado River Basin in the Piceance geologic basin in northwestern Colorado. Water acquisition in the SRB is studied in the Pennsylvania portion of the basin. Subbasins shaded in yellow were used for local analyses within basins, as described in each study area chapter. (Shale and tight gas basins data source: U.S. EIA 2014b.)**

**Analytical Approach.** The impacts of water withdrawals were characterized using the simple water balance approach applied by Roy *et al*. (2005), Reeves 2010, Tidwell *et al*. (2012), and Freyman (2014). A ratio between water withdrawn and the available volume of water quantifies the potential for water use imbalance, defined as:

$$\textbf{Water Use Intensity Index (WUI)} = \frac{\textbf{Water Use}}{\textbf{Available Volume}}$$

**Equation 3-1. General water use intensity index**

We adopt the terminology "water use intensity index" following Reeves 2010 and Weiskel *et al*. 2007. The water use intensity index ranges between 0 and 1.0 and is dimensionless. The water use intensity index is simply the proportion of water removed from the source. Water withdrawn is the volume removed from the source, and available volume is the volume of water in the water body at the location of withdrawal in a relevant time-step. Daily was the minimum practical time-step for calculating the water use intensity index. This analysis was performed at individual sites withdrawing from surface water and groundwater sources. An index was computed for each:

$$\textbf{SUI} = \frac{\sum \textbf{SW Water Withdrawn Volume or Flux}}{\textbf{Available Surface Water Volume or Flux}}$$

**Equation 3-2. Surface water use intensity index**

$$\textbf{GUI} = \frac{\sum \textbf{GW Water Withdrawn Volume or Flux}}{\textbf{Available Groundwater Volume or Flux}}$$

**Equation 3-3. Groundwater use intensity index**

The water use intensity metric proved useful for characterizing local water acquisition. It allowed expression of the relative proportion of water taken in short time intervals and in terms relevant to other water users, including ecological resources. It could be readily quantified, consistently applied, and assessed on a daily basis and at every level of flow. At the same time, it could be related to common flow frequency metrics. It has been used by researchers understanding the nexus between energy and water (e.g., Tidwell *et al*. 2012) and others characterizing impacts of water use (Reeves 2010, Freyman 2014). As will be shown, it provided a direct means to statistically quantify effects on streamflow impact, and it could also be directly translated to water quality impacts.

The water use intensity metric provided a scalar of potential impact. Clearly, when consumption is high relative to available volume (i.e., SUI or GUI approaches 1.0), there is greater risk of over-withdrawal, with potential impact on other users. The index level where impact occurs may differ for each type of user; therefore we propose no particular threshold value of concern. In comparing consumption to availability, some have referenced values as low as 0.4 (Freyman 2014; Hurd *et al*. 1999), 0.5 (Richter 2014), while others have referenced values as high as 0.7 (Tidwell *et al*. 2012).

**Water Availability.** An estimate of the volume of water in a water body was needed to perform the water use intensity calculation. USGS streamflow data were the primary source of information on water availability. We applied various techniques to estimate daily streamflow volume at ungaged withdrawal locations based on gaged sites. These included a combination of empirical and hydrological modeling that were used as needed given the availability of weather and streamflow data in each area. The water use intensity index calculation did not require high precision in flow estimates.

HSPF and SWAT are hydrologic models available for estimating daily streamflow. Each is a widely used deterministic model that produces a watershed streamflow hydrograph on a daily or finer time-step while accommodating some of the spatial and temporal variability in land use, vegetative cover, and soils that influence streamflow response to precipitation. Calibration steps were important to ensure that a good match to known streamflow records was achieved. We worked with both models, finding strengths in how each performed certain tasks in the process of watershed hydrological modeling. Ultimately, we relied primarily on HSPF for streamflow prediction, because it was computationally more conducive to the Monte Carlo approach we used for calibration and uncertainty analysis. We were also interested in potential impacts of hydraulic fracturing withdrawals on groundwater resources in the case study areas, so we used the groundwater model GFLOW™ to evaluate and visualize groundwater volumes and flux. Streamflow at gaged locations was also directly extrapolated to ungaged sites using an empirical approach based on area-weighting when appropriate. The empirical and modeled hydrologic data allowed computation of SUI and GUI at individual withdrawal sites.

**Water Quality**. Water quality was not measured in this study. Possible impacts to water quality were assessed in the context of the relationship between water volume and chemical concentration.

**Overview of Analyses.** Each case study featured three types of analyses. First, the water use data were accessed, compiled, and analyzed. From these data we developed facts, analyzed patterns, and summarized information at a variety of scales from local to basin-wide. The facts of water acquisition were summarized and are presented as an important product of this research. These data were then used to apply the water use intensity analytical approach to systematically quantify the water balance effects of observed hydraulic fracturing withdrawals on water bodies. Finally, scenario analyses were applied to reduce gaps related to water bodies, climate conditions, or levels of hydraulic fracturing activity that were not well represented in observed hydraulic fracturing withdrawals in each study area. The scenario analyses were typically focused in selected areas within the larger river basins, in a process that involved applying hydraulic fracturing withdrawal assumptions to lengthy (26-yr) hydrological records. Hydraulic fracturing activity has been ongoing in each study area sufficiently long to use observed usage patterns as a foundation for future water acquisition scenarios. The scenario analyses were designed to improve the project's ability to provide more generalized answers to its charge questions that could be applied beyond the study areas.

**Deviations of Project from Outline in the EPA 2012 Progress Report.** EPA's water acquisition project initially took a top-down approach to assessing water acquisition impacts by emphasizing watershed modeling and scenario analysis at the large basin scale, with some exploration of selected local areas within them as described in U.S. EPA (2012a). In 2013, EPA received feedback on the approach from the Science Advisory Board peer review panel and through technical workshops that encouraged greater focus on local effects. As a result, the project increased emphasis and data gathering on local hydraulic fracturing water acquisition, including water management practices that guide water allocation and industry practices that influence how much water is used and how it is sourced. This report incorporates a bottom-up approach stimulated by public input while applying the overall strategy outlined in U.S. EPA (2012a). The project has followed EPA's hydraulic fracturing Quality Management Plan (U.S. EPA 2012b, updated in 2014) and the quality assurance project plan for Project 5b (U.S. EPA 2013b).

A main goal of the project was to generate information from the case study areas that would have general relevance beyond the borders of the study areas and to properly account for climate fluctuations in representing effects on water availability. Specific hydraulic fracturing consumption scenario analyses were proposed to ensure that a range of potential hydraulic fracturing water demand with feasible drilling rates and potential reduction in demand through reuse were considered. We conducted our analysis in the context of climate variability and examined a much wider range of stream sizes and water body types than anticipated in U.S. EPA (2012a). With the greater emphasis on local information gathering, we adapted the scenarios to the local use patterns and projections in each study area. We also evaluated the potential for localized groundwater impact.

**About the Project Report.** Findings and analysis in each case study area are provided in chapters dedicated to each basin. Chapter 4 reports analysis of the Marcellus/Susquehanna River and Chapter 5 reports analysis of the Piceance/Upper Colorado River. These chapters describe data sources, analysis, empirical findings, and scenario analysis results. Chapter 6 summarizes and synthesizes finding from the two areas, emphasizing general similarities and differences and addressing the project charge questions. Data sources and quantitative methods used in each case study area are described relatively briefly in each chapter. Additional detailed information is provided in four appendices: a complete list of data sources and source information (Appendix A); a complete description of surface water hydrology methods, including hydrological modeling calibration and uncertainty analysis (Appendix B); a detailed description of groundwater hydrology methods, including GFLOW model calibration, uncertainty analysis, and findings (Appendix C); and additional detailed data and assumptions on water use applied in scenario analyses (Appendix D).

This report uses English units of measurement: water volumes are reported as gallons (gal), or millions of gallons (MG) for large numbers. We found that the case study areas were oriented to different units of measure, so we also provide volumes in acre-feet (ac-ft) in parentheses when discussing large volumes. Flow rate is expressed as cubic feet per second (cfs) as reported by USGS gage records, often translated to million gallons per day (MGD) to accommodate comparison with withdrawal volumes. (One cfs equals 0.646 MGD.) Area is expressed in square miles ($mi^2$). Large-volume water use data are rounded to three significant figures. All values are rounded independently, so the sums of individual rounded numbers may not equal the totals. Percentage changes discussed in the text are calculated from the unrounded data and are expressed as integers. All population data are rounded to two significant figures. All statistics and graphing were performed with R Statistical Software, version 3.0.1 (R Core Team 2013) or Microsoft Excel (2007).

# 4. MARCELLUS SHALE/SUSQUEHANNA RIVER BASIN

## Marcellus Shale Geologic Setting

The Marcellus Shale underlies nearly 95,000 $mi^2$ of the states of Ohio, New York, West Virginia, Pennsylvania, and Maryland (Fig. 4-1). The potential gas production from the Marcellus Shale makes it an important play for the nation's energy future, as it may contain as much as 363 trillion $ft^3$ of recoverable gas—enough to supply the needs of the entire nation for 15 years at the current rate of consumption (Soeder and Kappel 2009). The Marcellus is currently the largest producing shale gas basin in the United States, accounting for almost 40% of U.S. shale gas production after seven years of development (Fig. 4-2; U.S. EIA 2014c).

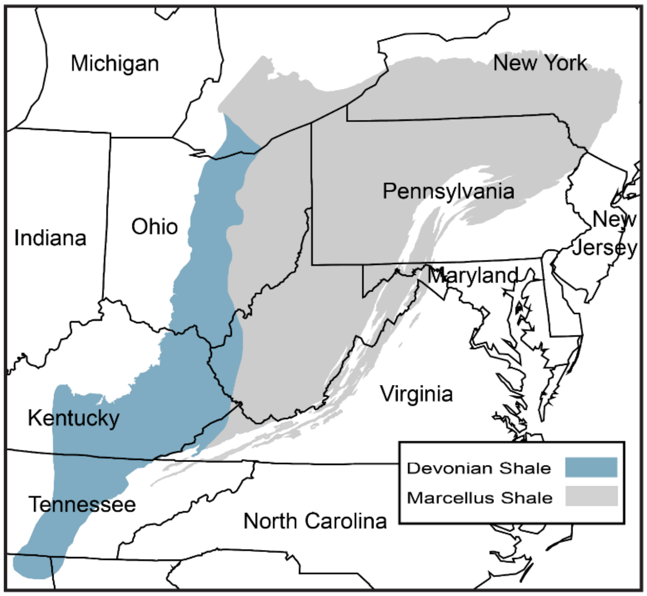


**Figure 4-1. Location of the Marcellus Shale and the Devonian Shale. (Map modified after Milici and Swezey 2006).**

The Marcellus Shale is composed of fine-grained sediments deposited as an organic-rich mud in a shallow inland sea that covered most of the North American continent over 350 million years ago during the Devonian period (Soeder and Kappel 2009). Sediments were transported westward from the Acadian orogeny, located approximately where the Appalachian Mountains now stand (Dott and Batten 1981). The basin deposits are shown schematically in Fig. 4-3. The Marcellus Shale was deposited across the Appalachian Basin before burial by an influx of younger continentally derived sediments (Fig. 4-3A). The basin floor subsided under the weight of sediment, resulting in a wedge-shaped deposit where the organic layer thins from east to west (Fig. 4-3B). Hydraulic fracturing gas extraction targets the basal organic rich layer that ranges in thickness from 150 to 300 feet and lies 4,000 to 7,000 feet below the earth's surface across the play.

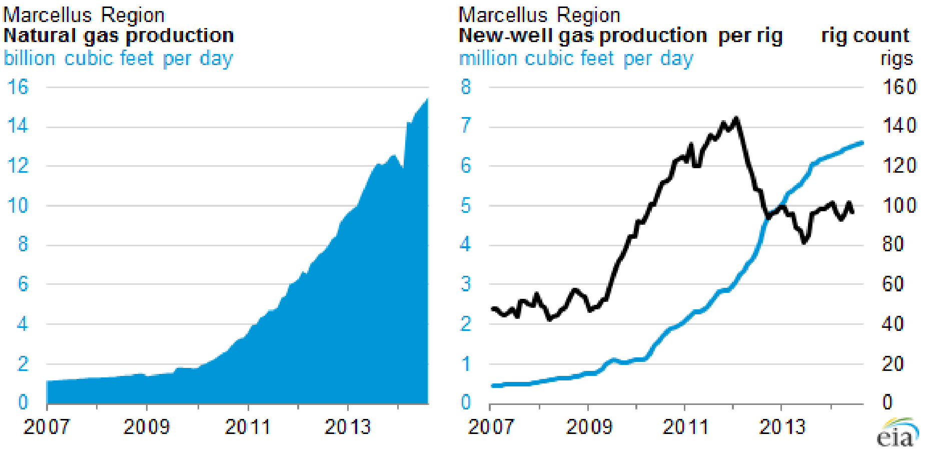


**Figure 4-2. Natural gas production in the Marcellus Shale. Natural gas production has increased rapidly since 2009. (Source: U.S. EIA 2014c.)**

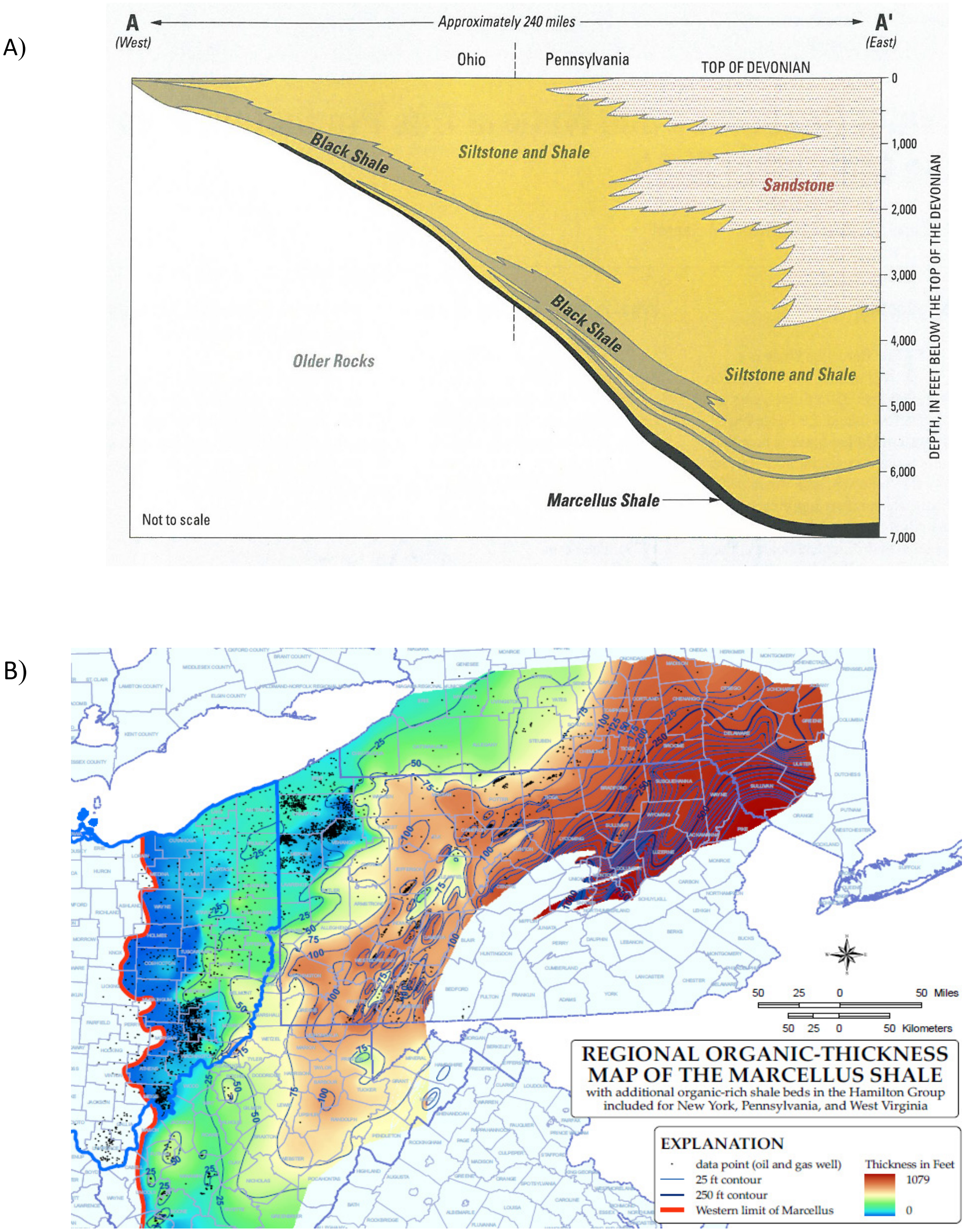


**Figure 4-3. Characteristics and extent of the Marcellus Shale, A) Thickness of the vertical depth to 7,000 feet. (Source: Soeder and Kappel 2009.) B) Surface area and thickness of organic-rich deposits targeted for hydraulic fracturing drilling. (Map source: Erenpreiss *et al*. 2011.)**

## Susquehanna River Basin Background

The most easterly and productive dry gas portion of the Marcellus Shale formation underlies the Susquehanna River Basin (SRB) that drains much of central Pennsylvania and portions of New York and Maryland into the Chesapeake Bay (Fig. 4-4). About 85% of the 27,510 mi$^2$ watershed is underlain by natural gas shale (Arthur *et al.* 2010), and this area has been a focal point for hydraulic fracturing in the Marcellus Shale (Vengosh *et al.* 2014).

**Hydraulic Fracturing and Drilling Activity**. Within the SRB, dry gas drilling activity has been centered in north central Pennsylvania. The earliest exploratory wells were drilled in the SRB in 2005 and production began in 2008 (Fig. 4-5). Drilling peaked in 2012 at 836 wells. Approximately 3,000 wells have been completed in the SRB since 2008 according to records provided by the Susquehanna River Basin Commission (SRBC) who tracks drilling activity and manages water use in the SRB. Most wells are located within a 17 county area that lies wholly or partially in the SRB. The Pennsylvania Department of Environmental Protection (PADEP) manages water use elsewhere in the state (2013b), as well as oil and gas extraction.

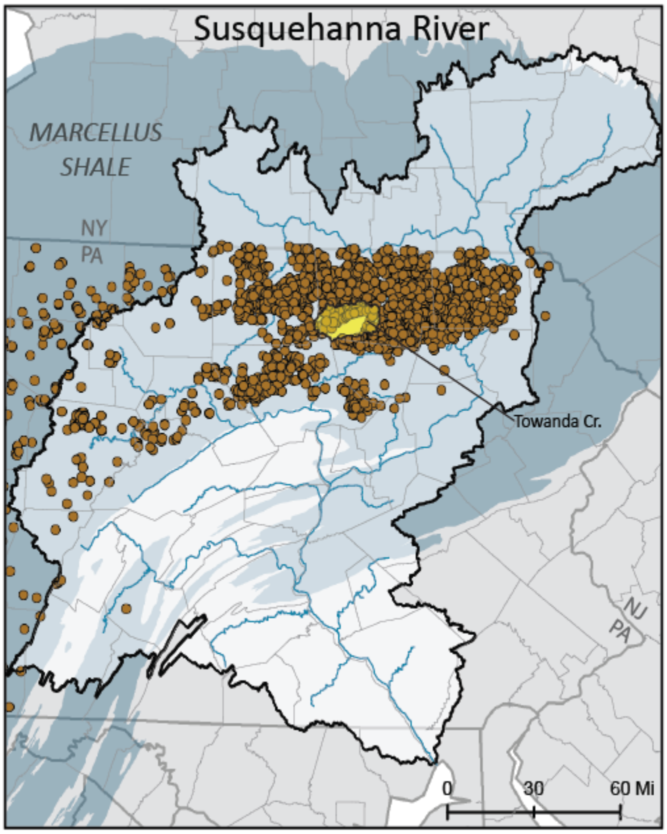


**Figure 4-4. Map of the Susquehanna River Basin, Marcellus Shale (blue shading), and location of drilled wells. (Data source: PADEP 2013a.)**

Annual drilling rates depend on economics. The current annual drilling rates are low relative to projections of future activity as 43,000 wells are expected over the next two decades (Johnson 2010), although realized drilling activity will depend on economics. Well density could reach 1 per 132 acres (U.S. EIA 2012b), and the annual drilling rate could reach 2,800 wells if this projection is realized (Beauduy 2009).

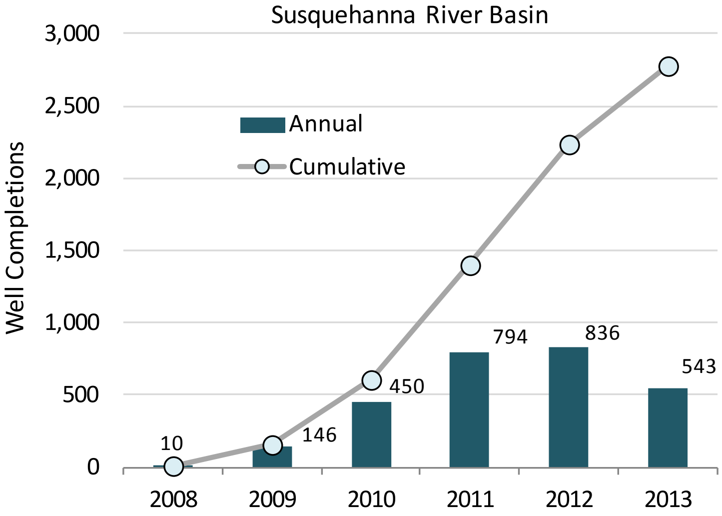


**Figure 4-5. Annual and cumulative well completions within the Susquehanna River Basin. (Data source: SRBC 2013a.)**

**Table 4-1. Statistics on injected and returned fluid volumes per well in the Susquehanna River Basin from 2008 to 2011 (n = 748). (Data source: SRBC 2013a.)**

| Hydraulic Fracturing Fluid Characteristics | Mean | Median |
|---|---|---|
| Total hydraulic fracturing water use (million gallons) | 4.25 | 4.31 |
| Total freshwater volume (million gallons) | 3.85 | 3.88 |
| % acquired water volume in injection fluid | 89.1% | 91.9% |
| % hydraulic fracturing wastewater in injection fluid | 13% | 8% |
| % flowback water returned | 7.3% | 4.7% |

SRBC tracked the volume of freshwater and hydraulic fracturing wastewater consumed at 748 individual hydraulic fracturing wells from 2008 to 2011. Mean and median volumes are reported in Table 4-1. Average hydraulic fracturing fluid volume injected into each well is 4.3 million gallons (MG), with about 13% composed of reused hydraulic fracturing wastewater. Available hydraulic fracturing wastewater is largely reused in the Marcellus Shale (Maloney and Yoxtheimer 2012), and return flow is 8% to 12% of what is injected. The portion of hydraulic fracturing wastewater reuse in the SRB is similar to other shale gas formations as reported by Vengosh *et al.* (2014).

**Geology, Hydrology and Climate.** The SRB is a major tributary to the Chesapeake Bay, contributing 25,000 million gallons per day (MGD) of freshwater to the bay on average. The climate in the SRB is classified as “cold humid” in the revised Köppen-Geiger classification system (Kottek *et al.* 2006). Long-term average precipitation ranges from 37 to 43 inches per year (McGonigal 2005). Rainfall is evenly distributed throughout the year, with the lowest average monthly rainfall in February (~2 inches) and the highest in July (~4 inches) (Arguez *et al.* 2012).

Surficial geology is made up of unconsolidated deposits of glacial and post-glacial origin and the nearly flat-lying sediment bedrock of the Appalachian Basin. The glacial and post-glacial deposits consist of till, stratified drift, and river alluvium. The bedrock consists primarily of interbedded shale, siltstone, and sandstone of Devonian to Pennsylvanian age. To date, almost all hydraulic fracturing drilling activity has occurred in the west and middle branches of the Susquehanna River and the Lower Chemung River subbasins (Fig. 4-7), which are geographically coincident with the Appalachian Plateau physiographic province whose landform is illustrated by the photograph shown Fig. 4-6. The uplands are broad and valleys narrow (Hunt 1974). Elevation ranges from 1,000 to 3,000 feet. The main branches of the Susquehanna River flow to the south while the smaller tributaries are constrained by the northeast-southwest-trending orientation of the Appalachian Mountains (Fig. 4-7).

Stratified drift aquifers and the Loch Haven and Catskill bedrock formations serve as primary groundwater drinking sources. Glacial till is also tapped as a drinking water source in some locations (Williams *et al.* 1998).

**Figure 4-6. West branch of the Susquehanna River near Renovo, Pennsylvania within the Appalachian Plateau physiographic region (Photo by J. Marasco, Source: Picasa. http://creativecommons.org/licenses/by-nc-nd/3.0/)**

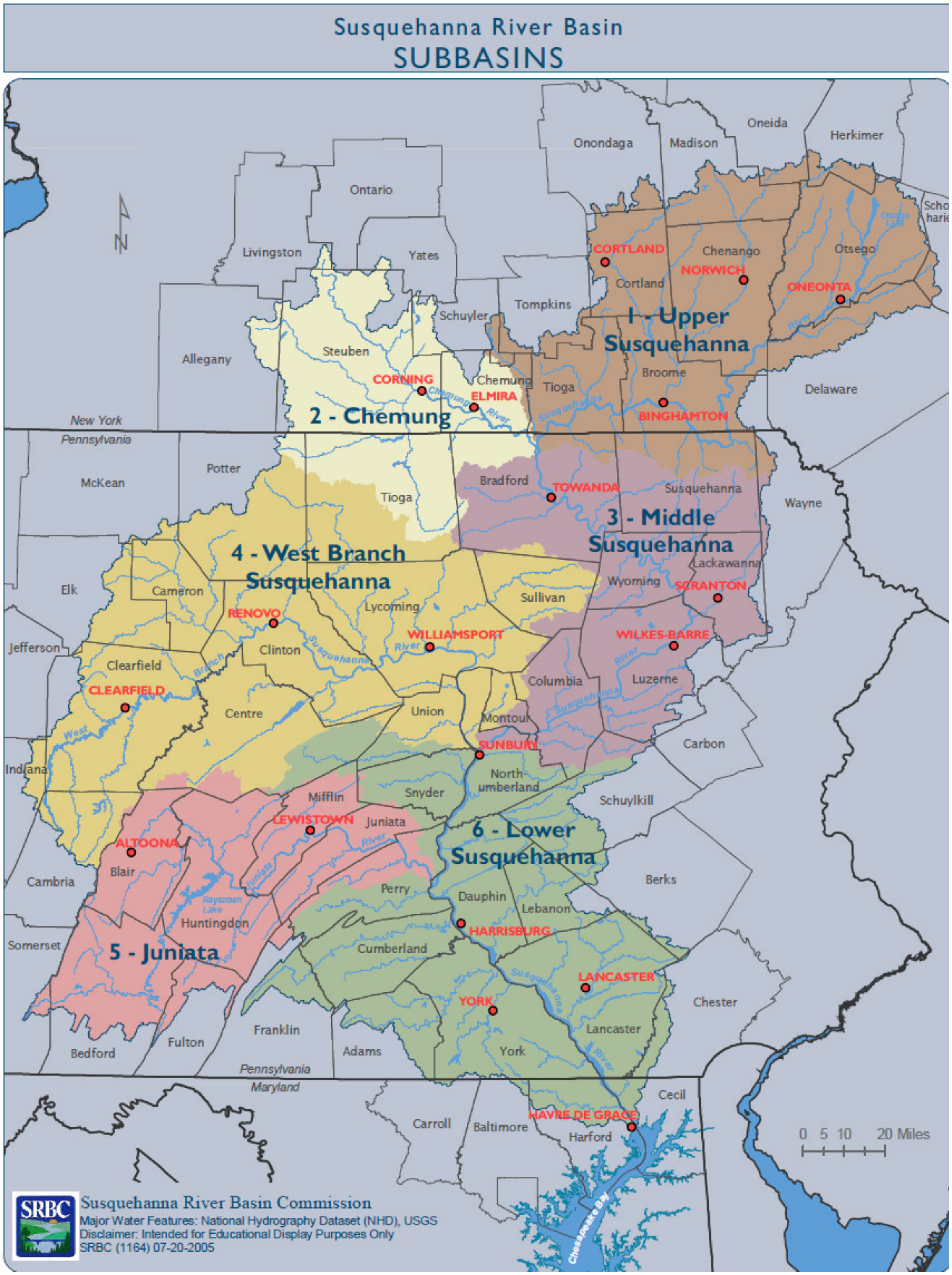


**Figure 4-7. Major subbasins, counties, and towns in the Susquehanna River Basin. (Map produced by SRBC, available at: http://www.srbc.net/atlas/downloads/BasinwideAtlas/PDF/1164a_SRBC_Subbasins.pdf.)**

**Figure 4-8. Aerial view of terrain, land use, and well pads in Bradford County. Distance between the two well pads is about 3500 feet. Multiple hydraulic fracturing wells can be drilled from one pad. The well pad in the upper left corner has a fracturing-operator-constructed freshwater storage pond. (Image Google Earth, PADCNR-PAMAP/USGS.)**

Hydraulic fracturing activity in the SRB has been concentrated in rural areas, away from more populous urban and industrial centers to the north in New York and south near Harrisburg. Land use is mixed agriculture and forests with small to moderately populated rural communities. Hydraulic fracturing activity occurs in a 17-county area but is centered in 14 within Pennsylvania including Bradford, Susquehanna, Tioga, Lycoming, Wyoming, Potter, Sullivan, Lackawanna, Clinton, Centre, Clearfield, Cameron, Blair, and Columbia.

Both surface and groundwater sources are generally widely available in the SRB (Arthur *et al*. 2010; SRBC 2012). Mean daily discharge of the Susquehanna River at Wilkes-Barre, Pennsylvania, based on 100 years of record is 9,000 MGD (basin area approximately 10,000 mi$^2$). Data on daily water use from the USGS 2005 water census is shown by user sector within the 14-county area in Fig. 4-9. Thermoelectric power generation and public water supplies are the largest water users. There is minor use by irrigation and industrial activity in this area. Water acquisition by the oil and gas (O&G) industry is quantified in the following section of this report based on data acquired from agency sources listed in Table 4-2. Aquaculture water was not included. At the large river basin scale, O&G water use is small relative to other sectors.

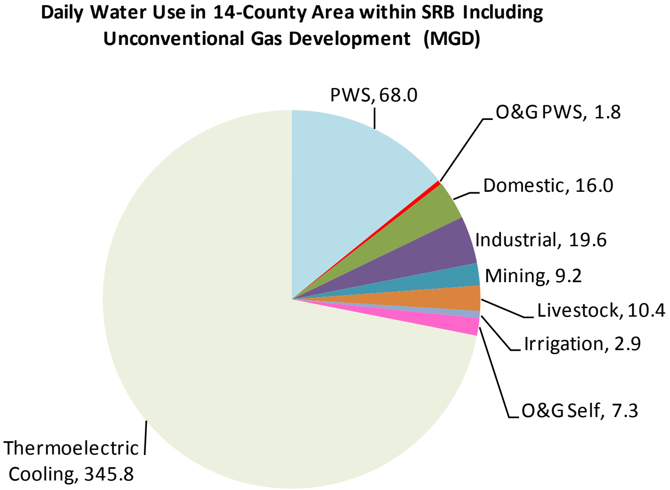


**Figure 4-9. Susquehanna River Basin daily water use by sector (in million gallons per day (MGD). (Data source: USGS 2014a.)**

**Water Allocation and Management.** All aspects of hydraulic fracturing in the SRB are regulated by the Pennsylvania Department of Environmental Protection (PADEP 2013a), except water acquisition, which is managed by the Susquehanna River Basin Commission (SRBC 2012). SRBC is a tri-state commission with broad authority to control water allocations and withdrawals based on the principles of riparian rights, which entitles landholders and others to whom acces has been granted to draw on the natural stream flow in reasonable amounts (SRBC 2012).

SRBC requires permits for any person or business seeking to withdraw water exceeding 100,000 gallons per day (GPD) from surface or groundwater sources, although hydraulic fracturing operators must obtain a permit for any water withdrawal. SRBC permits control daily withdrawals following policies to protect aquatic life. Daily pumping rate restrictions and passby flow thresholds shut down withdrawals during low flows for non-municipal users, depending on requested withdrawal amounts. O&G permittees must accurately monitor withdrawals and report daily usage. Permits are reviewed every four years and permit conditions are modified to reflect evolving SRBC policies. SRBC policies are available at SRBC (2013b). Elsewhere in Pennsylvania, PADEP requires a water management plan that has some common elements to SRBC permits.

**Water Use Data Sources.** Water withdrawal data were obtained from sources listed in Table 4-2. All public water suppliers must provide an annual report of water volumes delivered to customers to the Pennsylvania Department of Environmental Protection (PADEP). Since 2010, each facility must itemize the volumes sold to O&G customers. These data were accessed on PADEP’s State Water Plan interactive website (PADEP 2014a). PWS records were downloaded by county and searched for facilities reporting O&G sales.

SRBC maintains records of daily water withdrawn from self-supplied permitted sites monitored by O&G permittees. SRBC (2013a) provided the daily data for 2009 to 2013 by bulk download in response to a data request. SRBC also provided well consumption information on request (SRBC 2013d). SRBC policies, technical documents and maps are readily accessed on the SRBC website portal (SRBC 2013c).

The volume of water allocated by agencies is a key limitation on potential water use. Site data and appropriation limits were obtained for SRBC permits from the SRBC website portal (SRBC 2013c). Some PWS facility information was available on the PADEP State Plan website accessed through the Chapter 110 query (PADEP 2014b). The data sources used throughout the report are also compiled in Appendix A.

**Table 4-2. Water use data sources and reports for the Susquehanna River Basin.**

| Source | Data Type | Location | Query |
|---|---|---|---|
| PADEP 2014 | a. Annual public water system use report | http://www.pawaterplan.dep.state.pa.us/StateWaterPlan/WaterDataExportTool/WaterExportTool.aspx | Primary facility report, by year and county |
| | b. PWS facility information | | Chapter 110 (Act 220) registration |
| PADEP 2013a | Well drilling reports | http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297 | Wells drilled by county |
| SRBC 2013 | a. Water source acquisition volume | http://www.srbc.net/pubinfo/index.htm | Provided by the Susquehanna River Basin Commission (SRBC) by written request |
| | b. Miscellaneous reports, policies, maps | http://www.srbc.net/publicinfo/index.htm | Website search |
| | c. Docketed permits | http://www.srbc.net/wrp/ | Water Resource Portal/search for projects |
| | d. Gas well volume | http://www.srbc.net/pubinfo/index.htm | Provided by SRBC by written request |

## Sources of Freshwater for Hydraulic Fracturing

Water is supplied to the O&G industry for hydraulic fracturing from a combination of surface water and groundwater sources at public and self-supplied withdrawal sites. Some public water suppliers sell water to the O&G industry, while the majority of water is self-supplied from SRBC permitted sites. Water use data were available for 2010 to

2013 for the public water supplies and from 2009 to 2013 for the self-supplied withdrawal locations. During this time, 2,800 wells were drilled and hydraulically fractured in the SRB.

### *Public Water Suppliers and Use Statistics*

Public water suppliers include municipal suppliers that typically provide water to a variety of customers including domestic, commercial, industrial, and institutional, and for municipal functions such as watering parks or public pools. Public water suppliers also include many private entities with a collective water supply such as mobile home parks and homeowner associations. Many large institutions such as universities or prisons are also classified as public water suppliers. In all of Pennsylvania, there are about 24,000 public water suppliers in the PADEP database. Statewide, 105 of them sold 2.8 MGD of water to hydraulic fracturing operators in 2012—an average of 27,000 GPD per participating facility.

PADEP records for all PWSs within the SRBC and surrounding counties were searched for records of sales to O&G in each year since 2010, when separate reporting for O&G began. Of hundreds of PWS facilities within the counties where hydraulic fracturing drilling has been active (Fig. 4-10), 25 municipal suppliers distributed within 12 counties in the SRB have provided water to hydraulic fracturing operators at some time between 2010 and 2013. Four additional facilities are registered for O&G sales with SRBC but have not provided water to date. It appears that no type of PWS other than municipals have sold water to O&G and no PWS outside of Pennsylvania sold water for use in in the SRBC.

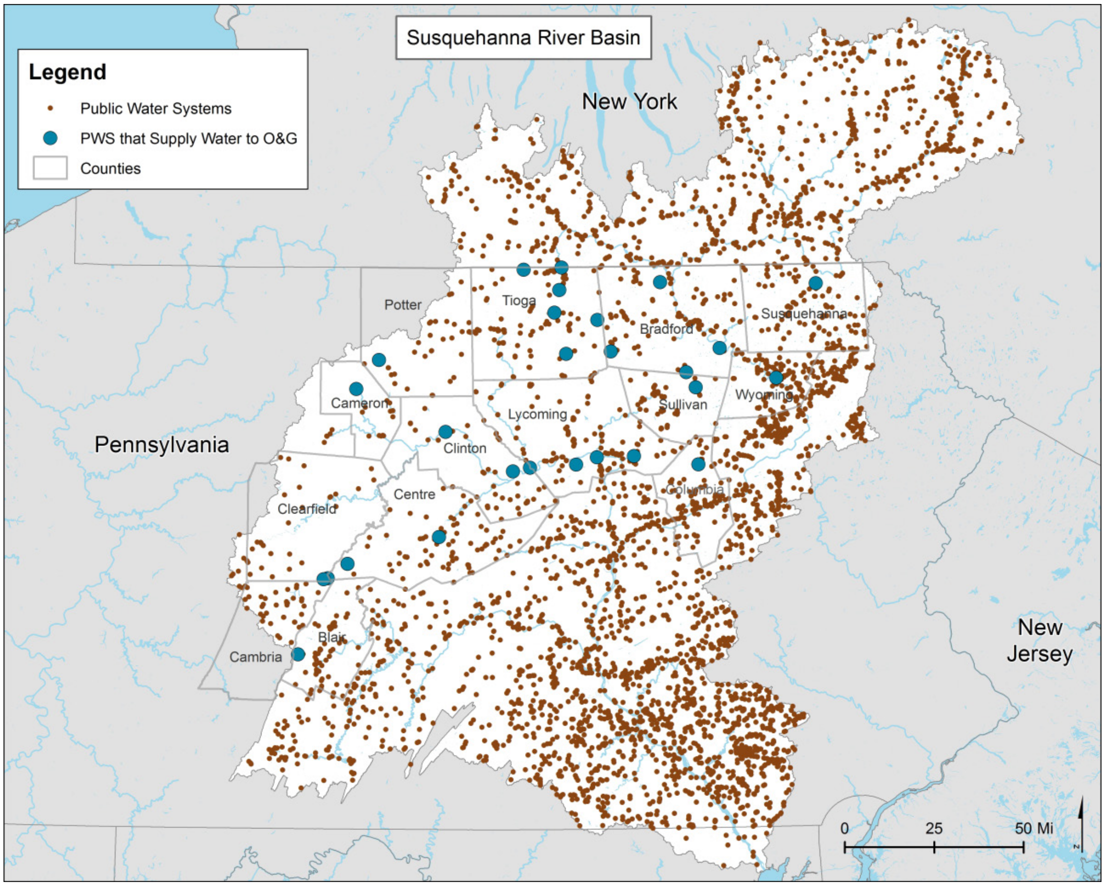


**Figure 4-10. General location of public water suppliers in the Susquehanna River Basin. Small circles shown all public water systems; large circles are public water systems that have sold water to oil and gas. (Data source: U.S. EPA 2012c for PWS location, PADEP 2014a for PWS that sold water to O&G.)**

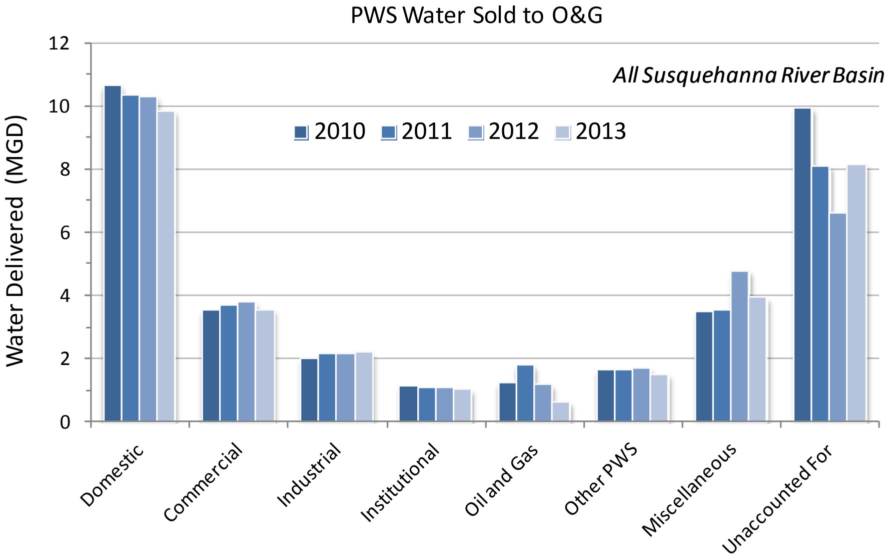


**Figure 4-11. Daily sales by user sector summed for the 25 public water systems that supply water to oil and gas in the Susquehanna River Basin. On average PWS provide about 5% of their water to the oil and gas industry for hydraulic fracturing. The category "Unaccounted for" includes leakage and other undocumented losses within the infrastructure. (Data source: PADEP 2014a.)**

Each facility annually reports the total number of connections and average daily water use by sector. User sectors include domestic, commercial, industrial, institutional, other PWSs, miscellaneous uses, and unaccounted for volumes that represent undocumented losses within the infrastructure. Daily sales summed for the 25 public systems that have sold water to O&G in the SRB are shown in Fig. 4-11. Collectively within this group, domestic households used 10 MGD, or about 30% to 35% of the facility sales. Commercial and industrial usage was 16% of daily sales. In 2010, the O&G portion of water sales by PWS was 7% of water sold (1.8 MGD). By 2013, water demand for hydraulic fracturing increased but the portion taken from PWS declined to 1%, indicating the industry was acquiring water from other sources. Because most PWSs acquire all or some of their water from groundwater sources, about 85% of the O&G water obtained from public suppliers came from groundwater.

The relative distribution of the sales by sector evident in Fig. 4-11 is consistent among most municipal PWSs, except for the O&G component. Many PWS facilities report that 30% or more of their daily production is routinely unaccounted for due to leakage and other undocumented losses within the infrastructure, about as much as supplied to households. O&G acquisition of water from public suppliers has declined by 65% since the 2011 peak. During this time, hydraulic fracturing operators have increased their ability to self-supply by obtaining permits, as described in the next section.

Each PWS facility has a daily operating capacity defined by permit or by pumping capacity. Sufficient facility operating information was obtained from the PADEP Chapter 110 query (PADEP 2014b) to establish an estimate of facility capacity, although our estimate may underestimate potential supply, especially for several of the facilities with multiple supply sources. The daily volume delivered as a portion of facility capacity is shown for the 25 PWSs in the 2011 peak use year in Fig. 4-12. Note that many of these facilities had no sales to O&G in this year, as was the case in all years. The participating PWS facilities routinely delivered about 30% to 70% of their operating capacity (average 49%) to all of their customers, although some appeared to operate near capacity. Some of these may have additional water sources that are not accounted for in our total. Public suppliers generally did not use much of their facility capacity to supply water to the O&G industry—only 4.6% on average, with a median less than 0.1% (Fig. 4-12). However, there was a wide range among individual PWS facilities. Two provided as much as 40% of their total production capacity for O&G use in 2011 (2080003 and 4410175), but neither operated near maximum capacity.

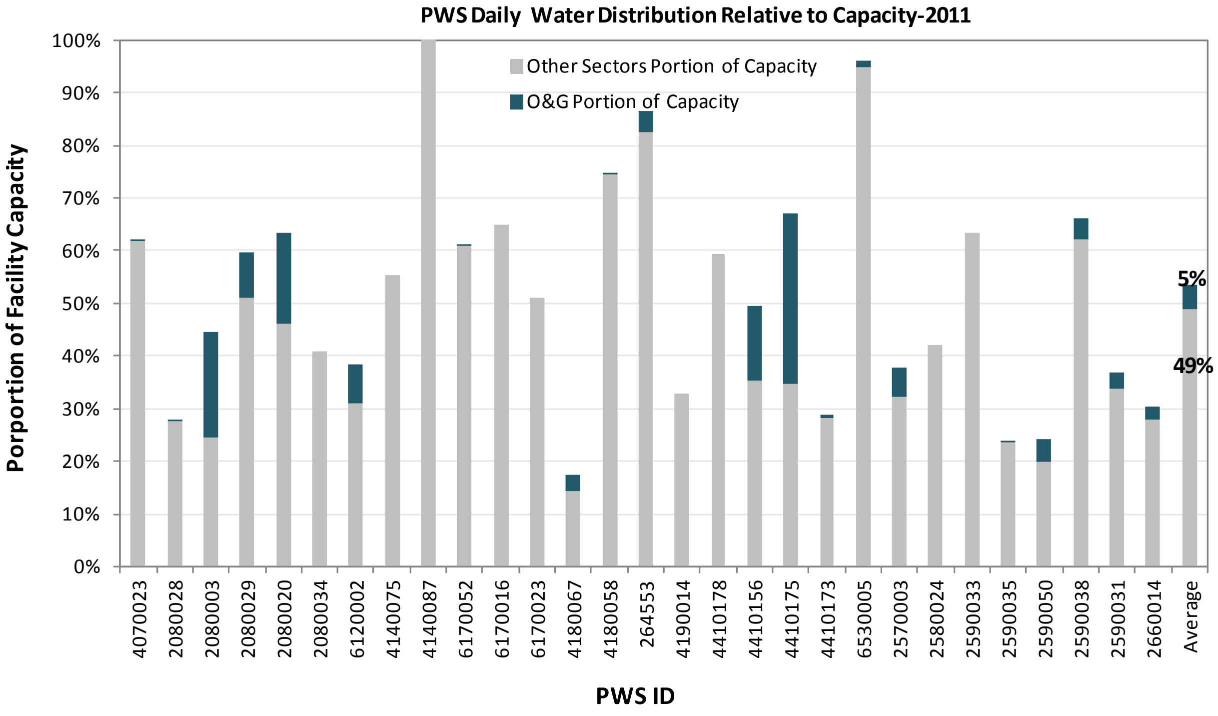


**Figure 4-12. Proportion of public water supply facility capacity used to provide water to the oil and gas industry at the 29 public water supply facilities registered to sell water for hydraulic fracturing in 2011. Facilities are identified by their PWS ID. Facility capacity is the maximum allowed by permit or pumping capacity; most operate at 30 to 70 percent capacity. Sales to the oil and gas industry generally average about 5% facility capacity. Most of the PWS registered to sell water to the oil and gas industry have not done so in a given year. From 2010 to 2012, 18 to 21 facilities were used. In 2013 12 facilities provided water to O&G. (Data source: PADEP 2014a, 2014b.)**

### *Self-Supplied Sources and Use Statistics*

Most of the water acquired for shale gas resource extraction was self-supplied from water bodies permitted by SRBC. Since hydraulic fracturing activity began in 2008, the O&G industry has rapidly expanded self-supplied capacity as companies, service operators, and local water purveyors have obtained permits to withdraw water from a variety of sources (Fig. 4-13). SRBC refers to active permits as “dockets”; this report uses the term “permitted.” SRBC maintains a list of active dockets (SRBC 2013c).

By 2013, 167 locations have been permitted for water withdrawal from 2008 to 2013. The inventory of sites is very fluid. New sites are added each year, while some were not renewed when their four-year permits expired (Fig. 4-13A). Table 4-3 provides statistics on the number of sites indexed by the contributing basin area in the case of rivers and streams for each year’s cohort of newly permitted sites. Some sites have never been used and many are used intermittently or for just one year. Between 2009 and 2013, water has been withdrawn from 112 sites with about 77 active in any given year (Fig. 4-13B). Increased use of self-supplied sources (Fig. 4-13A) was planned by SRBC and directly contributed to declining use of public water suppliers (Beauduy 2009).

Most of the water has been withdrawn from 97 sites on rivers and streams ranging in contributing watershed area from 1.5 to 10,500 mi$^2$. There are five commercial groundwater wells, of which three are used frequently, and a few small lakes and ponds that are rarely used. Authorities encourage use of mine-drainage-impaired waters—most, but not all, sites on small streams are classified as chemically impaired from mine drainage.

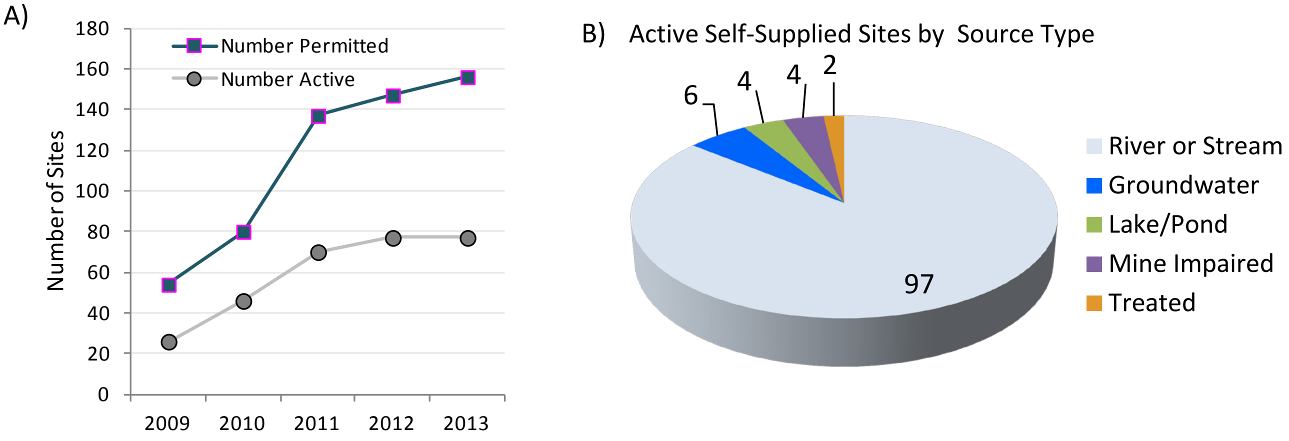


**Figure 4-13. Characterization of oil and gas self-supplied water sources in the Susquehanna River Basin. A) Number of sources by year. B) Number by water body type. (Data source: SRBC 2013a.) Most permitted sites withdraw water from rivers and streams.**

Permitted withdrawals are now widely distributed within 17 counties within the SRB and concentrated within five (Fig. 4-14). Thirty-six withdrawal sites are located on the mainstems of the west and middle branches of the Susquehanna River (watershed area >1,000 mi$^2$). Note that there are a few SRBC withdrawal sites outside the basin boundary in adjacent counties, indicating that there may be some inter-basin transfer of water. A check of their records showed that a very minor amount of water was brought into the SRB. Any water transported out of the basin is included in the analyzed records.

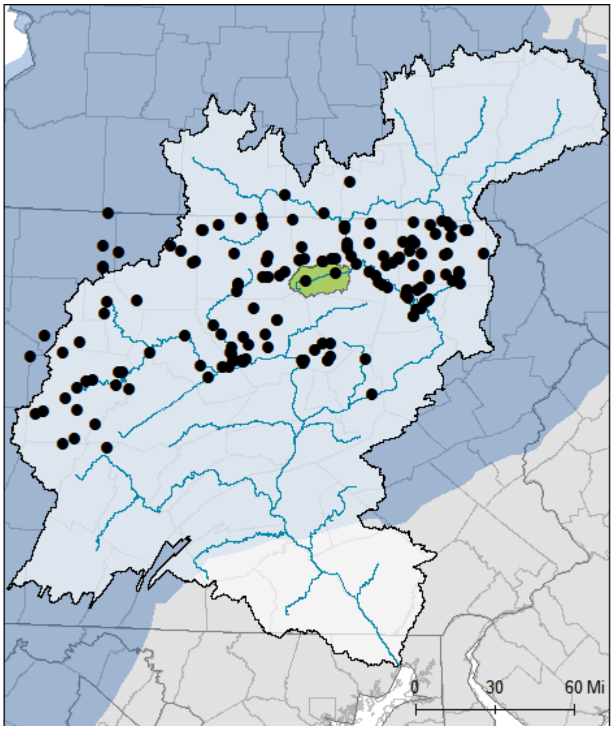


**Figure 4-14. Distribution of oil and gas self-supplied water sources for hydraulic fracturing in the Susquehanna River Basin. Sites are now, or have been, permitted by the Susquehanna River Basin Commission from 2008 to 2013. (Data source: SRBC 2013a.)**

The 31 O&G companies operating in the SRB register public and self-supply sites where they may acquire water with SRBC (2014). Just one small operator obtains all water from public suppliers. Although most variously list the PWSs shown in Fig. 4-12 as potential sources, most are known to self-supply from permitted sites that they or water service providers operate. It appears that companies share use of some sites.

**Table 4-3. New permits for surface water withdrawal for the oil and gas industry. (Location data source: SRBC 2013a. Basin areas were determined in this project.)**

| | | Basin Area (mi$^2$) | |
|---|---|---|---|
| **Year** | **Number** | **Median** | **Range** |
| 2008 | 25 | 300 | 8.9 - 8,884 |
| 2009 | 23 | 150 | 5.2 - 8,261 |
| 2010 | 28 | 75 | 1.7 - 8,489 |
| 2011 | 35 | 109 | 3.4 - 10,527 |
| 2012 | 25 | 150 | 13.6 - 8,248 |
| 2013 | 10 | 75 | 1.5 - 8,720 |

*Middle Susquehanna River water acquisition depot where water is first pumped into holding tanks*

*Middle Branch Susquehanna River withdrawal site near Towanda, PA*

*(6,500 mi$^2$)*

*Tunkhannock Creek (380 mi$^2$)*

*Mine-drainage impaired stream—Fall Brook (7 mi$^2$)*

**Figure 4-15. Examples of self-supplied withdrawal locations permitted by the Susquehanna River Basin Commission. (Approximate basin watershed area in parenthesis.)**

Nearly all water is trucked to its point of use, although some operators are building water delivery infrastructure, including pumping facilities and pipelines, to increase efficiency and to reduce truck traffic and costs. The widely distributed network of sites (Fig. 4-14) provides operators the flexibility to withdraw from sources nearer to gas wells and avoid concentrating withdrawals in any one location. Fig. 4-15 shows photographs of several active self-supplied withdrawal sites on a range of river sizes within the SRB.

SRBC withdrawal permits constrain the volume and timing of withdrawals with specifications developed for each site. Streamflow and groundwater are protected by limits on daily withdrawal volume and pumping rate. We considered the daily withdrawal limit as the "capacity" of the permit site to supply water to the O&G industry. Maximum daily permit limits are shown in Fig. 4-16. Permitted daily volume ranges between 0.04 and 3.0 MGD, shown categorically by withdrawal volume in Fig. 4-16A. Withdrawal volume varies between sites reflecting, but not solely determined by, river size (Fig. 4-16B). Withdrawals up to 3.0 MGD are allowed on the Susquehanna River. Some permittees have requested relatively high daily withdrawal limits (1 MGD) on very small streams, with the expectation of using them only during higher flows to fill storage reservoirs. Current permits would collectively allow 140 MGD to be withdrawn within the SRB to support hydraulic fracturing activity (Fig. 4-16C).

Fig. 4-16C organizes the information in 4-16A and B to illustrate the withdrawal capacity in relation to river size. The daily maximum permit capacities are cumulatively summed, ordering sites from largest to smallest basin area. The large river sites (>1,000 mi$^2$) make up a substantial portion of O&G permitted water withdrawal capacity (60 MGD). Sites with watershed area between 400 and 1,000 mi$^2$ add about 40 MGD of capacity; small streams with watershed area less than 40 mi$^2$ add another 20 MGD. There are 12 permitted sites on small streams (<10 mi$^2$) that can provide a small amount of water. In any year, all of these sites could be tapped for some portion of the annual water supply.

Permit capacity is already far greater than currently or likely needed in the future. Freshwater needs for hydraulic fracturing can be roughly approximated by well drilling rates. At the 2012 rate of 836 drilled wells (Fig. 4-5), each requiring 3.85 MG of freshwater for hydraulic fracturing (Table 4-1), about 9 MGD would be consumed (Fig. 4-16D). Drilling activity is projected to increase and could reach as high as 2,800 wells per year (Johnson 2010), which would require 30 MGD of freshwater (Fig. 4-16D) (Beauduy 2009; SRBC 2013e). The increased demand for freshwater under these projections could be readily accommodated at existing permit sites (compare Fig. 4-16D to 4-16C). Nevertheless, new sites are added each year to the portfolio of permitted sites which has had the effect of minimizing travel distance. In researching transportation characteristics of the hydraulic fracturing industry in the SRB, distance Gilmore *et al*. (2014) found that most truck trips to haul water were less than 10 miles.

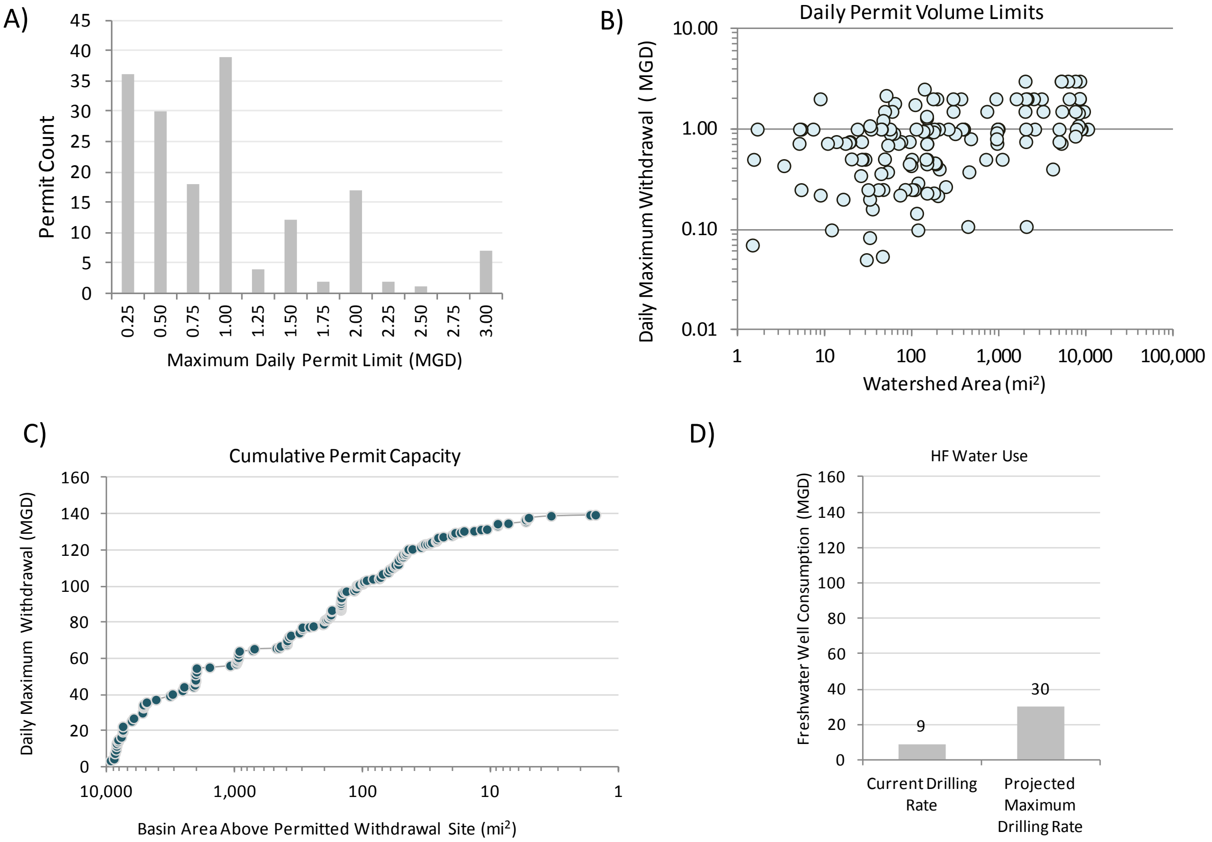


**Figure 4-16. Maximum daily withdrawal limits for oil and gas self-supplied water withdrawal sites. A) Count of permits by daily limit category. B) Daily permit limit in relation to contributing watershed area. C) Cumulative sum of site permit capacity, with sites ordered from largest to smallest basin area; for example, 60 million gallons per day can be acquired from sites with watershed areas greater than 1,000 mi$^2$. (Data source: SRBC 2013c.) D) Estimated hydraulic fracturing well freshwater consumption based on current annual drilling rate (840 wells) and future projected maximum rate of 2,800 (Beauduy 2009; Johnson 2010). O&G wells use an average of 3.85 million gallons per well of freshwater for hydraulic fracturing (Table 4-1). (Data source: SRBC 2013a.)**

SRBC has a low flow policy to protect aquatic biota and municipal supplies, requiring shutoff of hydraulic fracturing withdrawals when streamflow drops below a threshold, termed the "passby" flow. A passby is assigned only if the requested daily withdrawal volume exceeds a percentage of the lowest flows likely to be observed at a site (SRBC 2012). Low flow is defined by the $Q_{7,10}$ flow statistic, a common benchmark of extreme minimum flows at a stream gaging site. The $Q_{7,10}$ is the average minimum streamflow observed over seven consecutive days once every 10 years (USGS 1982). Note that the passby threshold is generally set at 20% to 25% of the mean annual flow if a low flow threshold is required and is likely to trigger in most years. The statistic is computed from measured flow records at USGS gages and applied to ungaged sites based on a basin area weighting methodology. Permit sites are referenced to real-time USGS gages, so that operators can be readily informed via internet when the passby is invoked. From 2009 to 2011, SRBC applied a single annual low flow value. Since 2012, SRBC has assigned biennial and then monthly passby thresholds. The passby flows can halt withdrawals at all sites except eight on Susquehanna River segments. These sites have no passby restriction given small maximum daily withdrawals relative to large river streamflow.

The annual volume of water that is self-supplied by the O&G industry was determined by summing the daily withdrawal volumes obtained from SRBC sites reported by operators (2013a). Results summed annually by source type are shown in Fig. 4-17 and daily in Table 4-4. In recent years, the O&G industry has self-supplied 2 to 3 billion gallons of water each year from 77 sites found mostly on rivers and streams distributed widely in the SRB and ranging in size from very small to very large. Less than 5% of the water is acquired from waters impaired by mine drainage. Virtually none comes from lakes, ponds, or impoundments other than those constructed by the O&G industry for temporary storage after initial withdrawal from permitted sites; sources of this type have only been used intermittently. Several commercial (but not public) groundwater wells supply water to O&G. Self-supplied daily withdrawals range from 0 to 3 MGD at the site level and sum to about 7 MGD for the SRB as a whole.

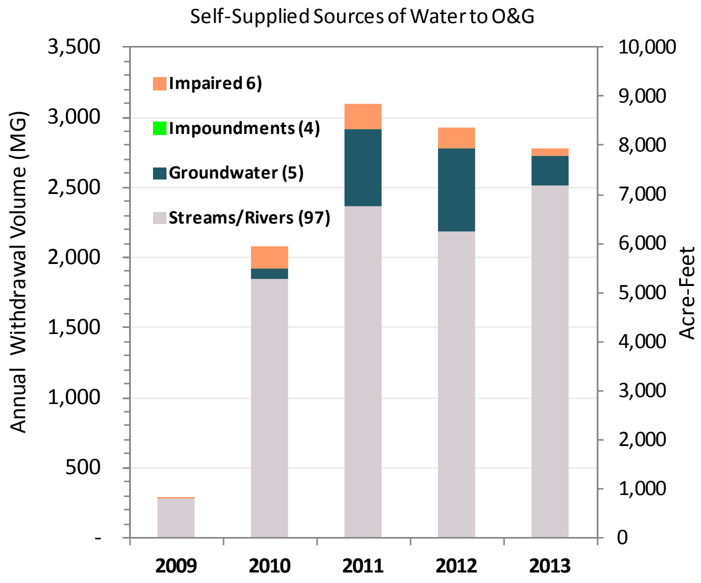


**Figure 4-17. Volume of water acquired from self-supplied sources annually by water source type. Number in legend refers to total number of active permitted sites in each category between 2009 and 2013. (Data source: SRBC 2013a.)**

**Table 4-4. Daily self-supplied water acquired for hydraulic fracturing in the Susquehanna River Basin (in million gallons per day). (Data source: SRBC 2013a.)**

| | Water Body Type | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|
| Quality surface water | Streams and rivers | 0.77 | 5.07 | 6.50 | 6.00 | 6.90 |
| | Lakes/Ponds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Groundwater | Groundwater | 0.00 | 0.20 | 1.49 | 1.62 | 0.57 |
| Impaired water | Impaired | 0.01 | 0.43 | 0.50 | 0.38 | 0.14 |
| Total | | 0.78 | 5.54 | 7.35 | 6.90 | 7.39 |

### Summary of Water Acquisition Volumes at the Susquehanna River Basin and County Scale

The combined public and self-supplied water volume supplied to the O&G industry for drilling and development of hydraulically fracturing O&G wells in the SRB is shown in Fig. 4-18. Annually, the O&G industry and service providers acquired about 3 billion gallons of freshwater for hydraulic fracturing, 82% of which was self-supplied (Fig. 4-18A) and most of which came from surface water (Fig. 4-18B). Almost 18% was acquired from PWSs in the peak year of 2011 (Fig. 4-18A), but this source has declined in significance. The cumulative total daily use at self-supplied sites has ranged widely during this period, peaking at 14 MGD in winter 2012 (Fig. 4-19). The daily summation reveals that water use occurs every day of the year.

The water volumes accounted for at sources matched reasonably well with water consumed at well pads independently tracked by SRBC and PADEP (Fig. 4-18A). The difference between the two is hydraulic fracturing wastewater reuse (about 12% on average), consistent with the individual well water consumption statistics at hydraulic fracturing sites (Table 4-1).

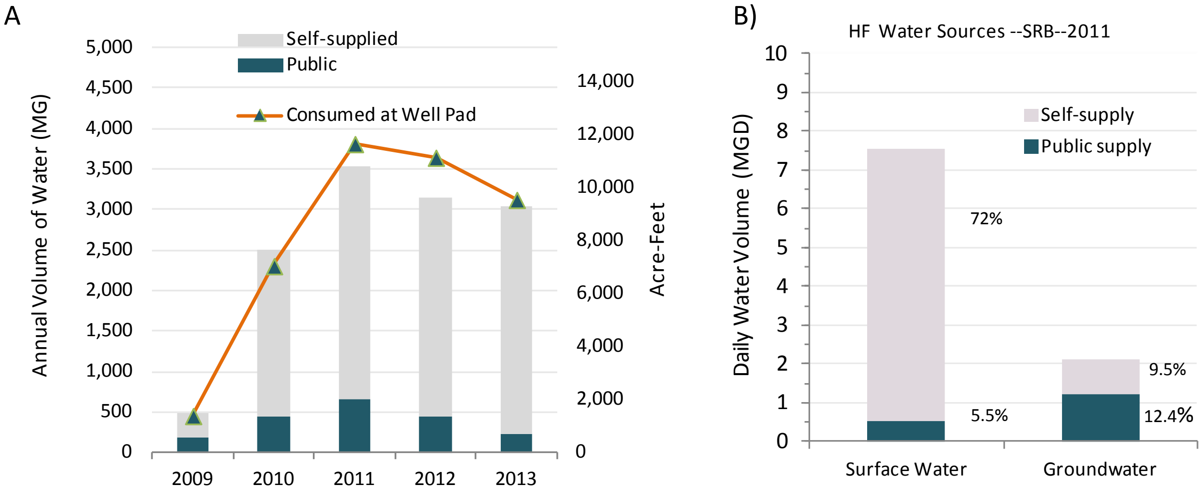


**Figure 4-18. Total volume of water acquired by the oil and gas industry in the Susquehanna River Basin from public water systems (data source: PADEP 2014) and self-supplied from permitted sites. A) Annual acquired water volume and volume consumed at well pads tracked independently by the Susquehanna River Basin Commission. B) Daily source of water. (Data sources: PADEP 2014a; SRBC 2013a.)**

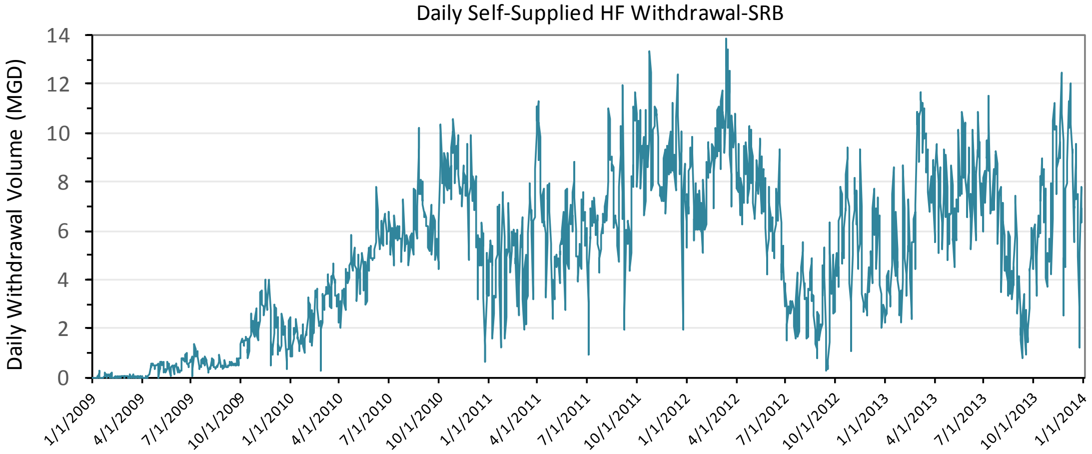


**Figure 4-19. Daily self-supplied water withdrawal for hydraulic fracturing in the Susquehanna River Basin summed for all active sites. (Data source: SRBC 2013a.) Withdrawals occur every day. Withdrawals peaked in 2012 at 14 MGD and have dipped with slowed drilling reflecting lower gas prices in 2013.**

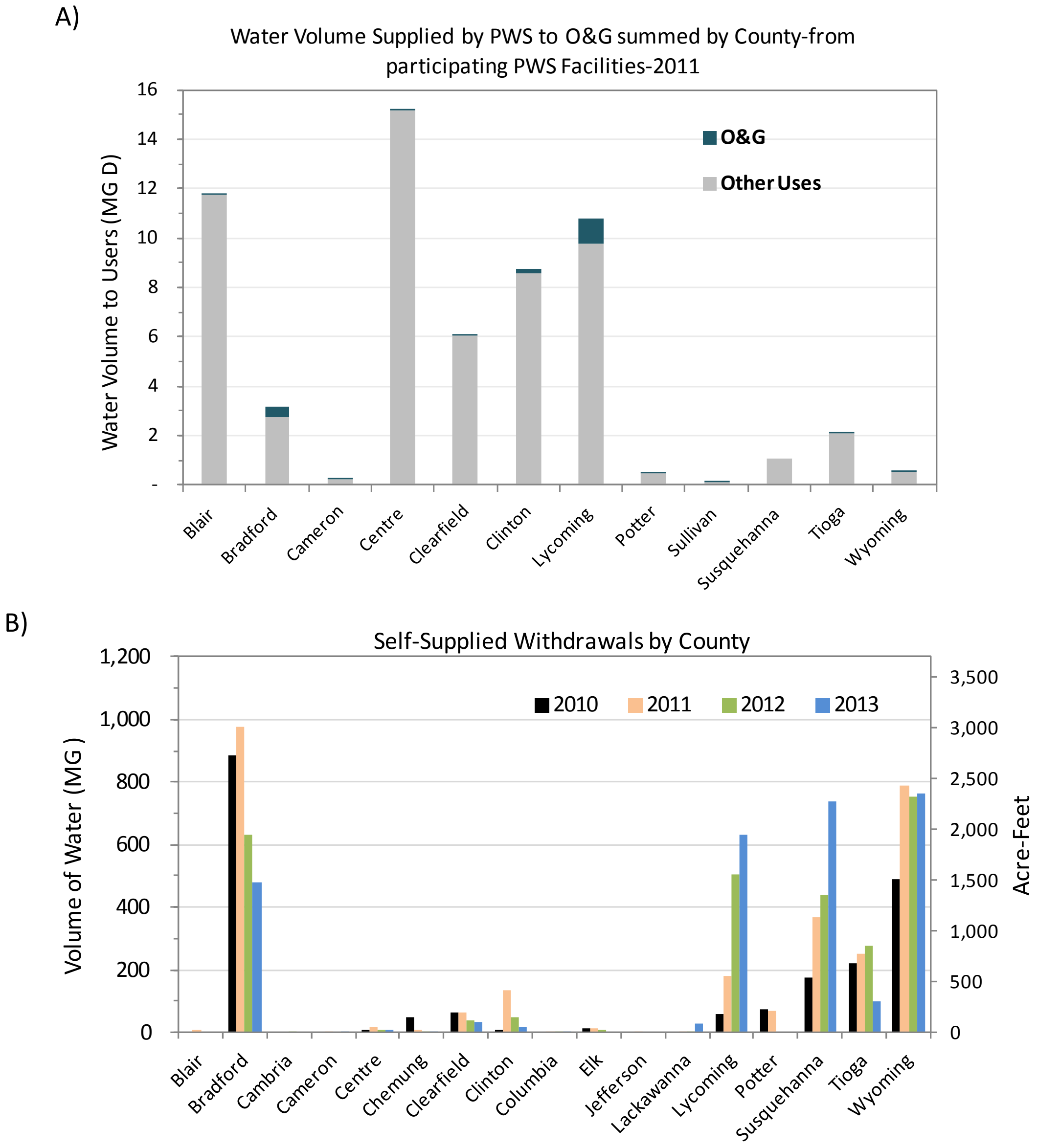


**Figure 4-20. Acquisition of water for hydraulic fracturing by the oil and gas industry acquired from public water systems and self-supplied, summed by county. A) Daily sales to oil and gas from 25 public water systems in 2011, summed by county. (Data source: PADEP 2014a). B) Annual volume of freshwater self-supplied by the oil and gas industry, summed by county. (Data source: SRBC 2013a.)**

The volume of freshwater supplied by PWSs and self-supplied sources is summed annually by county in Fig. 4-20. Purchase of water from public water systems by the oil and gas industry was distributed among counties (Fig. 4-20A). Most of the PWS water was acquired in Bradford and Lycoming Counties, but the O&G proportion of sales was not large relative to other users in any county. Annual self-supplied volume for hydraulic fracturing summed by county is shown for individual years in Fig. 4-20B. Early in the history of hydraulic fracturing development in 2010, much of the freshwater was acquired in Bradford County. As the hydraulic fracturing activity center expanded, water acquisition increased in Lycoming, Susquehanna, and Wyoming Counties and decreased in Bradford County. Most water was acquired in these four counties, where drilling is most active, and very little has been acquired elsewhere to date.

## Water Use Intensity Analysis at Self-supplied Sites

Most water used for hydraulic fracturing is self-supplied from rivers and streams (72%), so water balance analysis focuses on this group. Oil and gas operators must monitor all water withdrawals at each site every day with a good-quality meter, and submit records to SRBC quarterly. Withdrawals are recorded in GPD. These data were used as provided from SRBC (2013a). There were 87,581 daily observations in the combined site data record for surface water sites from 2009 to 2013, including days with no withdrawal. Withdrawals occurred on 29,907 days (termed "site-days"). The impact of withdrawals on site water balance is evaluated with the surface water use intensity index (SUI, eq. 3-2) on observed hydraulic fracturing withdrawals at permitted sites. Groundwater withdrawals were assessed with the groundwater use intensity index (GUI, eq. 3-3) at the end of this chapter.

Daily streamflow volume was required to calculate SUI for each location. However, nearly all of the withdrawal sites were ungaged. Therefore, daily streamflow was estimated for each withdrawal site from a nearby USGS gaged site using an area-weighting factor. (SRBC uses a similar method for estimating streamflow characteristics for permit applications.) There were 56 USGS gages ranging in watershed area from 5.2 to 11,220 mi$^2$ available to estimate ungaged sites, matching the range of watershed area in the populations of withdrawal sites. Withdrawal sites were paired with USGS gages based on nearby location and contributing watershed size.

Some error was introduced in SUI calculations using estimated streamflow. The area-weighting method was cross-validated using five pairs of USGS gages. In each pair, flow was estimated for one gage based on observed flow at its paired gage, replicating the procedure used to estimate flow at ungaged sites. A Nash-Sutcliffe (NS) model efficiency coefficient that compares daily estimated and observed flow as a ratio (Nash and Sutcliffe 1970) was calculated from daily comparisons of estimated and measured flow. The closer the model efficiency is to 1, the more accurately the estimated data represents the observed data. Comparisons are provided in Table 4-5.

The ln-transformed NS$_{\ln}$ score exceeded 0.90 for four of the five pairs, indicating an excellent match between the paired sites despite large differences in watershed area between the pairs in some cases. The NS$_{\ln}$ score was 0.70 for the smallest sites. Although this was still a quite satisfactory score, results suggest that extrapolated streamflow records for smaller streams were likely to have more error. See Appendix B for more discussion of hydrologic streamflow methods and USGS data used for SUI analysis.

**Table 4-5. Cross-validation of area-weighting method. Each pair represents two gaged watersheds. Flow for the second member of each pair was estimated by extrapolating values from the first member of the pair, with the Nash-Sutcliffe (NS) and ln-transformed NS$_{\ln}$ scores indicating the fit between this estimation and the actual observed flows. "Distance" is the straight-line distance between the two gaging stations.**

| Pair | Gage ID | Area (mi$^2$) | Distance (mi) | NS | NS$_{\ln}$ |
|---|---|---|---|---|---|
| 1 | USGS 01541500 | 371 | 3 | 0.83 | 0.91 |
| | USGS 01541303 | 474 | | | |
| 2 | USGS 01532000 | 215 | 4 | 0.96 | 0.95 |
| | USGS 01531908 | 112 | | | |
| 3 | USGS 01541000 | 315 | 9 | 0.76 | 0.97 |
| | USGS 01541200 | 367 | | | |
| 4 | USGS 01553700 | 51 | 22 | 0.76 | 0.7 |
| | USGS 01552500 | 24 | | | |
| 5 | USGS 01503000 | 2232 | 36 | 0.96 | 0.98 |
| | USGS 01515000 | 4773 | | | |

**Observed Hydraulic Fracturing Withdrawals.** Examples of the daily withdrawal records at six sites illustrate some general patterns of hydraulic fracturing operations (Fig. 4-21). The sites range in contributing watershed area from 7.4 mi$^2$ (Fall Brook) to approximately 10,000 mi$^2$ (Susquehanna River). Streamflow is shown as a daily flow volume expressed in MGD to facilitate calculation of SUI. One MGD equals a daily instantaneous flow rate of 1.55 cfs as typically reported at USGS stream gages. Note that the vertical axis for daily streamflow and withdrawal volume is log-scaled.

Use varied by site, but sites on larger rivers tended to be used more often (~40%–65% of the days), while those on smaller streams tended to be used more episodically. Smaller sites were collectively used about 20% of days. Whether maximum daily limits were withdrawn varied considerably between sites and between days at each site. Operators withdrew the maximum allowed at times, but often withdrew less. Most sites were used at about 10% to 12% of their total capacity combining days of use and permit allowance to estimate total volume available. Hydraulic fracturing operators withdrew year-round except when passby flows were invoked and adhered to their permit restrictions regarding maximum daily withdrawals and passby periods, as evident in Fig. 4-21.

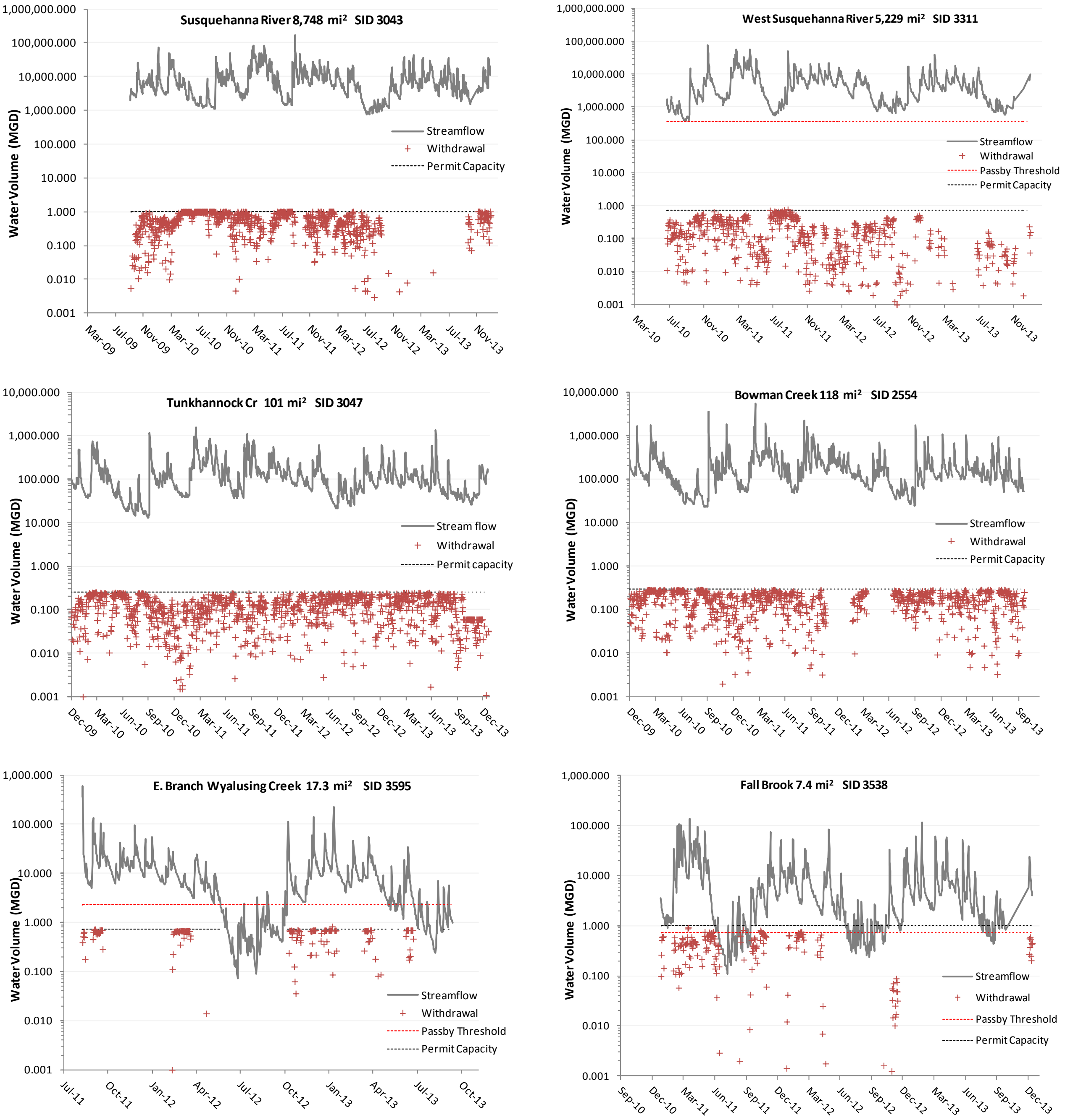


**Figure 4-21. Self-supplied permitted sites have a daily withdrawal limit and may have a minimum maintenance flow (passby). Permittees must accurately monitor and report daily withdrawals. Daily streamflow, withdrawals, permit limits, and passby flows (if required) are shown for six oil and gas withdrawal sites representing a range of contributing watershed sizes as examples. Note that the Y-axis is log-scaled. Fall Brook (7.4 mi$^2$) is the smallest stream shown and is on a mine-drainage impaired stream. Three sites do not have passby thresholds. (Data source: SRBC 2013a.)**

A count of daily withdrawal volume for all sites and all days is shown in Fig. 4-22. Median daily withdrawal of all observations was 0.2 MGD. Streamflow ranged over six orders of magnitude from the largest to smallest streams and generally increased exponentially as a function of basin area. Flow in the Susquehanna River fluctuated around 10,000 MGD, while flow in Fall Brook fluctuated around 10 MGD. Streamflow ranged at least two orders of magnitude between storms and intervening dry periods over the course of the year at each site. Daily withdrawals could only vary from 0 to 3 MGD reflecting permit limits. Withdrawals were nearly four orders of magnitude lower than flow at the large river sites but just one order of magnitude lower than flow in the smallest streams (Fig. 4-21). Thus, higher SUI was more likely in smaller streams.

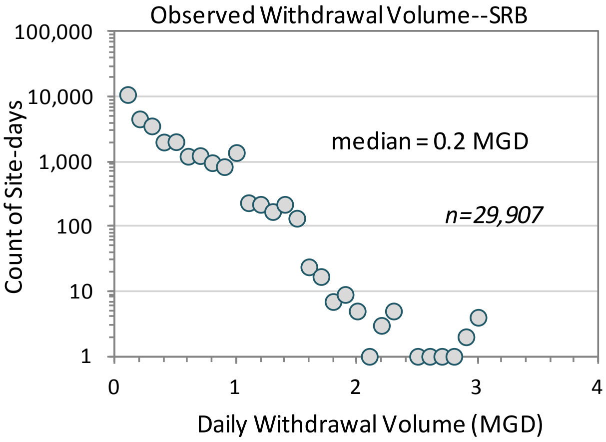


**Figure 4-22. Count of daily volume withdrawals, all sites combined. The majority of daily water withdrawals were less than 0.5 MGD. (Data source: SRBC 2013a.)**

**Surface Water SUI Analysis.** The 97 surface water sites had a wide variety of streamflow and daily withdrawals as illustrated in Fig. 4-21. Water balance represented by SUI divides withdrawal volume by streamflow and ranges from 0 to 1.0, with 1 meaning all water was taken. SUI should be strongly dependent on streamflow, which in turn strongly depends on watershed area. Daily SUI computed for all combined site-days from 2009 to 2013 is shown in relation to streamflow in Fig. 4-23A. The highest 6% of observations are shown in relation to basin area in Fig. 4-23B. Count by SUI category is provided in Table 4-6. The categorized SUI distribution is shown for individual sites in Fig.4-24.

Overall, SUI due to hydraulic fracturing withdrawals was very low; 98% of the SUI values were less than 0.1 and 94% were less than 0.02. SUI greater than 0.1 occurred only when streamflow was less than 20 MGD (30 cfs) (Fig. 4-23A). Flow this low is rare in larger rivers (>1,000 mi$^2$), but occurs with increasing probability in smaller rivers and streams. SUI did not exceed 0.01 when flow exceeded 200 MGD (309 cfs). Higher values of SUI had a strong association with watershed area (Fig. 4-23B) and did occasionally occur in the smallest streams. SUI greater than 0.4 and 0.7 was observed 83 and 14 times, respectively, during the five-year period from 2009 to 2013 (Table 4-6).

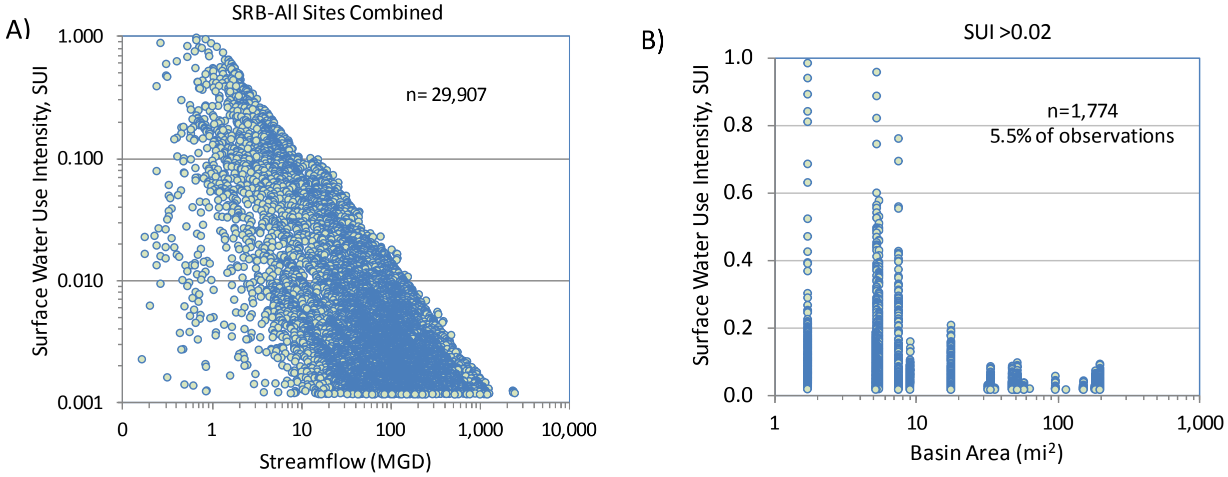


**Figure 4-23. Daily surface water use intensity index (SUI) for all withdrawal sites in the Susquehanna River Basin used to source water for hydraulic fracturing from 2009 to 2013. Only values for days when water was withdrawn are included. A) SUI in relation to daily streamflow volume. Note that the axes are $\log_{10}$ scaled. B) SUI values greater than 0.02 plotted by watershed area. (Data source: SRBC 2013a.)**

**Table 4-6. Count of daily SUI for all permit sites on days when water was withdrawn from 2009 to 2013 (n = 29,907). (Data source: SRBC 2013a.) The no passby scenario has more observations since there are no restrictions on withdrawals.**

| | Actual Observed | | Scenario Assuming No Passby Shutdown |
|---|---|---|---|
| **SUI Category** | **Number of Observations** | **% of Observations** | **Number of Observations** |
| 0-0-0.10 | 29,313 | 98.0% | 32,585 |
| 0.11-0.20 | 344 | 1.15% | 1,587 |
| 0.21-0.30 | 107 | 0.36% | 610 |
| 0.31-0.40 | 60 | 0.20% | 329 |
| 0.41-0.50 | 34 | 0.11% | 247 |
| 0.51-0.60 | 25 | 0.08% | 154 |
| 0.61-0.70 | 10 | 0.03% | 103 |
| 0.71-0.80 | 3 | 0.01% | 104 |
| 0.81-0.90 | 6 | 0.02% | 78 |
| 0.91-1.0 | 5 | 0.02% | 1,589 |
| Total | 29,907 | | 37,386 |

Fig. 4-24A uses boxplots to show five years of SUI observations at individual sites, identified by their basin area. Higher SUI was rare at river and stream locations under standard conditions, e.g. when permitting requirements for daily withdrawal limits and passby flows were in place. SUI never exceeded 0.1 when watershed area was greater than 17 to 27 mi$^2$, regardless of daily permit limits. SUI values greater than 0.2 occurred only in the smallest streams with watershed areas less than 7.8 mi$^2$, although we note that the bulk of SUI observations were less than 0.2 at all sites. Two of the very small streams were mine-drainage-impaired and had special permitting considerations allowing larger-volume withdrawals (1 MGD). Two were required to draw from small offstream ponding structures that may prevent impacts implied by the high SUI but maybe not realized due to the onsite water storage. Nevertheless, they also illustrate that small streams defined by contributing basin area less than 10 mi$^2$ are generally vulnerable to high water use intensity from hydraulic fracturing withdrawals. All SUI values exceeding 0.4 occurred at the three sites with basin area less than 7 mi$^2$ (Fig. 4-24A).

The general patterns of SUI in relation to observed rate of withdrawals and streamflow indexed by basin area shown in Fig. 4-24A are influenced by SRBC's low flow policies. The passby flow threshold designated in permits is designed to reduce impacts of water withdrawals on the daily water balance by ceasing withdrawals during lower flows. We illustrate the influence of the passby restriction by recalculating SUI on days when a passby shutdown would have been in effect, assuming the permit limit was withdrawn when normally no water would be pumped. This assumption will overestimate withdrawal effects, because hydraulic fracturing operators do not always withdraw their full quota, nor would they necessarily have used the sites on these days as evident in Fig. 4-21. The distribution of SUI assuming no passby flows were in place is shown by site in Fig. 4-24B and SUI count is included in Table 4-6. The scenario analysis suggests that the frequency of higher SUI would increase significantly and could involve sites with basin area up to about 700 mi$^2$ without the passby shutdown.

The passby policy protects aquatic life and supplies used by other users including PWS, as public supplies are not subject to low flow restrictions. There are strategies that allow withdrawals during passby shutdown periods. Operators can divert to public suppliers. Increased O&G use of PWSs during shutdown periods could not be explored, as PWS use is reported as an annually averaged daily value (PADEP 2014a).

O&G companies have constructed numerous small impoundments distributed throughout the SRB that store freshwater. One can be seen in the aerial photograph in Fig. 4-8, and one is shown at ground level in Fig. 4-25. Slonecker *et al*. (2012) counted 560 larger and 121 smaller temporary impoundments in Bradford County alone while performing a landscape analysis of hydraulic fracturing in the region. Some—like the one pictured in Fig. 4-25—are supplied by pipeline rather than trucks.

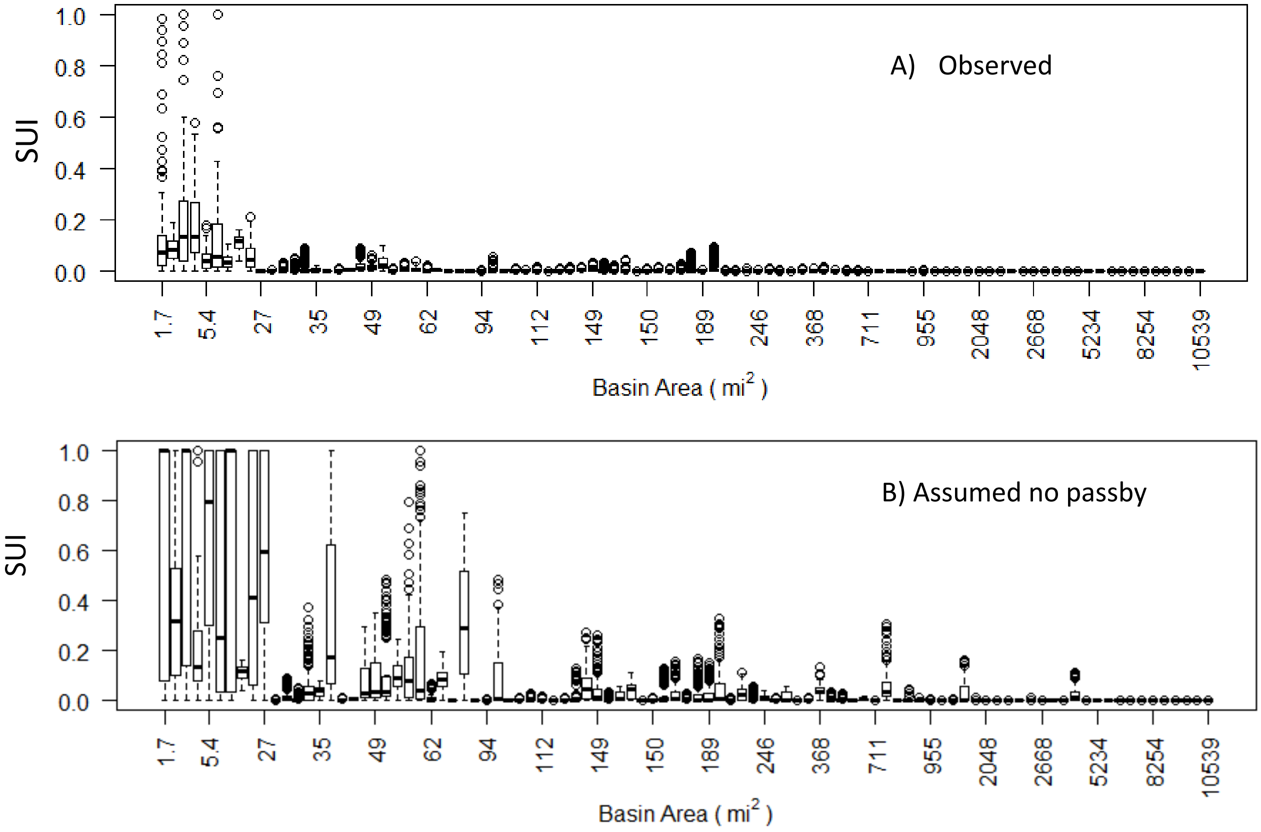


**Figure 4-24. Observed surface water stress index at permit sites on all days when water was withdrawn for hydraulic fracturing from 2009 to 2013 (n = 29,907). Sites are identified and displayed in order of their contributing watershed area. A) Observed record. B) Simulated effect of passby by withdrawing each site's maximum daily limit on days when passby would have been in effect. Upper and lower lines show the 5th and 95th percentiles; circles show the remainder of the population between the 95th and 100th percentiles. (Data source: SRBC 2013a.)**

Using Google Earth measuring tools to assess dimensions, we estimated that most of these impoundments have a 2 to 5 acre storage area and can hold 5 to 10 MG of water, or enough to fracture 2.5 wells. This total was confirmed in interviews with Southwestern Energy (November 14, 2014). In Bradford County, O&G impoundments collectively can store more than 5,500 MG of water to augment supplies during periods of passby shutdowns, enough to hydraulically fracture almost 1,400 wells. The increasing amount of privately owned storage capacity could have contributed to the decreasing use of municipal water supplies evident in Fig. 4-18A.

The observed withdrawals in SRB from 2009 to 2013 may not represent the full potential impact of hydraulic fracturing withdrawals. The time frame of available data was short and

**Figure 4-25. Photograph of O&G freshwater impoundment to service hydraulic fracturing water needs.**

extreme low flows may not be represented. Very small streams can provide water for hydraulic fracturing but are not well represented in the permitted sites at present—their use could be more prevalent in the future here or in other areas. The growing number and increased density of permitted sites could have a "cumulative" effect not addressed in site-by-site analyses. Hydraulic fracturing drilling rates have been relatively static for three of the five years of available data and are projected to be higher in the future. Groundwater wells provide water to hydraulic fracturing, but availability of water is difficult to quantify. We addressed these potential effects of these factors on SUI and GUI by extending what we learned from observed hydraulic fracturing water use patterns with scenario analysis and modeling.

### Scenario Analysis of Hydraulic Fracturing Withdrawal on Water Use Intensity

Climate, watershed size, cumulative withdrawals, increased water demand, and groundwater impacts were further explored by hindcasting SUI for hydraulic fracturing withdrawal scenarios at local stream sites using historical streamflow records. Analyses were conducted in selected subbasins within the SRB focusing on smaller basin areas that appear most likely to experience high use intensity from withdrawals (less than 500 mi$^2$). Small towns and more than 60 of the permitted withdrawal sites are located in 26 named subbasins of smaller rivers and creeks within this basin size (HUC 8-12). We present four scenario analyses related to water balance associated with hydraulic fracturing water acquisition designed to:

- Improve understanding of small stream, climate, and potential hydraulic fracturing water demands on local water use intensity by dividing a watershed into first- to fifth-order streams and applying withdrawal rates to mimic current and projected maximum drilling rates over 26 years;
- Demonstrate passby effects on SUI at a USGS gaged site over a lengthy flow record;
- Consider cumulative permit effects based on observed withdrawals in a watershed with multiple active hydraulic fracturing withdrawal permits;
- Explore groundwater volumes and pumping impacts at several groundwater wells currently providing water for hydraulic fracturing.

Surface water availability was determined from long-term USGS gages extrapolated to subwatersheds using various methods. Observed records were directly used for some analysis or extrapolated to small stream sites using the hydrologic simulation model HSPF. Groundwater modeling techniques were used for aquifer analysis.

We focused our scenario analysis on Towanda Creek, a small river in Bradford County with watershed area of 215 mi$^2$ (Fig. 4-26). The watershed is representative of hydraulic fracturing activity as well as natural physiography and land use in the area.

We chose this watershed, because it has two USGS streamflow gaging sites and two nearby rain gages with a lengthy record to allow model parameterization and calibration. There has been hydraulic fracturing well drilling in the basin, and there are two permitted self-supplied withdrawal sites. Towanda Creek joins the middle branch of the Susquehanna River at the town of Towanda, Pennsylvania. There are two municipal water suppliers in the watershed that have provided water for hydraulic fracturing from groundwater wells. See Figs. 4-4 and 4-26A for location of the Towanda Creek watershed within the SRB, Fig. 4-26B for hydrologic use and measurement landmarks within the watershed, and Fig. 4-26C for location of existing hydraulically fractured wells.

Bradford County and the Towanda Creek watershed are located in the Appalachian Plateau physiographic province within the Pleistocene glacial margins. Surficial geology is composed of horizontal inter-bedded sandstones, siltstones, and claystones and unconsolidated glacial and alluvial deposits in the valleys. Towanda Creek consists of two main branches (HUC-10) that join above the gage at Monroeton. Two sedimentary formations characterize the two branches, with the Chemung formation in the northern branch and the Lock Haven formation in the southern. This gives rise to a dichotomy in topography and land use that occurs more generally throughout much of the Appalachian Plateau region in the SRB (Fig. 4-27A).

Land use in Towanda Creek in the northern branch is mixed agriculture with interspersed small towns (Fig. 4-27A). The southern branch, with greater relief, is predominantly forested and is protected as a state game reserve. There is moderate topographic relief in the Towanda Creek with elevations ranging from 770 feet at the outlet to 2436 feet above sea level along the northwestern divide. Topography is subdued with broad valleys and moderate relief in the northern branch subbasin and steeper with incised valleys in the southern branch. Soils are primarily well-drained loamy inceptisols and entisols formed in glacial and alluvial parent material (Grubb 1986). Rainfall differed somewhat between the two weather stations, and land use and topography varied with the geology. The variable physiography, land use, and weather within the Towanda Creek basin allowed it to represent the wider range of variability in these characteristics within the region.

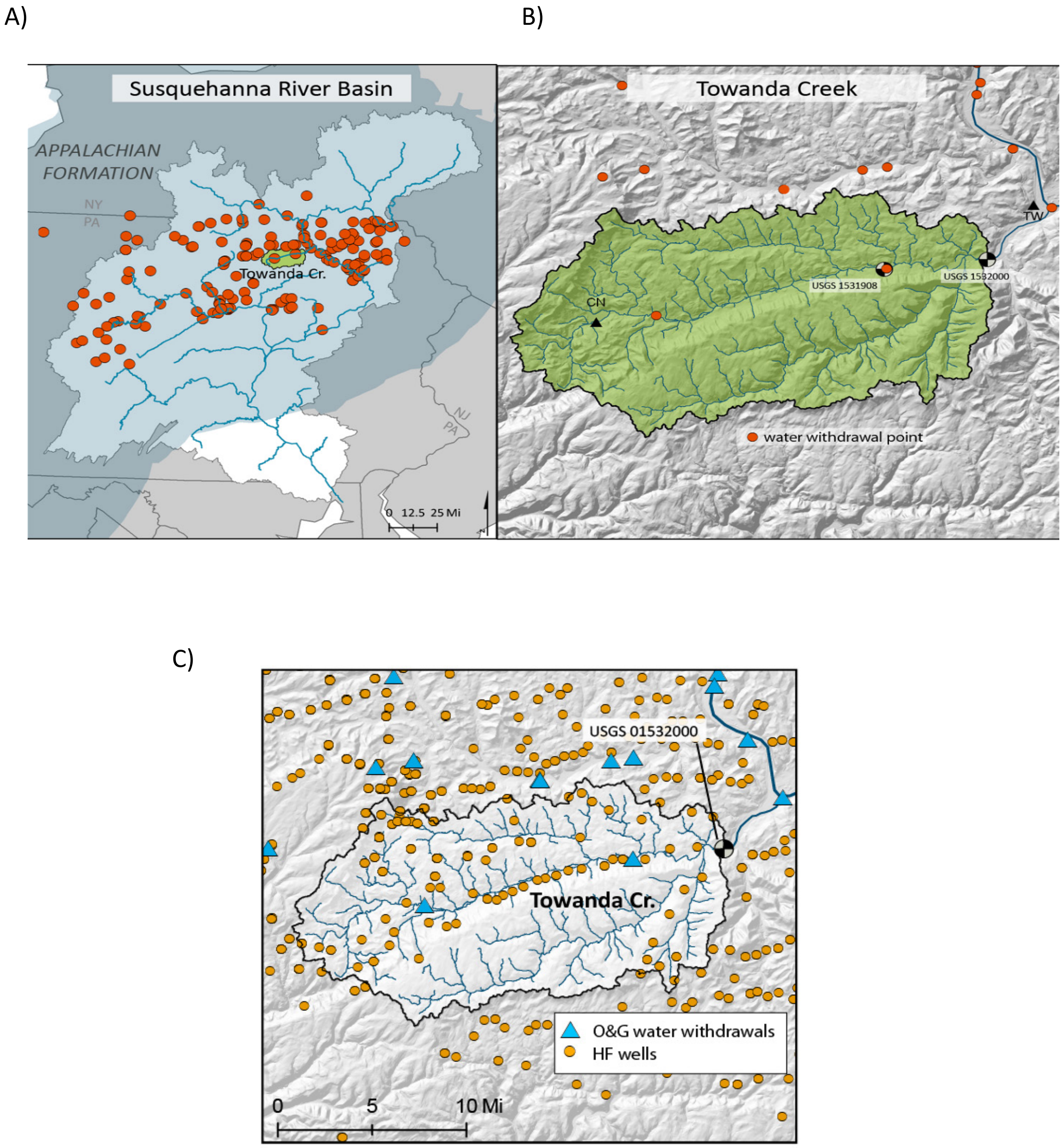


**Figure 4-26. Towanda Creek basin in Bradford County, Pennsylvania. A) Basin location map within the Susquehanna River Basin, with permitted self-supplied hydraulic fracturing withdrawal sites (red dots). B) Shaded relief map of the Towanda Creek watershed, showing meteology sites as black triangles labeled "TW" and "CN" (source: NOAA 2013), USGS gages (source: USGS 2014b), and permitted withdrawal sites (red dots). C) Map with existing hydraulic fracturing wells added as orange circles, showing withdrawal sites as blue triangles. (Data sources: PADEP 2013a for hydraulic fracturing wells, SRBC 2013a for permitted withdrawal locations.)**

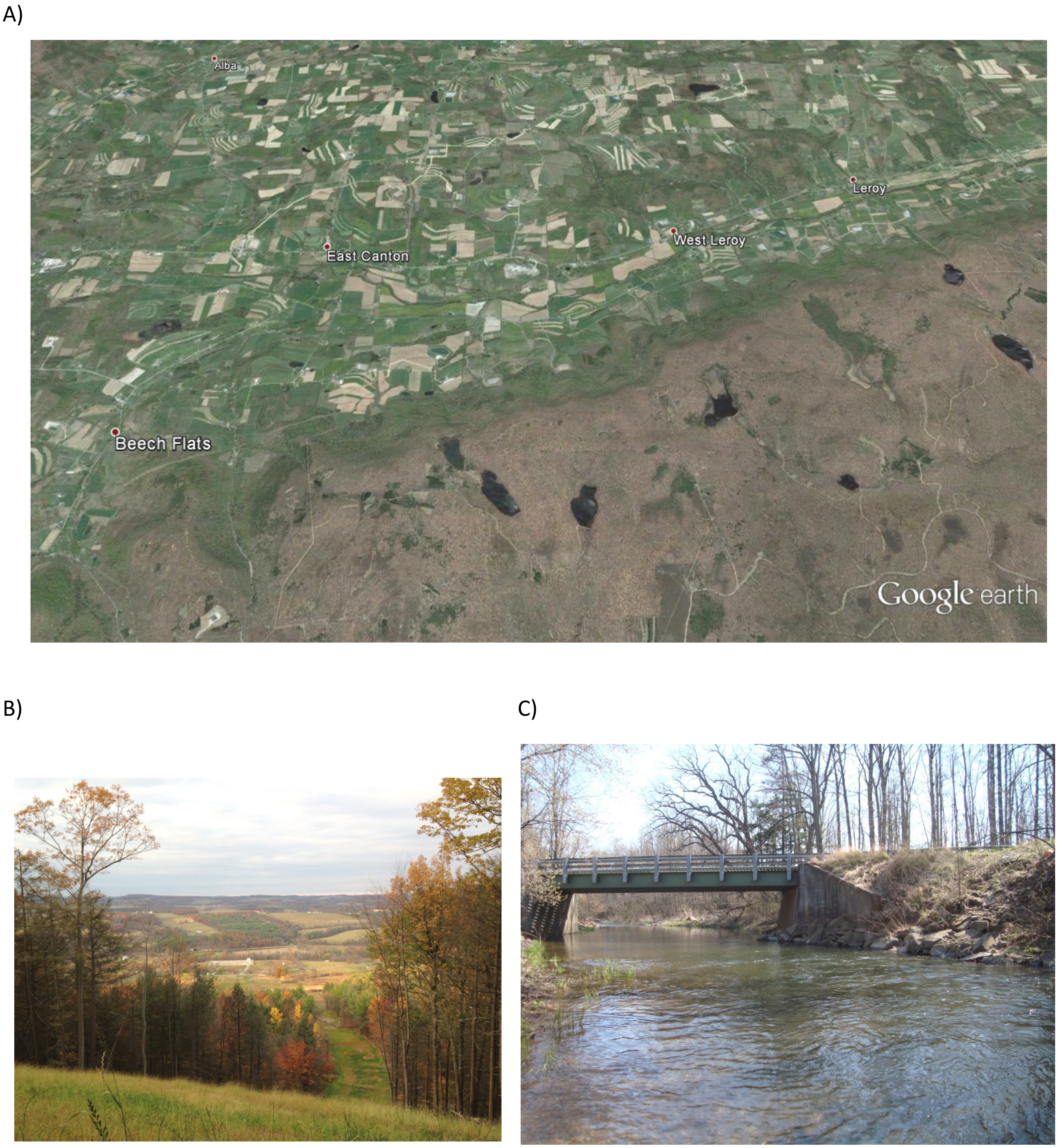
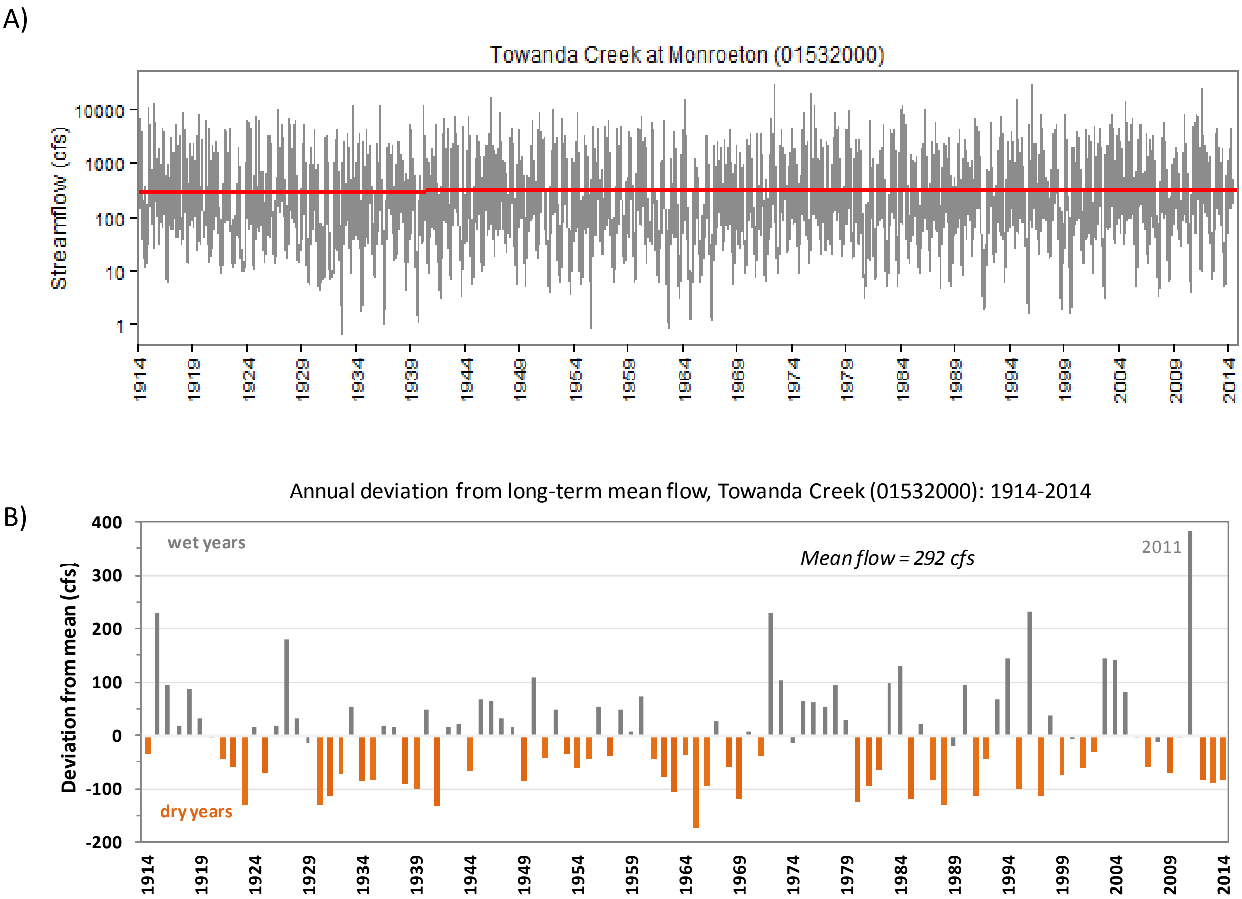


**Figure 4-27. Visual display of land use, topography, and river size and form in the Towanda Creek basin. A) Aerial photograph at 15,000 feet, showing a portion of the southern branch of Towanda Creek with forest and steeper topography at the bottom, and the northern branch with subdued topography and agricultural land use at the top, divided by a ridgeline at center. (Image from Google Earth, USDA Farm Service Agency, 2013). B) Landscape perspective looking into the northern branch of Towanda Creek from the ridgeline between the north and south branches. A gas pipeline right-of-way is in the foreground. C) Towanda Creek mainstem at about river mile 15. (Source: Wikipedia.org; image by Labenedict.)**


Towanda Creek at Monroeton (01532000)

Annual deviation from long-term mean flow, Towanda Creek (01532000): 1914-2014

**Figure 4-28. Long-term flow at the USGS gaging station at Monroeton (USGS 01532000). A) Mean daily flow, in cfs, with the average of daily means for the total period shown as the red line. B) Annual deviation from the mean, in cfs. (Data source: USGS 2014b.)**

**Table 4-7. Flow statistics at USGS gage in Towanda Creek (01532000; 215 mi$^2$) for various time periods used in this analysis. The scenario analysis used 1987 to 2012; 2009 to 2013 is the period of water withdrawal for hydraulic fracturing. Data in cfs; 1 cfs = 0.65 MGD. (Data source: USGS 2014c.)**

| Time Period | Mean of Daily Flow (cfs) | Deviation from Long-Term Mean (cfs) | Median of Daily Flow (cfs) | Average Seven-Day Low Flow (cfs) | Minimum Flow (cfs) |
|---|---|---|---|---|---|
| 1914–2013 | 293 | 0 | 120 | 10.9 | 0.7 |
| 1987–2012 | 306 | +13.6 | 139 | 10.6 | 1.7 |
| 2009–2013 | 322 | +29.6 | 155 | 9.7 | 4.1 |

The USGS flow gaging station in Towanda Creek at Monroeton (USGS 01532000) has operated since 1914. The 100-year streamflow record is shown in Fig. 4-28, with mean daily (A) and deviation from the annual mean (B). Flow statistics for time periods pertinent to this study are provided in Table 4-7, including the long-term record (1914 to 2013), hydraulic fracturing activity (2009 to 2013), and scenario analysis (1987 to 2012). SUI will vary commensurate with deviation of streamflow from the norm. The recent period of hydraulic fracturing activity was generally wetter than average, with higher mean and minimum flows.

**Scenario: Assess Hydraulic Fracturing Withdrawal Over Longer Climate Record and Stream Size.** In this scenario analysis, we extended analysis of hydraulic fracturing withdrawals from five years to 26 years, thus increasing coverage of variable climatic conditions. The scenario also considered much smaller subbasins, including first-order headwaters as small as 0.3 mi$^2$. This scenario simulated hydraulic fracturing withdrawals to meet current and projected water needs with future drilling rates.

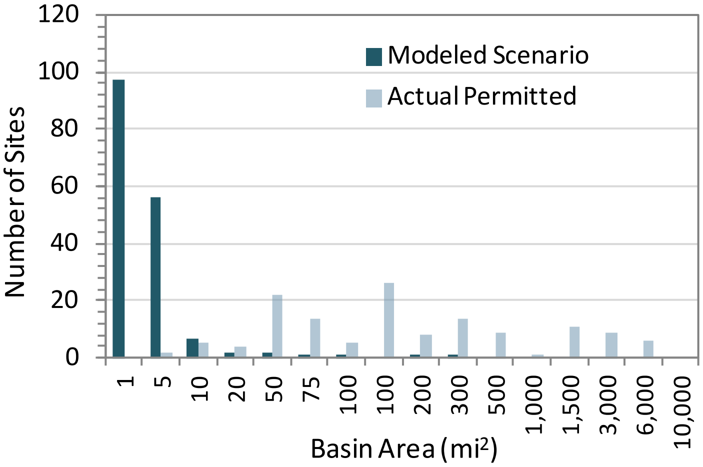


**Figure 4-29. Comparison of contibuting watershed area of Towanda Creek subbasins used for scenario analysis and Susquehanna River Basin Commission–permitted surface water sites in the Susquehanna River Basin. (Data source for permitted sites: SRBC 2013a.)**

First, the watershed was divided into a nested set of subbasins from first to fifth order using the Strahler stream ordering method to establish streamflow prediction points below each change in stream order. The process was automated by the ArcSWAT extension for ArcGIS 10.0, which divides the watershed into units associated with individual stream segments that are defined based on a user-specified accumulation threshold for perennial streamflow. The perennial streamflow location was estimated as the "blue line" on USGS 1:24,000 maps, and a portion were field-verified during annual low flow in November 2013. Subbasins were aggregated into watersheds encompassing the entire contiguous area upstream of each subbasin outlet where streamflow was predicted. In all, 168 subbasins were delineated: 134 were located on first-order streams, 26 on second-order streams, five on third-order streams, two on fourth-order streams (the north and south branches of Towanda Creek), and one on the fifth-order basin corresponding to Towanda Creek at the Monroeton USGS gaging station. The areas of subbasins established in the Towanda watershed overlap SRB permitted sites as shown in Fig. 4-29. The scenario analysis contains many smaller streams that are not permitted in SRBC at present, but could feasibly provide water for the O&G industry in the SRB and elsewhere.The subbasins are varied in land use and vegetative cover between the north and south branches reflecting the variability illustrated in Fig. 4-27.

**Scenario Water Availability Estimates.** There are no USGS gages of comparable size to the smallest subbasins that could be used for empirical extrapolation of daily streamflow. Thus we opted to use a streamflow simulation model (HSPF) to generate a daily flow record at each stream prediction location. HSPF is a widely used, freely available, FEMA-endorsed deterministic model for streamflow and water quality simulation (Bicknell *et al.* 1997; FEMA 2014). Based on user-supplied input data including spatially and temporally distributed weather, soils, topography, and land cover, the model partitions water to hydrologic processes including evapotranspiration, infiltration, surface runoff, and exfiltration of water from subsurface as streamflow (Bicknell *et al.* 1997). Land use was acquired from the Multi-Resolution Land Characteristics Consortium. Climate data including temperature and precipitation were obtained from the NOAA National Climate Data Center (NOAA 2013) for the two meteorological sites. Soils data were obtained from the Natural Resources Conservation Service. (See Appendix A for a compendium of data sources and Appendix B for additional discussion of the hydrologic model, data sources, calibration procedures, and uncertainty analysis.)

Streamflow measured at the USGS gaging station was used for calibration and validation. HSPF was calibrated using a Monte Carlo method to optimize the parameter set that best matched simulated with observed streamflow at the

USGS-gaged Towanda Creek outlet. The objectives of the calibration were to (1) favor good prediction of low flows over high flows and (2) minimize over-fitting the model by retaining as few parameters as possible. In general, HSPF tended to overestimate low flows and underestimate high flows, but the calibration approach identified an optimized parameter set that agreed well with observed flows across a range of magnitudes. Originally, the project intended to use both HSPF and SWAT hydrologic models to estimate streamflow. The choice of Monte Carlo calibration methods precluded use of SWAT due to computational inefficiencies introduced with this approach. (See Appendix B for more discussion of model application.) Calibration resulted in a weighted Nash-Sutcliffe (WNS) score of 0.74, which exceeds common performance thresholds used for raw WNS (Moriasi *et al.* 2007; Narasimhan *et al*. 2005).

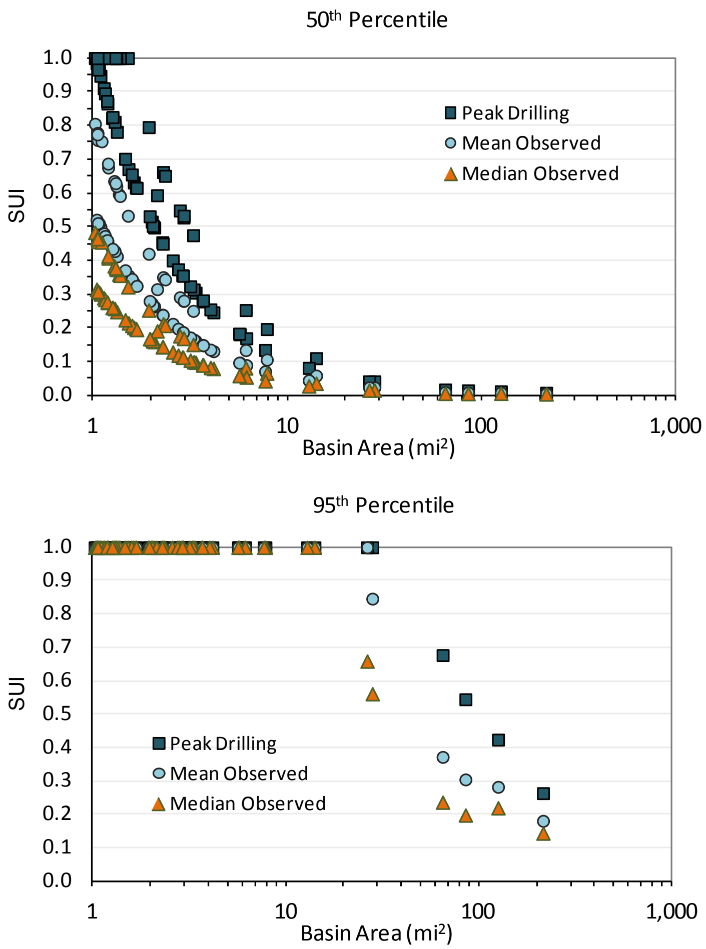
Once calibrated parameter sets were established, streamflow was simulated at all 168 streamflow prediction points in Towanda Creek for the period 1987 to 2012, chosen due to availability of necessary weather data. This period increased representation of low flows relative to the 2009 to 2013 period of hydraulic fracturing activity (Table 4-7), but still did not encompass the lowest flow of 0.7 cfs observed in Towanda Creek in 1932.

**Scenario Consumption Estimates.** Scenarios were designed to test all flows in the 26-year period in proportion to their occurrence at each site. Each day, a volume of water was withdrawn that included a “background” volume (accounting for unmeasured withdrawals for uses such as irrigation, livestock watering, and residential), and a hydraulic fracturing volume assumed to be consumed in hydraulic fracturing wells drilled in the Towanda Creek basin. Background consumption was estimated from county water use rates determined from data from the USGS water census, U.S. Census Bureau, and the U.S. Department of Agriculture. Background use was on the order of 0.1 MGD per mi$^2$, but varied with land use in each subbasin. See Appendix D for more information on derivation of water use assumptions in scenario analysis.

Three hydraulic fracturing scenarios were applied as summarized in Table 4-8. Two reflected current withdrawals in the SRB, including the median (0.19 MGD), and mean (0.31 MGD) daily withdrawal observed at all permitted sites. The third represented a future peak drilling rate. U.S. EIA (2014c) projects increased production in the Marcellus Shale in future decades, with well density eventually reaching 4.9 wells per mi$^2$ (U.S. EIA 2014c). Johnson (2010) and SRBC (Beauduy 2009) estimate that as many as 2,800 hydraulic fracturing wells could be drilled annually. Based on area, the total prorates to about 52 hydraulic fracturing wells per year in the Towanda basin, or about one well per week (4 MG), requiring 0.57 MGD of freshwater. In 2011, 33 hydraulic fracturing wells were drilled and stimulated in the Towanda basin (PADCNR 2014a), so the selected maximum drilling rate appears reasonable. The daily water withdrawals for hydraulic fracturing used in all three scenarios have been routinely observed in streams with basin area as small as 1.7 mi$^2$. The scenario analysis assumed that all hydraulic fracturing wells consume water from one source every day for 26 years, rather than distributing withdrawals among the subbasins. This analysis ensures that the entire flow history is sampled in proportion to the frequency that each flow occurs. SUI calculations were performed at each stream prediction location. No passby was used.

**Table 4-8. Description of hydraulic fracturing withdrawal scenarios applied to 26 years of streamflow (1987–2012) in subbasins of the Towanda Creek watershed in Bradford County, Pennsylvania.**

| Scenario ID | Towanda Creek Withdrawal Scenarios for Surface Water Use Intensity Index Analysis | | | |
|---|---|---|---|---|
| | Water Demands | Hydraulic Fracturing Demand Assumptions | MGD | cfs/day |
| Median observed | Hydraulic fracturing current demand | Median daily of all permitted withdrawal sites | 0.19 | 0.3 |
| Mean observed | Hydraulic fracturing current demand | Mean observed of all permitted withdrawal sites | 0.31 | 0.5 |
| Peak drilling | Hydraulic fracturing peak demand | One well per well @ 4.0 MG/week | 0.57 | 0.9 |
| Background | Unmeasured background water use by other users | Irrigation, livestock, and residential assuming rates based on county-scale assessment (on the order of 1,000 GPD/mi²) | Variable depending on land use in each subbasin | — |



**4-30.Surface water use intensity (SUI) distribution statistics for withdrawal scenarios applied to subbasin streamflow prediction points in Towanda Creek. Withdrawal scenarios include peak drilling, mean, and median withdrawals (see Table 4-8). A) 50th percentile of the distribution simulated for 26 years. B) 95th percentile of the observations.**

**Long-term SUI.** SUI values from the 26-year simulated flows are summarized by population distribution statistics of median and 95th percentile in Fig. 4-30. The small streams emphasized in this analysis have relatively low streamflow much of the year. SUI follows basin area closely as an index of available flow and varies with withdrawal volume. The scatter within each withdrawal scenario reflects the differences in rainfall and land use between the subbasins. In small streams less than 10 mi$^2$, withdrawals can approach or equal available streamflow frequently during most years evident in SUI exceeding 0.4 for 50 to 95 percent of the time. For example, the median SUI under the mean observed withdrawal scenario exceeds 0.5 for watersheds less than approximately 2 mi$^2$ (Fig. 4-30A). The 95th percentile of SUI values for all three scenarios equaled 1.0 in watersheds less than 30 mi$^2$ (Fig. 4-30B).

The 95th percentile of SUI declined to less than 0.2 in watersheds greater than about 200 to 300 mi$^2$ for the peak drilling scenario and at about 70 mi$^2$ for the median scenario. The same threshold was observed at about 5 mi$^2$ at actual hydraulic fracturing withdrawals sites (Fig. 4-24A), reflecting the higher flows observed during the limited period of active hydraulic fracturing operations (2009 to 2013). The scenario analyses demonstrate the vulnerability to over-withdrawal in smaller streams, especially in watersheds smaller than 10 mi$^2$ and extending to larger watersheds infrequently. It is clear that SUI is sensitive to basin area and volume withdrawn.

Fig. 4-31 shows SUI at streamflow prediction points in Towanda Creek for the peak drilling withdrawal at median streamflow. The larger subbasins could maintain lower SUI for the withdrawal volumes at commonly occurring flows, but most small streams that are potential withdrawal sites for hydraulic fracturing could not.

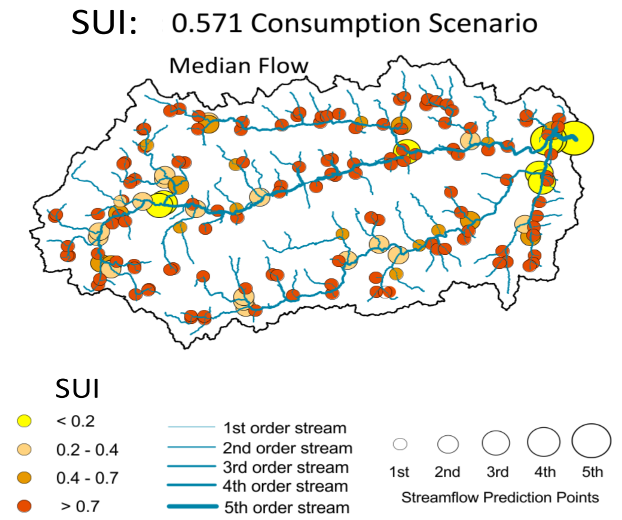


**Figure 4-31. SUI at peak drilling and median flow at subbasin streamflow prediction points in Towanda Creek subbasins. The Towanda Creek basin is approximately 23 miles from mouth to headwaters and 11 miles in width.**

**Regional Flow Equation Estimates of SUI Thresholds.** Basin area thresholds to support minimum streamflow necessary to support hydraulic fracturing withdrawals could also be estimated from regional flow equations. These equations apply multiple linear regressions to long-term USGS flow records, including geographic factors that influence streamflow, to develop estimates of flow rates for flow frequency statistics. Equations predict streamflow (cfs) as a function of basin area and often include parameters such as precipitation or land use factors that improve prediction precision. Regional regression equations are used as a basis for SRBC permit specifications (SRBC 2003, 2012). Stuckey (2006) provided regionalized streamflow regression equations for Pennsylvania that include basin area, mean annual precipitation, mean elevation, and percent of the watershed in forest cover, glaciated, and in urban land use as predictive variables. These methods are more readily available for most users than spatially explicit hydrologic modeling as used in our scenario analyses, but they do not provide daily flow estimates.

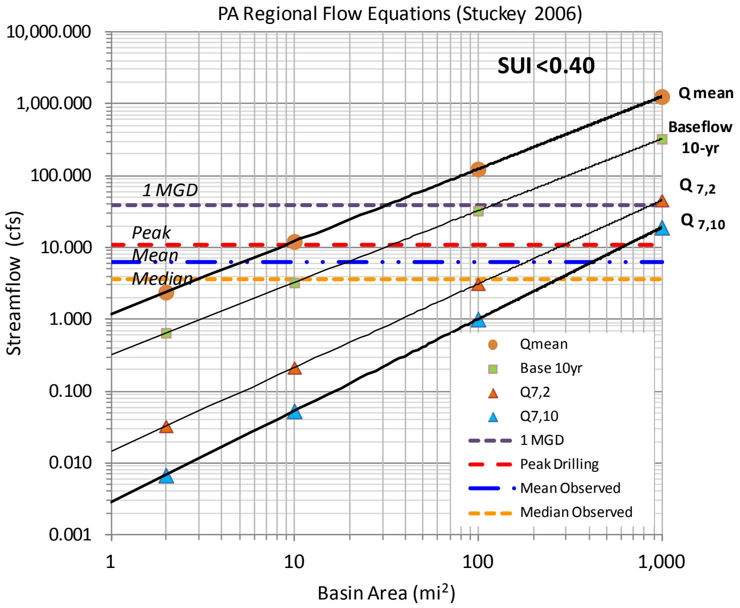


**Figure 4-32. Pennsylvania regional flow equations applied to the Towanda Creek watershed with withdrawal scenarios. (Model source: Stuckey 2006.) SUI exceeds 0.4 where flow statistics (diagonal) intersect withdrawal volumes (horizontal lines).**

The regression predictions for several flow statistics, including mean annual and the average annual seven-day low flow with 2-year ($Q_{7,2}$) and 10-year return intervals ($Q_{7,10}$) for the Towanda Creek basin, are shown in Fig. 4-32. A few individual data points are included to assist the reader locate the diagonal line for the four flow frequency statistics.

In this example, we seek the basin areas for each of the withdrawal scenarios (Table 4-8) that will produce a SUI no greater than 0.4. We included a fourth withdrawal of 1 MGD for this analysis. A minimum flow of 25% was maintained to mimic the passby flow. The flow threshold can be determined with the regional equation by converting the total withdrawal volume to streamflow rate (cfs) and dividing by the SUI threshold of interest. The streamflow regressions remain in the same position on the chart with each withdrawal scenario, but the withdrawal lines move up and down depending on the selected SUI threshold. Fig. 4-32 shows results for SUI 0.4 or lower.

For SUI to be less than 0.4, flow must be above the horizontal withdrawal line. The basin area thresholds can be identified by tracing horizontally along the withdrawal volume line to where each intersects the flow statistic line. For example, the median withdrawal of 0.19 MGD (lowest horizontal line) can be supported while maintaining the SUI at less than 0.4 at mean annual flow when basin area exceeds 3 mi$^2$, at the 10-year baseflow when basin area is about 10 mi$^2$, at $Q_{7,2}$ when basin area exceeds 100 mi$^2$, and at the 10-year low flow $Q_{7,10}$ when basin area exceeds 300 mi$^2$. The regressions are primarily determined by basin area, but they are also sufficiently sensitive to the land use and climate input parameters that results will vary somewhat from basin to basin. The regional equations confirm that the necessary watershed size to support typical hydraulic fracturing withdrawals in the SRB varies over orders of magnitude from low flow to high flow dependent on withdrawal volume.

We compared regional regression with HSPF simulation for low flow ($Q_{7,10}$) and annual mean flow ($Q_{mean}$). Mean flows across a wide range of drainage areas were very close using these two methods. The best-fit HSPF $Q_{7,10}$ estimates agreed closely with the regional equation-derived estimates, particularly in smaller watersheds, which were the focus of much of this analysis. HSPF tends to estimate lower $Q_{7,10}$ flow than the regional equations, particularly in larger watersheds. (See graphical comparisons of the regional equation and HSPF comparison in Appendix B.)

**Scenario Illustrating the Effect of Passby on SUI in a Small River.** This scenario analysis demonstrates the effect of the passby flow at a site in a small river. For this computation the same volume of water was withdrawn daily from Towanda Creek at the location of USGS gage (01532000, B.A. 215 mi$^2$) from 1987 to 2012. The passby threshold (12 cfs) and withdrawal limit of 1 MGD were specified in the permit of a nearby O&G withdrawal site. The computations were performed with and without the passby flow assigned to the site. Results are shown in Fig. 4-33. No background consumption was included.

The minimum flow restrictions assigned by the passby threshold would have been invoked on 770 days during the 26-year period. SUI in the more recent years of 2009 to 2013 was generally lower than in the decade of the 1990s. The passby was significant in preventing higher SUI. Without the passby, SUI greater than 0.4 would have occurred on 103 days, and SUI exceeding 0.7 would have occurred on 25 days (Fig. 4-33 and Table 4-9). Even in this small river (see Fig. 4-27C), SUI would have reached as high as 0.9. With the passby flow restrictions, there would have been no days exceeding 0.1 (Fig. 4-33B). The count of days of SUI with and without passby is provided in Table 4-9.

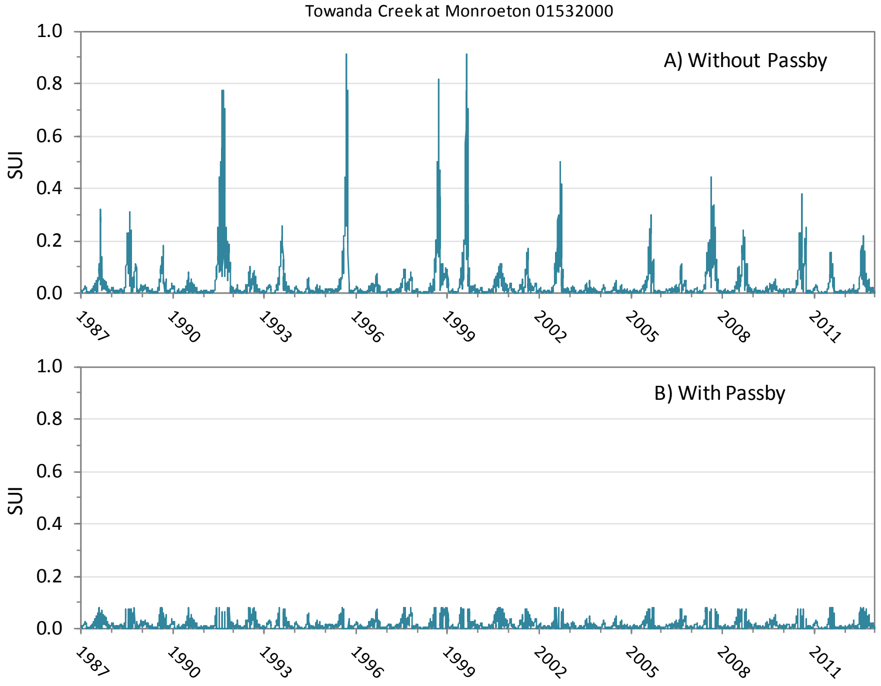


**Figure 4-33. Simulated daily surface water use intensity index computed with the U.S. Geological Survey gaging record at Towanda Creek (USGS 01532000) from 1987 to 2012, assuming 1.0 MGD withdrawal for hydraulic fracturing and background consumption of 0.3 million gallons per day. Scenarios calculated with passby flow (A) and without passby flow (B). (Data source: USGS 2014b.)**

**Table 4-9. Count of days by surface water stress index category with withdrawal simulation of 1 million gallons per day with and without passby flows applied to Towanda Creek (1987 to 2012, n = 9,497). (Data source: USGS 2014b.)**

| SUI Category | Count of Days | |
|---|---|---|
| Less than or equal to | **With Passby** | **Without Passby** |
| 0-0-0.10 | 9497 | 8593 |
| 0.11-0.20 | 0 | 549 |
| 0.21-0.30 | 0 | 188 |
| 0.31-0.40 | 0 | 64 |
| 0.41-0.50 | 0 | 42 |
| 0.51-0.60 | 0 | 20 |
| 0.61-0.70 | 0 | 16 |
| 0.71-0.80 | 0 | 20 |
| 0.81-0.90 | 0 | 3 |
| 0.91-1 | 0 | 2 |

Passby threshold flows can shut down hydraulic fracturing withdrawals a number of days each year, since they generally are set at 20% to 25% of the mean annual flow. The full 100-year flow record at the Towanda gage was analyzed for frequency of occurrence of the passby on an annual basis. SRBC applied an annual low flow passby until permit renewal in 2013 when monthly values were assigned. The number of days on which a passby would have occurred using both approaches is shown in Fig. 4-34. Over 100 years, the annual passby would have been invoked 7.4% of total days (2,726), and would have involved as many as 160 in the 100-year drought (1931). The monthly passby tends to add 10 to 20 days of closure each year. Although it may appear in Fig. 4-34 that passby occurrence was less frequent during the recent 26-year modeling period, the annual proportion of days in passby was about the same as in the 71 preceding years.

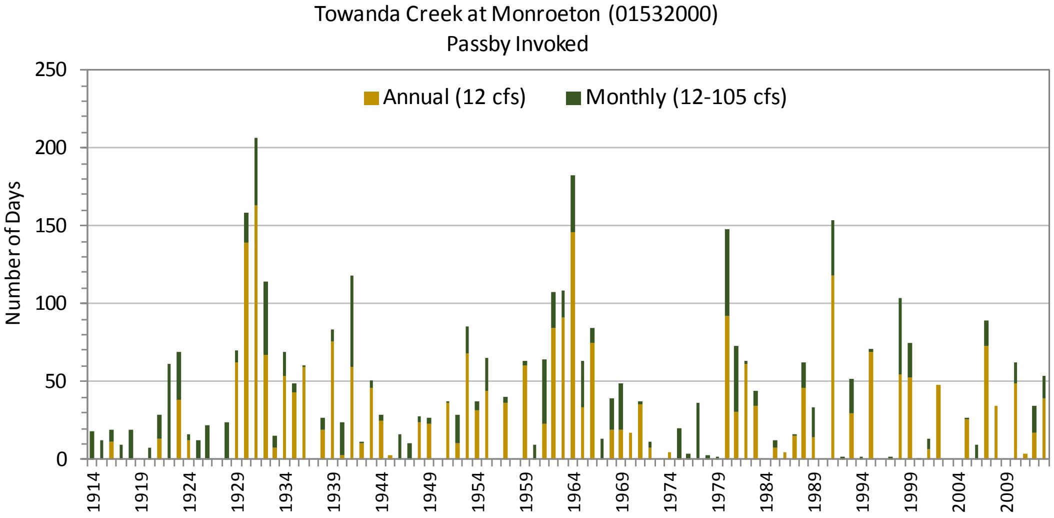


**Figure 4-34. Count of days each year that the flow fell below the passby flow assigned by the Susquehanna River Basin Commission to U.S. Geological Survey Towanda Creek gaging station. SRBC first assigned an annual passby flow level. A monthly passby is now assigned during renewal of permits. (Data source: USGS 2014b.)**

**Scenario Evaluating Cumulative Permit Effects.** As the number of permitted sites grows, they begin to accumulate in 30 HUC 8 to 10 tributaries to the Susquehanna River. Some are in relatively close proximity, probably reflecting locations where streams can be legally and safely accessed near major roads. In this scenario, we briefly examine the cumulative effects of individual permits. We selected one location on Wyalusing Creek where four withdrawal sites are located within a basin area of approximately 150 to 190 $mi^2$. We summed the daily withdrawals and the permit capacity at the four sites and withdrew the combined volume from the streamflow at one of the sites. Total permit capacity for the group was 5.43 MGD (nearly twice the permitted volume at any single site in the SRB).

Fig. 4-35 shows SUI associated with the summed observed withdrawals and maximum capacity, assuming all volume was taken at each site every day. Observed SUI were low for actual withdrawals (< 0.01), and increased to a maximum of 0.16 had the full capacity been used. This example does not indicate significant cumulative effect from multiple permits, which are limited by the passby shutdowns, as shown in Fig. 4-33. SUI would be significantly higher at this level of withdrawal if passby flows were not in effect as illustrated in Fig. 4-33.

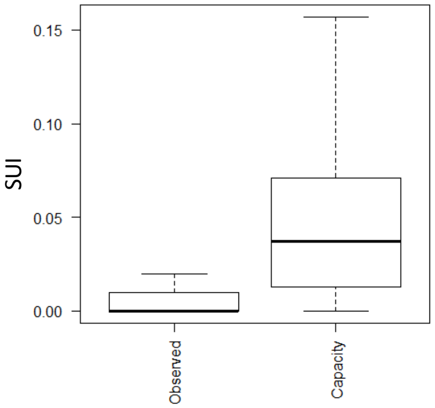


**Figure 4-35. SUI analysis of cumulative withdrawals from four permitted sites on Wyalusing Creek. Box plots are the distribution of the SUI for the combined daily withdrawals. Boxes are 75% percentiles; bars are 95th percentiles. (Data source: SRBC 2013a.)**

## Analysis of Hydraulic Fracturing Water Acquisition on Groundwater

Groundwater supplies about 20% of the water used for hydraulic fracturing in the SRB, or about 2 MGD (Fig. 4-36). Groundwater-based providers are distributed throughout the SRB and include seven self-supplied sites and 15 active PWSs (Fig. 4-37). Of this group, two commercial (but not public) wells have provided most of the self-supplied groundwater, and two municipal PWSs have provided 40% of all of the publically supplied water (Fig. 4-36). The majority of groundwater is obtained in Bradford, Lycoming, and Wyoming Counties. Figure 4-37 includes all PWSs that are available as identified to SRBC. While available, they do not all provide water to O&G.

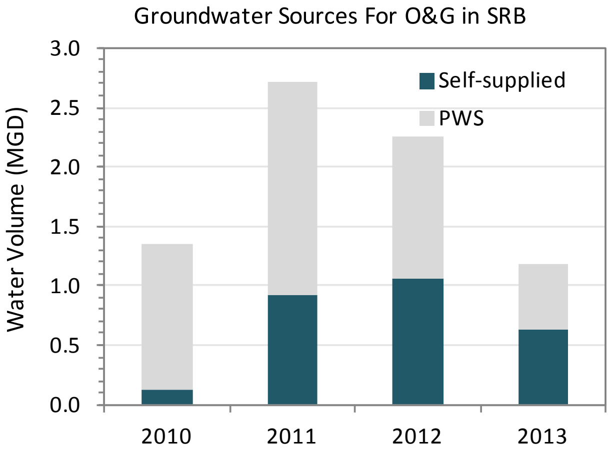


**Figure 4-36. Daily rate of groundwater supplied to the oil and gas industry from public water systems and self-supplied sources. (Data sources: PADEP 2014a; SRBC 2013a.)**

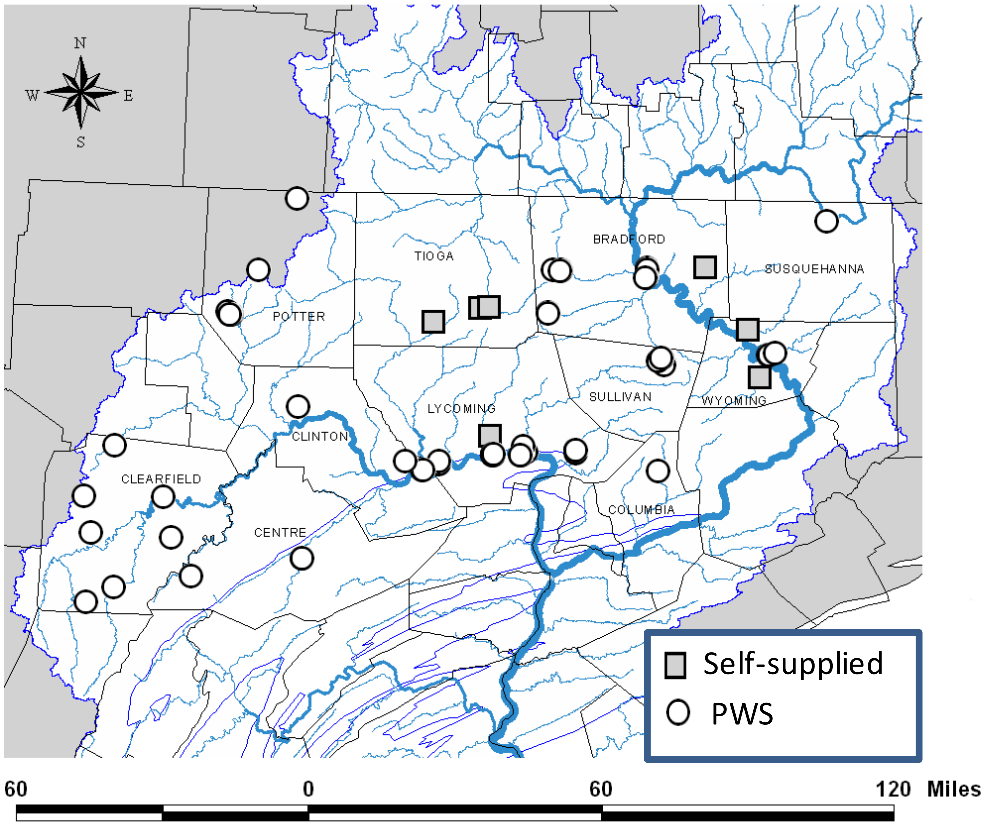


**Figure 4-37. Groundwater wellfields currently available for water acquisition by the oil and gas industry in the Susquehanna River Basin. Circles represent public water systems with documented supply to the oil and gas industry. (Data source: U.S. EPA 2012c.) Squares represent self-supplied (private) sources permitted by the Susquehanna River Basin Commission. (Data source: SRBC 2013c.)**

In this rural area within the SRB where hydraulic fracturing is active, water resource use is low as there is relatively low population or industrial use. Usage is centered near towns that utilize public supply wells, springs, or domestic wells. Many towns within the Susquehanna River valley are situated on or adjacent to alluvial fans of large tributary streams that overlie saturated sand and gravel (outwash or ice-contact deposits) and commonly tap thin permeable sand and gravel zones just above bedrock or a few feet into fractured bedrock for water supply (Heisig 2012). The alluvial floodplains are about 50 to 150 feet thick, and store a significant volume of water that is in exchange with the river and continually recharged by rainfall. Confined and unconfined aquifers within the valley-fill are the only potential groundwater source of large municipal, commercial, or industrial supplies in this area (Heisig 2012). Usage in the upland area consists of widely spaced domestic wells that tap the bedrock aquifer.

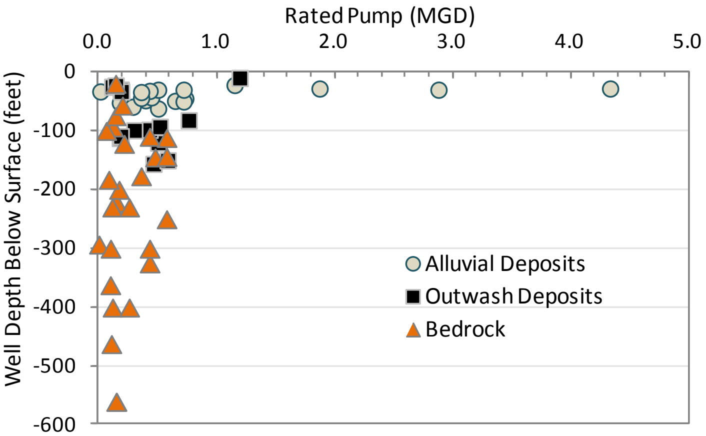


**Figure 4-38. Depth and pumping capacity of public and self-supplied groundwater sources registered to supply water for hydraulic fracturing in the Susquehanna River Basin classified by geology type. (Data sources: PADCNR 2014a; PADEP 2013a; SRBC 2013c.)**

The relationship between well depth, pumping capacity, and geologic substrate at the public and private groundwater supply sites that are registered to provide water to hydraulic fracturing operators is demonstrated in Fig. 4-38. The highest yielding wells are found in the river alluvium and glacial outwash. The majority of wells are relatively low-yielding and mixed between tapping alluvium, glacial outwash, and bedrock aquifers. Domestic wells in the uplands tend to be deeper.

We were interested in assessing the potential impacts of hydraulic fracturing acquisition on groundwater resources, although determining available water volume was not as straightforward as it was for surface water. In this section we explore groundwater withdrawal effects at two spatial scales: the Towanda Creek watershed scale (215 mi$^2$) and the local site scale. The questions guiding the analysis were: 1) What is an effective extent of the groundwater reservoir? and 2) How does groundwater use at the watershed and local scale affect other users and streamflow?

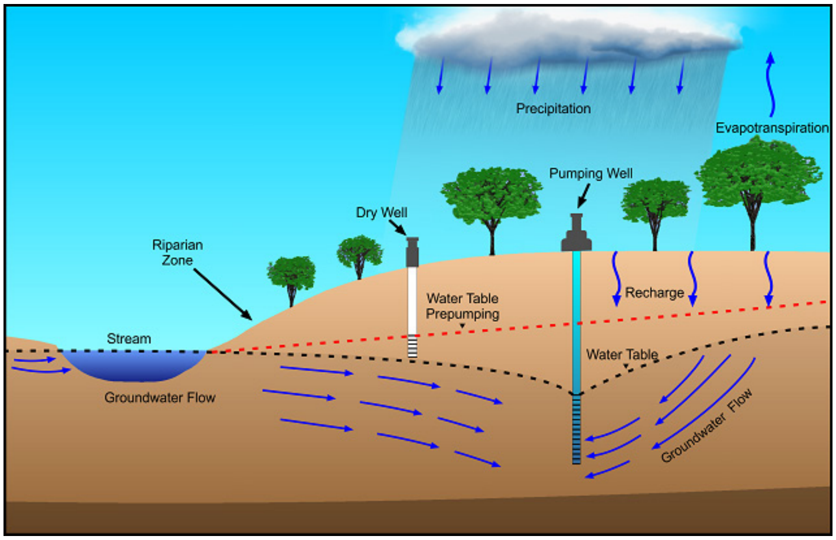


**Figure 4-39. Schematic of the hydrologic water cycle with emphasis on groundwater interactions with surface water flow and possible impacts from water withdrawals.**

**Groundwater Basics.** Precipitation transfers water from the atmosphere to the land surface and initiates the water cycle (Fig. 4-39). Some water is lost back to the atmosphere through evaporation and transpiration, and some travels to streams relatively quickly during storms via overland flow. Precipitation infiltrates into the soil, where some is tightly held by surface tension in the unsaturated soil matrix and some moves slowly downgradient through porous soil and rock to topographic lows carved by streams. Groundwater saturates the valley low points and exfiltrates to become streamflow. A small fraction percolates into the deep bedrock strata. Streamflow and subsurface water are intimately associated and are in a continuous process of exchange (Dunne and Leopold 1978.) Groundwater supplies streamflow between rain events and streams also feed water into the saturated alluvium. The top of the saturated zone, called the water table, is largely coincident with the water surface in streambeds (Freeze and Cherry 1979).

The dynamic coupling between groundwater and surface water is evident when the USGS streamflow gage is compared with a nearby USGS groundwater observation well in the alluvial valley in the Towanda Creek basin for a 4-year period (Fig 4-40). The base of the well is in the bedrock of the Lock Haven formation. The stream and water table in the adjacent alluvium are tightly coupled, as the elevation of the water table rises during rainfall and falls as the aquifer drains to the stream during intervening dry periods. The portion of precipitation that makes it way to the water table and eventually to streams through subsurface flow paths is termed “recharge.” We use the annual recharge as the approximation for the dynamic and replenishable storage volume in the watershed’s groundwater reservoir.

**Watershed Groundwater Volume.** Recharge to streams through groundwater flow paths can be estimated from streamflow records by partitioning the hydrograph into stormflow and baseflow (periods between rainfall events). This can be a subjective interpretation if only the flow record is available, as there are no clear indicators of a change from stormflow to groundwater in the streamflow trace. Stream chemistry can be used in field studies to more accurately identify stormwater. There are a variety of baseflow separation methods and different methods give different results reflecting stormflow partitioning choices (Eckhardt 2008). USGS has developed several tools that apply systematic rules to automate baseflow separation of USGS daily streamflow data, including RORA and PART. PART designates groundwater discharge to equal streamflow on days that fit a requirement of antecedent recession, and linearly interpolates groundwater discharge for other days; the method has been shown to be effective in characterizing baseflow over long periods of record (Rutledge 1998).

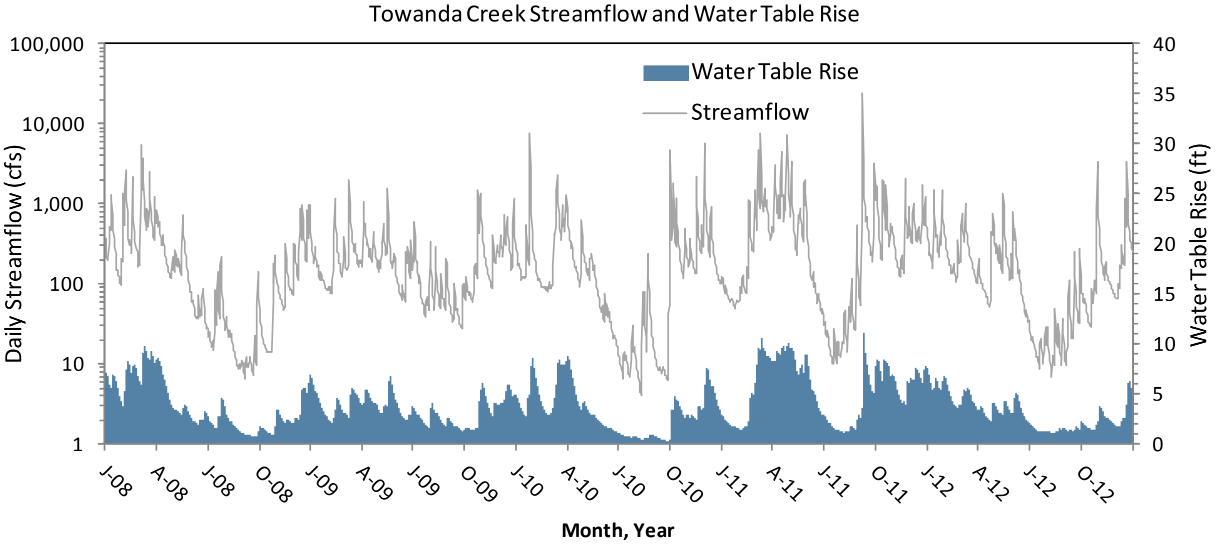


**Figure 4-40. Daily hydrograph of streamflow in Towanda Creek at the U.S. Geological Survey (USGS) gage at Monroeton (01532000) and USGS observation well BR92 (414330076280501) located in alluvium in the same general area from 2008 to 2012. Water table rise is referenced from a datum set at 12 feet below land surface (the maximum depth observed) to reverse the data provided as depth to water table for easier visualization of the tight coupling of water table rise and streamflow. (Data source: USGS 2014b.)**

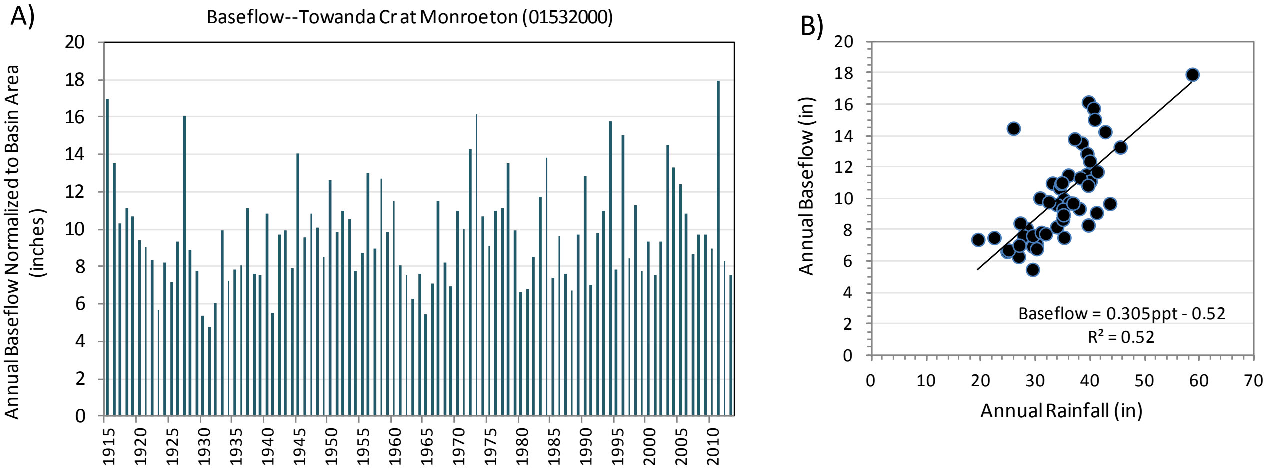


**Figure 4-41. Annual baseflow normalized to watershed area of 215 mi$^2$ at the U.S. Geological Survey Towanda gage at Monroeton from the period of record 1915 to 2012 using PART baseflow separation. A) Annual baseflow, and B) Relationship between annual rainfall and annual baseflow. (Data source: USGS 2014b.)**

PART was used to determine annual baseflow for the Towanda Creek basin from 1915 to 2012 using the flow record at the USGS Towanda gage (Fig. 4-41A). Annual baseflow is expressed as inches per year by normalizing the annual baseflow water volume by watershed area. Annual streamflow and baseflow ranged widely from year to year based largely on precipitation, with annual baseflow averaging 31% of annual rainfall (Fig. 4-41B). Average baseflow for the 100-year record was 9.8 inches/year, ranging from 4.8 to 17.9 inches. To estimate the basin's annual recharge, we used a baseflow of 9.6 inches per year (the 50th percentile) as the high estimate and 6.0 inches per year (5th percentile) as a low estimate. For managing groundwater withdrawals, SRBC defines the annual baseflow (recharge) during a 1 in 10 year average annual drought to be the sustainable limit for groundwater withdrawals, equal to 5.7 inches per year in this location (SRBC 2005). We assumed that the annual groundwater recharge was equal to the annual baseflow at the USGS Towanda gage. The baseflow volumes normalized by watershed area were translated to water volume and listed in Table 4-10 as assumptions for groundwater reservoir estimates.

The storage of groundwater beneath a watershed is filled by groundwater recharge. We estimated the groundwater reservoir volume based on water table depths observed in drilled well logs assisted by the groundwater model GFLOW. GFLOW solves for regional and steady groundwater flow in single layer aquifers (Haitjema 1995). The model is well documented and accepted within the groundwater modeling community (Hunt 2006; Yager and Neville 2002), with particular application to shallow groundwater flow systems involving groundwater/surface water interactions (Johnson and Mifflin 2006; Juckem 2009) and for recharge estimation (Dripps *et al*. 2006).

We used GFLOW™ to distribute areal recharge volume and to generate the spatial distribution of the elevation of the water table surface within the watershed. The water table was set by anchoring it at the location of the upper extent of the perennial stream channel network. The perennial streamflow location was estimated as the "blue line" on USGS 1:24,000 maps, and a portion were field-verified during annual low flow in November 2013 with good agreement. GFLOW created a gridded digital model of the water table elevation from the stream elevation points considering the hydraulic conductivity and saturated thickness of the substrate. The water table at annual average baseflow is shown as the upper surface in Fig. 4-42. The water table generally follows the topography (Freeze and Cherry 1979). See Appendix C for a detailed discussion of how the groundwater model was applied and calibrated.

Aquifer depth below the water table surface was determined from well drilling logs. Domestic well logs were obtained from the Pennsylvania Department of Conservation and Natural Resources Groundwater Information Systems (PADCNR 2014a). When drilling hydraulic fracturing wells in this area, O&G operators record the depth of the freshwater aquifer based on permeability as they drill through to deeper gas reserves. Hydraulic fracturing well logs were obtained from PADCNR (2014b). Hydraulic fracturing well logs indicate average fresh groundwater thickness of about 420 feet depth on average in this watershed. Risser *et al.* (2005) measured a freshwater aquifer thickness of 442 feet at the Gleason Test Hole located just to the west of the Towanda Creek watershed. Domestic water wells are drilled to an average depth of 160 feet. Domestic well pump placement is often shallower than maximum aquifer depth to minimize the depth necessary to ensure a reliable supply. The freshwater aquifer with the two thicknesses is shown in Fig.4-42.

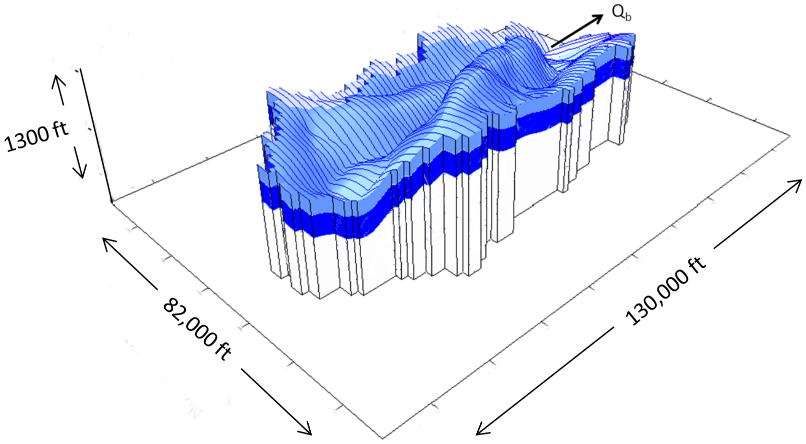


**Figure 4-42. Conceptual depiction of groundwater volumes within the Towanda Creek watershed. The vertical scale is exaggerated relative to the other two scales. The top surface is the water table generated by the groundwater model GFLOW. The light blue aquifer depicts the average depth of domestic water wells. The darker blue aquifer is the additional depth to the base of the freshwater aquifer based on hydraulic fracturing well logs. (Data sources: Well drilling logs for the watershed were obtained from the Pennsylvania Groundwater Information Systems database, PADCNR 2014a. Hydraulic fracturing drilling logs were obtained from PADCNR 2014b.)**

The volume of water within the freshwater aquifer depends on the drainable porosity, or specific yield, of the rock. Two estimates of groundwater aquifer volume were calculated based on the aquifer thickness of the Towanda Creek watershed area, and a high and low estimate for porosity of 10% and 5% respectively. Results are provided in Table 4-10. With these assumptions, the calculations suggested a large volume of water within the groundwater reservoir in Towanda Creek. The minimum estimate is 359,000 million gallons of water (1 million acre-feet). The annual recharge is about 3% to 6% of the total reservoir volume.

**Table 4-10. Groundwater aquifer volumes, annual recharge, and withdrawn volume for public and domestic water supplies, agricultural uses, and by the O&G industry for hydraulic fracturing. High and low estimates envelop the range of aquifer parameters used to estimate the volume of water in the groundwater reservoir. See Table 4-11 for withdrawal estimates.**

| Groundwater Reservoir Scenario | Assumptions | Total Aquifer Volume | Average Recharge | Withdrawn from Aquifer |
|---|---|---|---|---|
| High storage volume | Porosity: 10%<br>Recharge: 9.6 inches per year<br>Total freshwater aquifer thickness: 400 feet<br>Oil and gas municipal withdrawal: 75 MGY | 1,800,000 MG | 35,800 MGY (130 MGD) | 378 MGY (1.04 MGD) |
| Low storage volume | Porosity: 5%<br>Recharge: 6.0 inches per year<br>Domestic well aquifer thickness: 160 feet<br>Oil and gas groundwater withdrawal: 75 MGY | 359,000 MG | 22,400 MGY (61 MGD) | 378 MGY (1.04 MGD) |

**Groundwater Withdrawal.** There are at least 126 active water wells in the Towanda Creek watershed drawing from both bedrock and alluvial aquifers that are used for a variety of purposes, including domestic supplies primarily, some industrial use including O&G, and farming (Fig. 4-43). About 8,800 people live in the basin in several small towns (U.S. Census Bureau 2010). Average per capita use rate is assumed to be 60 GPD. Groundwater use in the Towanda Creek watershed, on a daily and annual basis, is shown in Table 4-11. Municipal supplied water use by specific user sectors was obtained from the PWS data from PADEP (2014a), as discussed in an earlier section. As done for SUI analysis, irrigation and livestock use for the basin were estimated using USDA and USGS county-level estimates of water use.

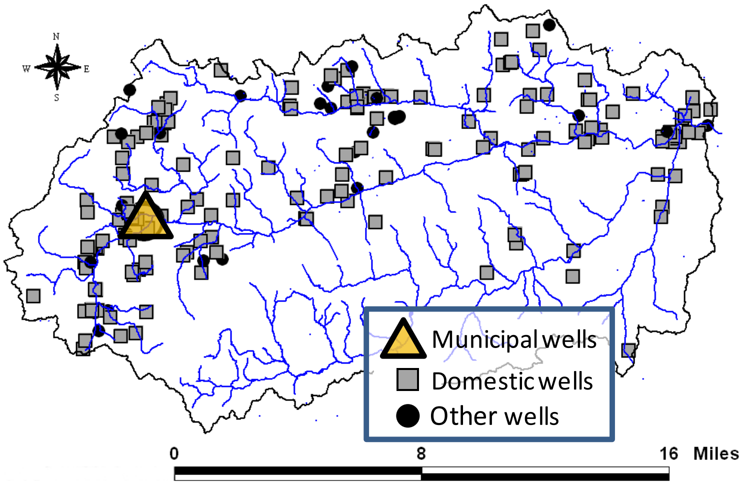


**Figure 4-43. Groundwater wells in the Towanda Creek watershed based on PaDCNR (2014a). (The unpopulated southern part of the watershed is the forested portion, protected as a state game reserve.)**

At the watershed scale, the groundwater reservoir and annual recharge are large compared to annual withdrawals by all users (Table 4-10). Annual average groundwater use in the Towanda Creek watershed including pumping withdrawals supporting hydraulic fracturing ranges between 1.1% to 1.7% of annual recharge for the high and low cases, respectively. The potential for hydraulic fracturing impact on groundwater resources at the watershed scale of 215 mi$^2$ appears to be small.

This does not mean that site-scale impacts cannot occur. Zhou (2009) observed that groundwater systems are in dynamic equilibrium in which long-term average recharge equals long-term average discharge under natural conditions. However, pumping groundwater locally disturbs this equilibrium, and will cause a decrease in groundwater levels and induce new recharge patterns. A "safe" or sustainable yield cannot be defined by natural recharge alone (Bredehoeft 2002; Zhou 2009).

Pumping groundwater resources at a well can affect the sustainable production of other wells or streams within its vicinity. When a well is pumped, water flows through the permeable material toward the pump, creating a so-called "cone of depression" radiating outward from the pump's location and depth. Drawdown of the water table is directly proportional to the pumping rate and inversely proportional to aquifer properties (Freeze and Cherry 1979). If pumping is too strong relative to the aquifer's ability to move water, nearby wells could go dry or the well could capture the natural streamflow from adjacent channels. The concept of pumping drawdown and potential impacts to other wells or streamflow is illustrated in Fig. 4-39. In the next section, we examine local drawdown impacts using the groundwater flow model GFLOW™.

**Table 4-11. Estimated daily and annual groundwater use in the Towanda Creek basin. Municipal withdrawals are based on reported volumes in 2011 (PADEP 2014a). Self-supplied domestic water is based on daily use per person. Agricultural uses are estimated from U.S. Department of Agriculture data.**

| Use | Daily Use MGD | Annual Total MG |
|---|---|---|
| Domestic Water Self Supplied | .411 | 150 |
| Municipal Water Supply | .093 | 34 |
| Municipal Other | .146 | 53 |
| O&G from PWS (Peak Year) | .205 | 75 |
| Agricultural Irrigation | .021 | 8 |
| Agricultural Livestock | .160 | 58 |
| TOTAL | 0.943 | 378 |

**Local Groundwater Use and Impact.** One small municipal water supply located in the Towanda Creek basin (Fig. 4-43) is one of several in the SRB that have had larger sales to O&G (Fig. 4-12). PWS 2080003 supplies water from two wells drilled into the stratified drift upstream of the confluence and between Towanda Creek and a smaller tributary. Drillers' logs report total well depth of 110 and 120 feet, and pumps are rated at 300 and 350 gallons per minute. The capacity of the two wells combined is 0.942 MGD. There is no other permit limit.

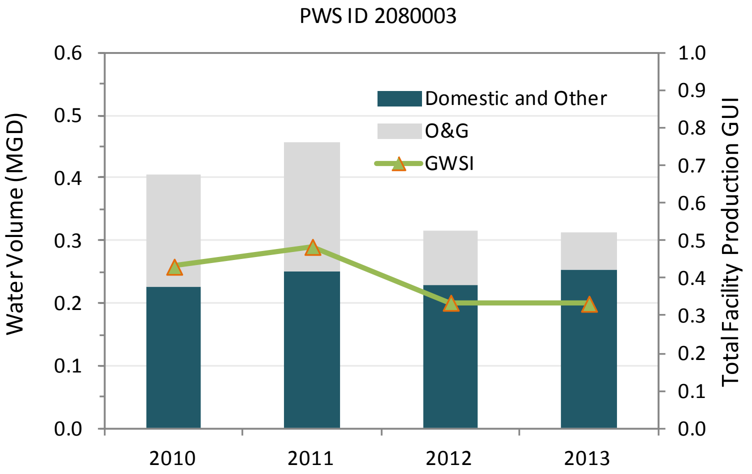


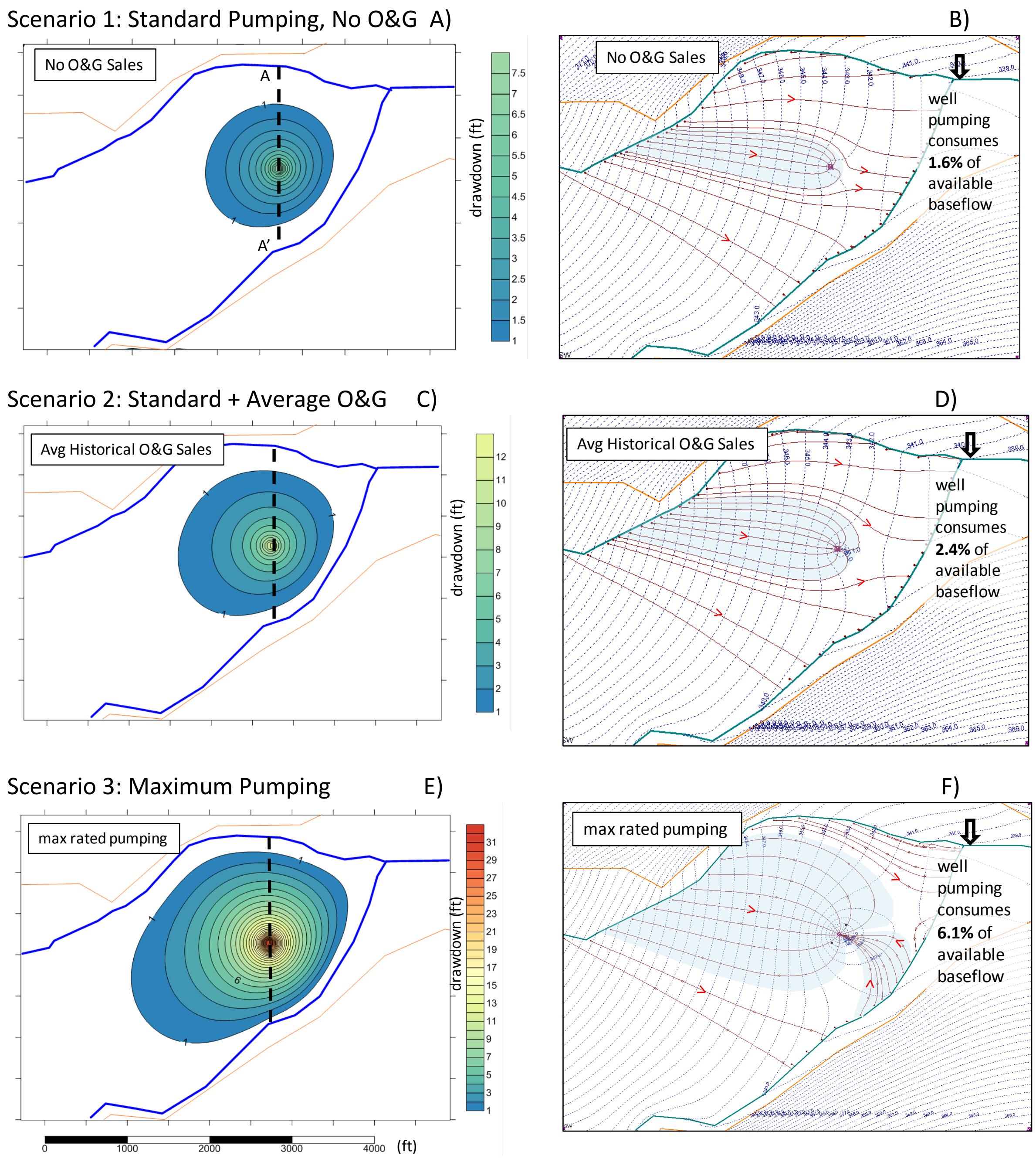
**Figure 4-44. Daily water use at PWS 2080003 municipal water supply in the Towanda Creek basin. Facility groundwater stress index was calculated as proportion of total water delivered from the facility in relation to its pumping capacity. (Data source: PADEP 2014b.)**

PWS 2080003 typically provides 0.24 MGD of water for domestic, commercial, industrial, and municipal use (Fig. 4-44), using about 25% of facility water production capacity. PWS 2080003 has sold from 0.05 to 0.2 MGD to O&G, depending on year, using an additional 6 to 22% of facility capacity. O&G water sales peaked in 2011. This contributed to facility-level sales of 0.48 MGD that consumed 75% of available capacity (GUI=0.75) in the peak use year. Sales to O&G have declined since 2011. Because pumping rates are known at this facility, it serves as an example where groundwater drawdown effects on the water table can be demonstrated with modeling.

The municipal wellfield introduces changes to the dynamic equilibrium of the subsurface geohydrologic system, as does any pumping well. The groundwater system response to rainfall is quick, and from the modeling perspective, instantaneous. The GFLOW™ groundwater model was shown to be effective at characterizing steady state flow in the unconfined glacial outwash aquifer, both at the scale of the Towanda Creek watershed (215 mi$^2$) and the local pumping wellfield at the PWS, as shown next. The model was calibrated to USGS observed baseflow and USGS observed static water table observations. The groundwater modeling (GFLOW™) and mapping (SURFER™) produced maps of the continuous water table surface (spatial grid), and the flow into, or out of, stream segments. The details of groundwater methods are described in Appendix C.

Potential for high groundwater use intensity has two aspects. In addition to the localized drawdown of the water table about the pumping center, the wellfield can capture induced recharge and water from nearby surface water features. Both influences are shown for this wellfield in Fig. 4-45 for three pumping scenarios: (1) steady annual averaged pumping to satisfy base-level drinking water and other municipal demands; (2) steady annual averaged pumping, reflecting base-level pumping plus historical annual sales to O&G; and (3) maximum rated pumping with drawdown to the base of the aquifer, assuming that the PWS sold 100% of maximum daily production. The following analysis was for average geohydrologic conditions (11.0 inches/year recharge associated with 2000–2011 observations).

The maximum pumping scenario sets the facility GUI at 1.0 and produces the largest area of drawdown, as shown in Fig. 4-45E. In comparison, the GUIs associated with scenario 1 (shown in Fig. 4-45A) and scenario 2 (Fig. 4-45C) are 0.26 and 0.40, respectively, which is a typical use level compared to other PWSs (Fig. 4-12). A vertical cross-section of the drawdown associated with the pumping scenarios is shown in Fig. 4-46. Any other wells in the cone of depression could be affected by drawdown in the municipal wellfield, but there are no known private drinking water wells within the potential impact area for any of the pumping rates. Source water assessment and wellhead protection programs for the PWS are in place to manage any potential risks.



Scenario 1: Standard Pumping, No O&G A)

B)

Scenario 2: Standard + Average O&G C)

D)

Scenario 3: Maximum Pumping E)

F)

**Figure 4-45. Groundwater–surface water interactions at the PWS 2080003 municipal groundwater wellfield under average recharge and baseflow conditions (2000–2011). Towanda Creek is the lower stream. Scenario 1 involved no sales to O&G and historical well supply to domestic and other uses; (A) shows the cone of depression associated with a GUI = 0.016 and (B) shows the zone of capture and consumption of creek baseflow (1.6%). Scenario 2 involved average historical sales to O&G in addition to average supply to domestic and other uses and GUI = 0.40; (C) shows the cone of depression associated with GUI = 0.40, and (D) shows the zone of capture and consumption of creek baseflow (2.4%). Scenario 3 involved the maximum rated pumping; (E) shows the cone of depression associated with GUI = 1.00, and (F) shows the zone of capture and consumption of creek baseflow (6.1%).**

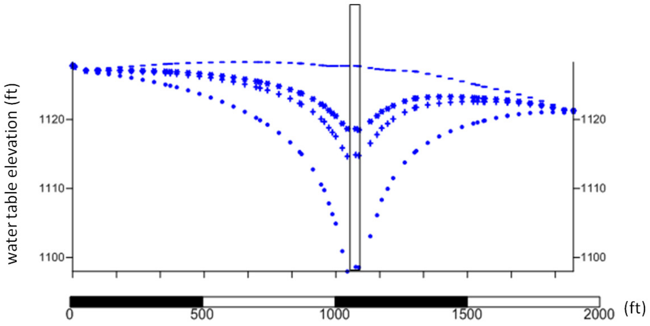


**Figure 4-46. Groundwater cone of depression associated with cross section A–A' for the wellfield for three scenarios shown in Figure 4-45. From the top down: pre-pumping condition, scenario 1 (no sales to oil and gas), scenario 2 (average sales to oil and gas), and scenario 3 (maximum drawdown). The vertical axis is greatly exaggerated relative to the horizontal axis.**

The PWS wellfield receives groundwater that originated as nearby surface water. As shown in Fig. 4-45F, under the maximum pumping scenario, the wellfield captures water from the tributary and Towanda Creek adjacent to PWS 2080003, in addition to water from the outwash valley to the west, and a small amount from recharging waters in the shaded source water zone. In the maximum pumping scenario, the volume of water captured from the baseflow of the streams, in comparison to the total baseflow at the confluence, is 6.1%, which represents SUI of 0.06. Under scenario 1 with GUI equal to 0.26, the capture of baseflow from the tributary is about 1.6% of baseflow. Under scenario 2, the capture of baseflow from the tributary is about 2.4% when the facility GUI is 0.40. Under dry conditions (6 inches/year recharge, one in 10 year recurrence), the stream capture use intensity for maximum rated pumping increased to 10% at maximum facility pumping capacity. These findings support use of the background consumption in surface water analysis reported earlier in that these withdrawals can influence surface water availability. In summary, the PWS sales to date to O&G have been 10 to 40% volume of the municipal capacity, but the additional well discharge was shown to have localized impact on drawdown and streamflow capture was shown to be 2 to 6% under average and low flow conditions.

**Self-Supplied/Private Water Use and Impact (O&G).** There are six self-supplied groundwater permitted sites in the SRB, of which two have not been used to date. Permit and use information on the four active sites is provided in Table 4-12. These wells supply nearly 1 MGD of water in the SRB, or about 15% of self-supplied freshwater for hydraulic fracturing, varying by year. Streamflow capture and pumping effects such as demonstrated for the public wellfield example can occur at these well-used sites, as previewed in Appendix C for SID 3711/3712.

Groundwater withdrawals are also permitted by SRBC. As a condition of permitting, permittees must conduct constant rate pumping tests and monitor the drawdown at nearby wells to evaluate potential impacts that may require restrictions or mitigation, all of which are contained in docket reports (SRBC 2013c). SRBC has assigned a surface water passby flow to protect the stream from groundwater withdrawal during low flow, when tests demonstrate interaction with adjacent streams. Because of the requirements for pump tests and site evaluation, it is unlikely that there are impacts on other users from the operation of these wells to supply water for O&G.

**Table 4-12. Source of freshwater from private wellfields in the Susquehanna River Basin (water use in MGD; pump ratings data from SRBC 2013a; total depth of wells data from PADCNR 2014a). Average daily volume was computed as total volume taken by number of days used.**

| Name | County | Pump Rated MGD | Total Depth (ft) | 2010 MGD | 2011 MGD | 2012 MGD | 2013 MGD | Peak Pumping Groundwater Use Intensity Index |
|---|---|---|---|---|---|---|---|---|
| SID 3823 and 3837 (two wells) | Tioga | 0.54 | 126 | 0 | 0.05 | 0.18 | 0.10 | 0.46 |
| SID 3792 | Bradford | 0.364 | 225 | 0 | 0 | 0 | 0.26 | 0.72 |
| SID 3594 | Wyoming | 0.54 | 122 | 0.04 | 0.13 | 0.16 | 0.17 | 0.77 |
| SID 3711/3712 (3 wells) | Wyoming | 0.864 | 60 | 0.08 | 0.57 | 0.55 | 0.36 | 0.66 |

## Vulnerability of Rivers and Streams to Depletion with Hydraulic Fracturing Withdrawals

Local effects of hydraulic fracturing water withdrawals can be assessed on a daily basis by relating the amount of water acquired for hydraulic fracturing to the water available at the source (SUI). This study has shown the SUI of actual water withdrawals subject to controls and modeled streams under scenarios of hydraulic fracturing demand. Here we provide the general relationships between basin size, flow likelihood, withdrawal volume, and resulting SUI values that has broad application beyond this study area. Only with an examination of these factors working together can the full picture of the potential impacts from withdrawals be demonstrated.

SUI is a straightforward volumetric calculation with a simple mathematical structure that has the same meaning wherever it is applied. A given withdrawal volume compared to a given flow volume will always produce a specific value of SUI. The streamflow rate (expressed in cfs as done in USGS gaging records) necessary to meet a SUI target for specific withdrawal volumes (expressed in MGD) is provided in Table 4-13. The table gives $Q_{\text{critical}}$ values across a range of SUI thresholds and withdrawal volumes up to 13 MGD. To compute the table, the streamflow rate was converted to a daily volume, expressed as MGD.

$$Q_{\text{critical (cfs)}} = \text{Withdrawal Volume/SUI} \qquad \textbf{Equation 4-1}$$

Flow must exceed the critical cfs value for each withdrawal volume to remain lower than the selected SUI value. For example, if 1 MGD was withdrawn and the SUI threshold of interest was 0.5, the $Q_{\text{critical}}$ would equal 3.1 cfs. If streamflow were less than this flow rate, SUI would exceed 0.5.

What varies between rivers is the probability of observing various flow rates. At a site, streamflow fluctuates from seasonal low flow to floods in response to precipitation, and the range of possible flows is dependent on watershed size, which determines the collection area for rainfall. It often requires decades to experience the full range of streamflow at a site with mesoscale climate fluctuations. This is characterized at long-term streamflow gages with flow frequency metrics that express the probability of seeing certain flow volumes given the observed record.

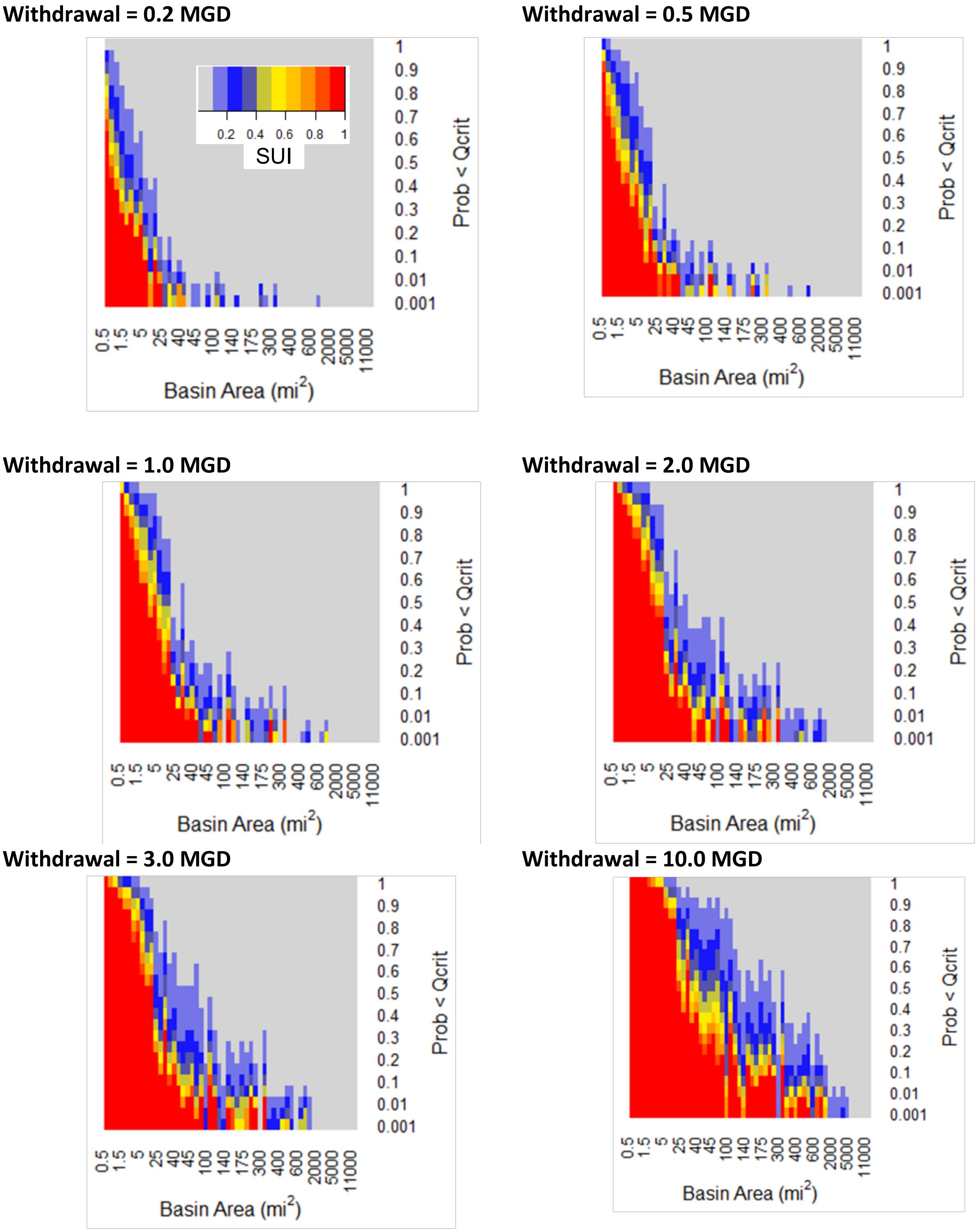
The extensive history of daily flow monitoring data available from USGS gaged sites can be harnessed to determine the probability of observing $Q_{\text{critical}}$ values at specific locations. We acquired data for 48 gaged streams (ranging from 5 to 11,000 $\text{mi}^2$) throughout the Susquehanna River Basin having records of at least 25 years, and added eight randomly selected streamflow records from the small subbasins (0.5–4 $\text{mi}^2$) in Towanda Creek generated by HSPF modeling. (See Appendix B for a list of USGS gages used in SRB analyses.) Examining only sites with a sufficiently long record ensured that climatic variability would be captured. We computed the frequency of flow observed and its probability of occurrence. With the streamflow probabilities established, we computed the likelihood of observing the SUI $Q_{\text{critical}}$ thresholds for the range of withdrawal shown in Table 4-13. The water use intensity "heat maps" are shown for six withdrawal volumes in Fig. 4-47. The probability of observing the SUI is on the right axis, and the SUI range is represented by the spectrum of color. The gray area in each display indicates SUI less than 0.1. The six withdrawal scenarios include the median (0.2 MGD) and mean (0.5 MGD) of actual observed withdrawals observed in the SRB.

At these common daily withdrawals, very small streams have higher SUI most of the time for all withdrawal volumes. Water is available a limited portion of the time. For example, if withdrawing 0.2 MGD, SUI is greater than 0.4 about 30% of the time (indicated by the red shades in Fig. 4-47). As withdrawal rate increases, higher values of SUI occur, though infrequently, in surprisingly large rivers. For example, at withdrawal of 3.0 MGD, SUI could exceed 0.4 in rivers up to about 500 $\text{mi}^2$ (red or yellow on the figure). We include the very high withdrawal rate of 10 MGD, because it is the sum of permitted withdrawals on several sites clustered very close together on the large Susquehanna River.

The flow in rivers differs due to factors other than basin area. However, for the same reason that regional flow equations can provide reasonable predictions of streamflow duration characteristics over wide areas, albeit with variation, Fig. 4-47 has broad applicability in this part of Pennsylvania and in general within the humid eastern climatic region. The withdrawal examples show that even larger rivers can occasionally have high water use intensity indicated by high SUI from moderate and feasible hydraulic fracturing withdrawals. SRBC prevents this by shutting off withdrawals at most sites when streamflow declines below thresholds established relative to the annual mean flow.

**Table 4-13. Minimum flow expressed in cubic feet per second needed to meet a surface water use intensity index (SUI) value at various daily withdrawal volumes, expressed in million gallons per day. The flow threshold is referred to as $Q_{critical}$ in this report. Each combination of withdrawal volume and SUI target has a $Q_{critical}$ value expressed in the table. For example, for a withdrawal of 1 MGD and SUI<0.3, flow must be equal or exceed 5.16 cfs.**

| | Surface Water Use Intensity Index (SUI) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | <0 .1 | < 0.2 | < 0.3 | < 0.4 | < 0.5 | < 0.6 | < 0.7 | < 0.8 | < 0.9 | ≤ 1.0 |
| ***Withdrawal (MGD)*** | Minimum Flow in cfs to Meet SUI at Withdrawal Rate ($Q_{critical}$) | | | | | | | | | |
| ***0.1*** | 1.55 | 0.77 | 0.52 | 0.39 | 0.31 | 0.26 | 0.22 | 0.19 | 0.17 | 0.15 |
| ***0.2*** | 3.09 | 1.55 | 1.03 | 0.77 | 0.62 | 0.52 | 0.44 | 0.39 | 0.34 | 0.31 |
| ***0.3*** | 4.64 | 2.32 | 1.55 | 1.16 | 0.93 | 0.77 | 0.66 | 0.58 | 0.52 | 0.46 |
| ***0.4*** | 6.19 | 3.09 | 2.06 | 1.55 | 1.24 | 1.03 | 0.88 | 0.77 | 0.69 | 0.62 |
| ***0.5*** | 7.74 | 3.87 | 2.58 | 1.93 | 1.55 | 1.29 | 1.11 | 0.97 | 0.86 | 0.77 |
| ***0.6*** | 9.28 | 4.64 | 3.09 | 2.32 | 1.86 | 1.55 | 1.33 | 1.16 | 1.03 | 0.93 |
| ***0.7*** | 10.83 | 5.41 | 3.61 | 2.71 | 2.17 | 1.80 | 1.55 | 1.35 | 1.20 | 1.08 |
| ***0.8*** | 12.38 | 6.19 | 4.13 | 3.09 | 2.48 | 2.06 | 1.77 | 1.55 | 1.38 | 1.24 |
| ***0.9*** | 13.92 | 6.96 | 4.64 | 3.48 | 2.78 | 2.32 | 1.99 | 1.74 | 1.55 | 1.39 |
| ***1*** | 15.47 | 7.74 | 5.16 | 3.87 | 3.09 | 2.58 | 2.21 | 1.93 | 1.72 | 1.55 |
| ***1.1*** | 17.02 | 8.51 | 5.67 | 4.25 | 3.40 | 2.84 | 2.43 | 2.13 | 1.89 | 1.70 |
| ***1.2*** | 18.56 | 9.28 | 6.19 | 4.64 | 3.71 | 3.09 | 2.65 | 2.32 | 2.06 | 1.86 |
| ***1.3*** | 20.11 | 10.06 | 6.70 | 5.03 | 4.02 | 3.35 | 2.87 | 2.51 | 2.23 | 2.01 |
| ***1.4*** | 21.66 | 10.83 | 7.22 | 5.41 | 4.33 | 3.61 | 3.09 | 2.71 | 2.41 | 2.17 |
| ***1.5*** | 23.21 | 11.60 | 7.74 | 5.80 | 4.64 | 3.87 | 3.32 | 2.90 | 2.58 | 2.32 |
| ***1.6*** | 24.75 | 12.38 | 8.25 | 6.19 | 4.95 | 4.13 | 3.54 | 3.09 | 2.75 | 2.48 |
| ***1.7*** | 26.30 | 13.15 | 8.77 | 6.57 | 5.26 | 4.38 | 3.76 | 3.29 | 2.92 | 2.63 |
| ***1.8*** | 27.85 | 13.92 | 9.28 | 6.96 | 5.57 | 4.64 | 3.98 | 3.48 | 3.09 | 2.78 |
| ***1.9*** | 29.39 | 14.70 | 9.80 | 7.35 | 5.88 | 4.90 | 4.20 | 3.67 | 3.27 | 2.94 |
| ***2*** | 30.94 | 15.47 | 10.31 | 7.74 | 6.19 | 5.16 | 4.42 | 3.87 | 3.44 | 3.09 |
| ***2.1*** | 32.49 | 16.24 | 10.83 | 8.12 | 6.50 | 5.41 | 4.64 | 4.06 | 3.61 | 3.25 |
| ***2.2*** | 34.03 | 17.02 | 11.34 | 8.51 | 6.81 | 5.67 | 4.86 | 4.25 | 3.78 | 3.40 |
| ***2.3*** | 35.58 | 17.79 | 11.86 | 8.90 | 7.12 | 5.93 | 5.08 | 4.45 | 3.95 | 3.56 |
| ***2.4*** | 37.13 | 18.56 | 12.38 | 9.28 | 7.43 | 6.19 | 5.30 | 4.64 | 4.13 | 3.71 |
| ***2.5*** | 38.68 | 19.34 | 12.89 | 9.67 | 7.74 | 6.45 | 5.53 | 4.83 | 4.30 | 3.87 |
| ***2.6*** | 40.22 | 20.11 | 13.41 | 10.06 | 8.04 | 6.70 | 5.75 | 5.03 | 4.47 | 4.02 |
| ***2.7*** | 41.77 | 20.88 | 13.92 | 10.44 | 8.35 | 6.96 | 5.97 | 5.22 | 4.64 | 4.18 |
| ***2.8*** | 43.32 | 21.66 | 14.44 | 10.83 | 8.66 | 7.22 | 6.19 | 5.41 | 4.81 | 4.33 |
| ***2.9*** | 44.86 | 22.43 | 14.95 | 11.22 | 8.97 | 7.48 | 6.41 | 5.61 | 4.98 | 4.49 |
| ***3*** | 46.41 | 23.21 | 15.47 | 11.60 | 9.28 | 7.74 | 6.63 | 5.80 | 5.16 | 4.64 |
| ***3.5*** | 54.95 | 27.48 | 18.32 | 13.74 | 10.99 | 9.16 | 7.85 | 6.87 | 6.11 | 5.50 |
| ***4*** | 62.80 | 31.40 | 20.93 | 15.70 | 12.56 | 10.47 | 8.97 | 7.85 | 6.98 | 6.28 |
| ***4.5*** | 70.65 | 35.33 | 23.55 | 17.66 | 14.13 | 11.78 | 10.09 | 8.83 | 7.85 | 7.07 |
| ***5*** | 78.50 | 39.25 | 26.17 | 19.63 | 15.70 | 13.08 | 11.21 | 9.81 | 8.72 | 7.85 |
| ***6*** | 94.20 | 47.10 | 31.40 | 23.55 | 18.84 | 15.70 | 13.46 | 11.78 | 10.47 | 9.42 |
| ***7*** | 109.90 | 54.95 | 36.63 | 27.48 | 21.98 | 18.32 | 15.70 | 13.74 | 12.21 | 10.99 |
| ***8*** | 125.60 | 62.80 | 41.87 | 31.40 | 25.12 | 20.93 | 17.94 | 15.70 | 13.96 | 12.56 |
| ***9*** | 141.30 | 70.65 | 47.10 | 35.33 | 28.26 | 23.55 | 20.19 | 17.66 | 15.70 | 14.13 |
| ***10*** | 157.00 | 78.50 | 52.33 | 39.25 | 31.40 | 26.17 | 22.43 | 19.63 | 17.44 | 15.70 |
| ***11*** | 172.70 | 86.35 | 57.57 | 43.18 | 34.54 | 28.78 | 24.67 | 21.59 | 19.19 | 17.27 |
| ***12*** | 188.40 | 94.20 | 62.80 | 47.10 | 37.68 | 31.40 | 26.91 | 23.55 | 20.93 | 18.84 |
| ***13*** | 204.10 | 102.05 | 68.03 | 51.03 | 40.82 | 34.02 | 29.16 | 25.51 | 22.68 | 20.41 |


Withdrawal = 0.2 MGD

Withdrawal = 0.5 MGD

Withdrawal = 1.0 MGD

Withdrawal = 2.0 MGD

Withdrawal = 3.0 MGD

Withdrawal = 10.0 MGD

**Figure 4-47. Heat maps showing probabilities of experiencing various surface water use intensity index (SUI) values at a range of watershed sizes under several daily withdrawal scenarios based on streamflow records from 48 streams and rivers in Pennsylvania. Gray areas in the figures indicate SUI below 0.1. The SUI color scale used for all withdrawal volumes is shown as an inset in the upper left box. (Data source: USGS 2014a.)**

Fig. 4-47 shows that SUI is a function of basin area as a surrogate for streamflow volume and illustrates the probability of flow being less than critical flow dependent on withdrawal volume. We combined the 7,700 observations displayed in these figures and fit a multiple linear regression model to characterize the general observed patterns in the six panels. The regression equation (4-2) has an adjusted $R^2$ of 0.80:

$$\mathrm{Log(SUI)} = 0.057 + 0.07*\mathrm{Withdrawal} - 0.525*\mathrm{Log(Area)} - 0.954*\mathrm{FlowProb} \qquad \textbf{Equation 4-2}$$

where withdrawal is in MGD and basin area is in $mi^2$ and the FlowProb is the probability of experiencing flows below the $Q_{critical}$ threshold over a lengthy period of record. A probability of 0.9 means that 90% of flows in the basin are less than the observed flow. This equation will somewhat over-predict small values of SUI and under-predict large values of SUI.

A practical formulation of the relationship between these variables is to ask, “What is the probability of exceeding a threshold SUI at a site given its basin area with a certain withdrawal volume?” Another multiple linear regression model was fit to the data to answer this question:

$$\mathrm{Prob(SUI} \geq \mathrm{threshold)} = 0.67 + 0.432*\mathrm{Log(Withdrawal)} - 0.46*\mathrm{Log(Area)} - 0.46*\mathrm{Log(SUI)} \qquad \textbf{Equation 4-3}$$

The adjusted $R^2$ of the model increased greatly when very low SUI values (<0.01) and SUI equal to 1 were excluded. Adjusted $R^2$ for the clipped dataset was 0.85.

### Water Quality Impacts from Hydraulic Fracturing Withdrawals

The SUI approach also has direct implications for interpreting the potential impact of withdrawals on water quality. Water quality is determined by the concentration of pollutants within a volume of water; if the same amount of pollutant is added to a smaller volume of water, its concentration will be higher. If a pollutant such as sediment or nutrients is already in the stream, withdrawal of a volume of water for hydraulic fracturing will not impact water quality, as the pollutant is removed from the water equal to its concentration. If a discharge point is in the immediate area of a withdrawal location, the withdrawal will reduce the water volume and increase the concentration of the discharged pollutant. This effect is “concentration magnification” (CM)—the opposite of dilution. Without knowing the pollutant or its concentration, we can say it will be more concentrated in proportion to the withdrawal volume, and CM will be more significant where flow is lower.

The SUI metric we have used throughout this report is quite conducive to assessing the potential for pollutant concentration magnification, since it is a straightforward volumetric calculation. For those hydraulic fracturing withdrawal locations upstream of point source discharges, the CM can be calculated using the SUI (the percent of water removed from the stream at the hydraulic fracturing withdrawal site):

$$\mathrm{CM} = 1 / (1 - \mathrm{SUI}) \qquad \textbf{Equation 4-4}$$

The relationship between CM and SUI resulting from the equation is shown in Fig. 4-48. The CM approaches infinity (no water for dilution) as the SUI approaches 1.0. When SUI is 0.5, pollutant concentration magnifies by 2 times (CM=2).

The project quantified SUI for nearly 30,000 observed daily withdrawals of freshwater for hydraulic fracturing in the SRB. Most sites included in this analysis are not directly influenced by a point source discharge. However, this analysis uses these data assuming that each site could potentially be in this situation as a worst case scenario. Using these data, we examined potential real-world CM values that would have resulted from those withdrawals. SUI calculated for the 29,907 daily withdrawals from 2008 to 2013 was inserted into the CM equation (4-4). The calculation was performed as observed with a passby low flow withdrawal restriction in place. The calculation was also performed assuming no low flow restriction was in place, as was done for Fig. 4-24. Results are shown in Fig. 4-49, with the CM expressed as a percentage above the baseline constituent concentration, assuming no withdrawal occurred.

SUI was shown to be generally less than 0.1 in the SRB, even with no low flow passby restrictions in place (Figs. 4-23, 4-24; Table 4-6). This translates to CM nearly always less than 1% above the baseline case. However, CM above 30% would have been observed in almost 10% of the observations, reaching up to 100% on occasion. The CM would show the same relationship to basin area as an index of streamflow as SUI. CM values above 2 times in Fig. 4-49 were—not surprisingly—all in the very small streams. The passby cutoff limits also reduced potential impacts to water quality by limiting CM to less than 20% above baseline.

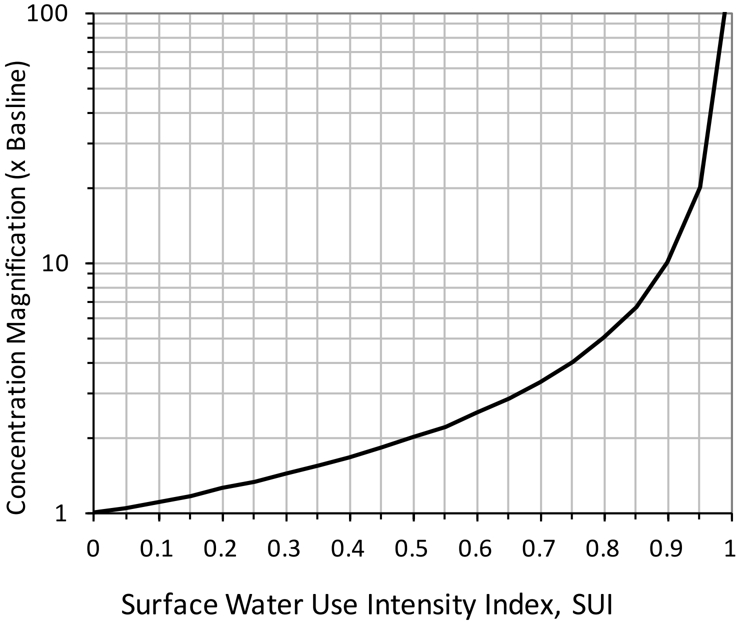


**Figure 4-48. General relationship between the concentration magnification and surface water use intensity index, SUI) which indicates the proportion of water taken from a withdrawal location.**

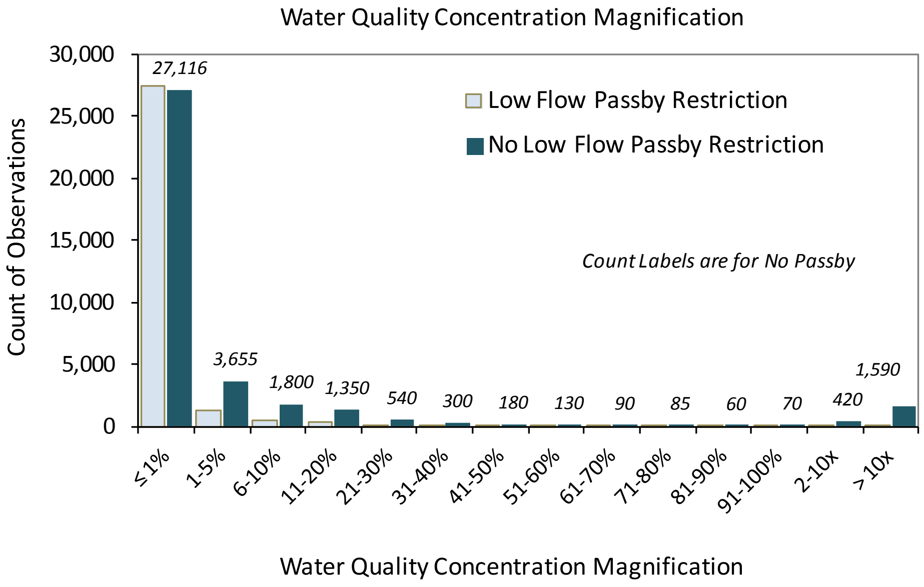


**Figure 4-49. Potential magnification of water quality pollutant concentrations at observed hydraulic fracturing withdrawals, assuming each site had an upstream point source discharge. The potential concentration magnification was determined daily from the surface water use intensity index (SUI) determined by streamflow and withdrawal volume at each site. Withdrawals ranged from 0.05 to 3.0 million gallons per day; basin area of sites ranged from 1.7 to 10,547 mi$^2$ (n = 29,907).**

## Susquehanna River Basin Synopsis

Public water systems provided about 20% of the total freshwater used for hydraulic fracturing in the SRB as a whole in 2011 and that volume has been declining significantly as self-supplied water has become available. Use of self-supplied water taken from rivers and streams in the 17-county area of the SRB where hydraulic fracturing has been active is essentially a new sector within the regional user portfolio as there is relatively little current use of this resource for drinking water or other municipal or agricultural uses. Other users rely primarily on groundwater. As these sources are developed through permitting, recent trends show reduced reliance on public water systems as planned by SRBC (Beauduy 2009). Self-supplied withdrawal sites are now widely distributed throughout the portion of SRB active in O&G extraction. Hydraulic fracturing wastewater is reused to the extent that it is available, contributing 13% of injection fluids used by O&G operators in the SRB.

Water acquisition by the O&G industry in the Susquehanna River Basin is managed by SRBC, which issues permits to operators for individual withdrawal sites. PADEP performs a similar function outside the SRB, and regulates and monitors gas well drilling procedures and activity. Permits include a variety of constraints related to how much, how fast, and when water withdrawals can take place. SRBC permits assign daily withdrawal and pumping rate limits, and set passby flow thresholds that cut off withdrawals during lower flow. The water management system operated by SRBC relies on minimum passby flow calculations, referenced to real-time flow monitoring stations that provide operators with timely information (via the Internet) to adjust operations.

The SUI approach used to evaluate hydraulic fracturing water withdrawals demonstrated that streams can be vulnerable from typical withdrawals, dependent on their size as indexed by contributing basin area. Small streams that could (and do) supply water to oil and gas operators have potential for high SUI for all or most of the year. Based on measured flow records throughout the region, and dependent on the withdrawal volume, there is an increased probability of higher SUI at average daily withdrawal volumes in watersheds less than 25 mi$^2$. In the absence of a passby, watersheds up to 600 mi$^2$ have some probability of higher SUI during infrequent droughts and at higher withdrawal volumes.

Groundwater resources are a major source of self-supplied and community drinking water supply. They have been a small component of O&G freshwater use. SRBC regulates groundwater sources requiring pump tests to ensure that neighboring wells and potentially connected streams are not affected by requested pumping rates. Several self-supplied groundwater permitted sites pump at fairly high rates, but well tests support these rates and there is no indication of problems.

SRBC water management is designed to ensure water availability for all uses including municipal water supplies and ecological communities. The system maintained very low surface water use intensity values at virtually all sites across a range of flow volumes using simple hydrological predictive measures and data made available by USGS. Hydraulic fracturing operations do not currently provide a challenge to public water supplies at a county or local scale in the SRB, due to controls on the large-volume withdrawals and industry use patterns that have distributed self-supplied water sources throughout a wide geographic area.

# 5. PICEANCE BASIN/UPPER COLORADO RIVER BASIN

## Uinta-Piceance Geologic Province

The Uinta-Piceance geologic province covers about 40,000 mi$^2$ in northwestern Colorado and Utah. The hydrocarbon sedimentary basin was deposited during the Cretaceous period 75 million years ago. Water and eroded sediment flowed from the mountains west of the present-day Rockies into a large epeiric sea that extended eastward across what is the Great Plains today (Hettinger and Kirschbaum 2002) (Fig. 5-1). Fine-grained sediments laid down in this sea are now the source of much of the shale gas and other hydrocarbon resources found in the interior basin from North Dakota to Texas.

The Uinta-Piceance basin is made of sediments derived from mountains and carried eastward by meandering rivers that deposited coarser sediments in nearshore and coastal-plain environments. The organic-rich sediments accrued in thick deposits in alluvial fans, floodplains, beaches, and swamps as the coastal zones of the epeiric seaway were gradually filled in with fine-grained muds (Johnson 1989) (Fig. 5-1). Over time, the sandy shoreline migrated repeatedly back and forth across the region, creating a thick transgressive/progressive sequence of mudstones and sandstones (Fig. 5-3). Originally one large sedimentary basin, the unit divided into the Uinta and Piceance Basins with the Laramide uplift at the Douglas Creek Arch 30 million years later, shown in Fig. 5-2 (Pranter and Sommer 2011). The areal extent of the Piceance Basin (locally pronounced “PEE-awnce”) is about 6,000 mi$^2$.

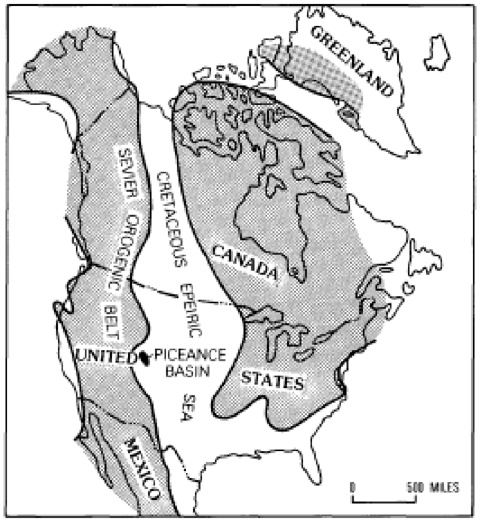


**Figure 5-1. Location of the Sevier orogenic belt in relation to the epeiric seaway in the Cretaceous period. Patterned areas represent land masses. (From Johnson 1989.)**

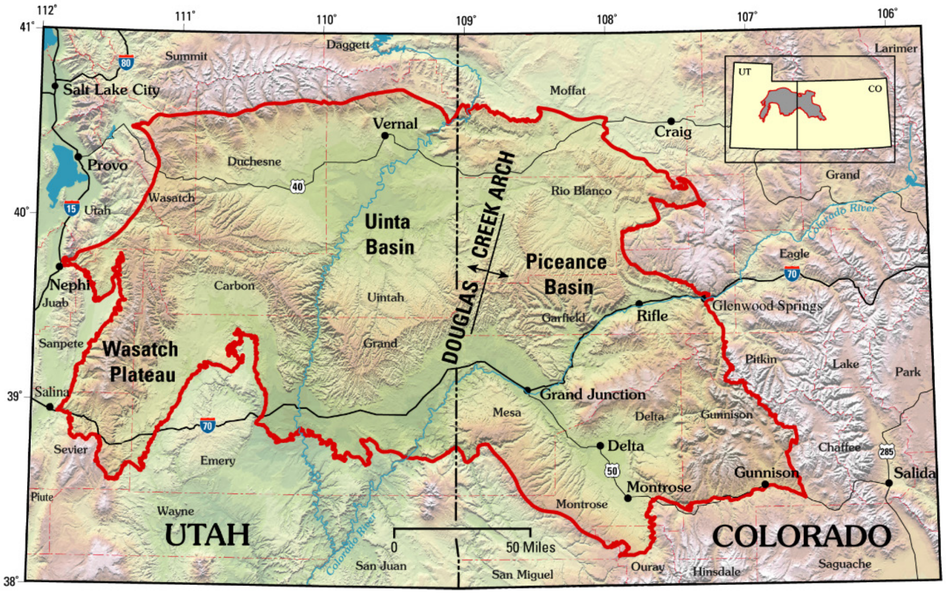


**Figure 5-2. Location of the Uinta-Piceance Province. (Map from USGS Uinta-Piceance Assessment Team 2003.)**

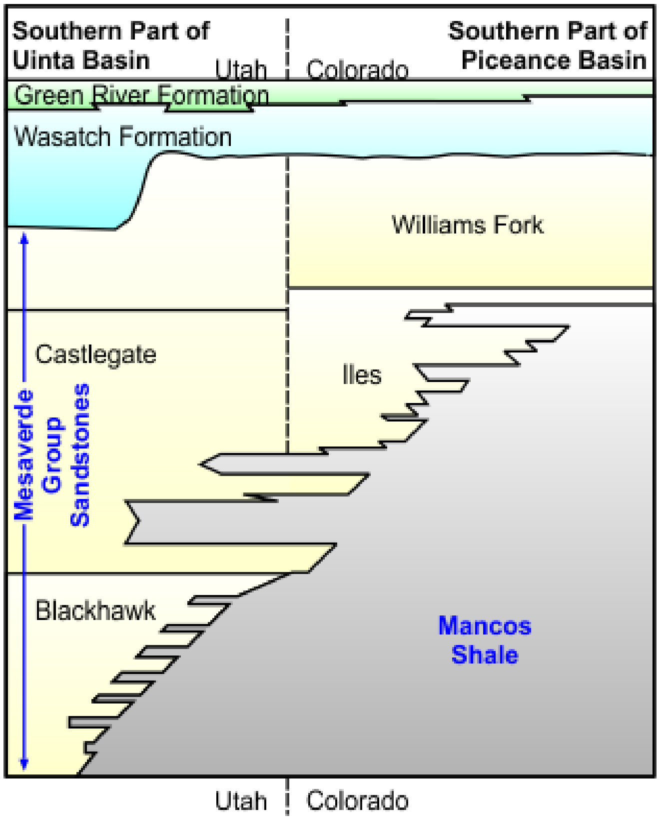


**Figure 5-3. Geologic formations in the southern part of the Uinta and Piceance basins. (After Hettinger and Kirschbaum 2002.)**

With burial and heating, the organic-rich sediments formed a variety of recoverable hydrocarbons trapped within the tight sandstones and mudstone organic-rich sediments (Johnson 1989). Formations of various sedimentary and hydrocarbon characteristics make up the total petroleum system (USGS Uinta-Piceance Assessment Team 2003), including the Mesaverde sandstone group and the Mancos Shale (Fig. 5-3), which both produce gas from unconventional reservoirs. The lower part of the Mesaverde is composed of blanket-like and near blanket-like sandstone reservoirs, whereas mainly discontinuous lenticular sandstone reservoirs deposited in fluvial coastal plains make up the upper part of the Mesaverde (Johnson 1989; Pranter and Sommer 2011; Dietrich and Johnson 2013). The Mesaverde sandstones thin to the east and interweave with the Mancos Shale mudrock deposits that accumulated in the offshore and open-marine environments of the interior seaway. The Mancos Shale deposits occur at shallower depths below the Piceance than in the Uinta Basin. The Green River formation near the top of the sedimentary sequence has kerogen-rich oil shale.

The clastic-rich reservoirs of the Piceance contain enormous reserves of natural gas, oil, and gas liquids in conventional and unconventional (continuous) deposits (Johnson and Roberts 2003; USGS Uinta-Piceance Assessment Team 2003). These include dry gas and wet gas in unconventional tight sand and shale deposits, coal methane, conventional oil, and oil shale. The USGS Uinta-Piceance Assessment Team (2003) assessed undiscovered conventional and continuous (unconventional) oil and gas in the Piceance (Table 5-1). The Piceance Basin contains one of the thickest and richest known oil shale deposits in the world and has been the focus of most ongoing oil shale research and development extraction projects in the United States (Johnson 1989). The U.S.EIA rated the Uinta-Piceance province as eighth in the United States in proven wet natural gas and 10th for proven crude oil plus condensate reserves (U.S.EIA 2009). There are an estimated 64 trillion gallons of in-place oil shale resources (USGS Uinta-Piceance Assessment Team 2003; Johnson 1989) of which 1.3 trillion may be recoverable (BLM 2006).

**Table 5-1. Estimated hydrocarbon reserves in the Piceance Basin. (Data source: USGS Uinta-Piceance Assessment Team 2003.)**

| Type | Undiscovered Reserves |
|---|---|
| Natural gas | 21 trillion cubic feet |
| Coalbed gas | 2.3 trillion cubic feet |
| Gas liquids | 43 million barrels |
| Oil plus lease condensate (oil shale) | 1.3 trillion barrels |
| Oil | 598 million barrels |

### Upper Colorado River Basin Background

The waterways of the Colorado River basin drain nearly 246,000 mi$^2$ of largely semi-arid to arid lands before entering the Gulf of California in Mexico (Fig. 5-4) (Bureau of Reclamation 2012). The Colorado River provides for the drinking water needs of 40 million people and industrial and agricultural water use in seven states and Mexico, including residents of Los Angeles, Phoenix, Tucson, Las Vegas, Denver, and Albuquerque. At the same time, the river system irrigates nearly 5.5 million acres of crops and pasture. The region that relies on the Colorado River for its water supply is one of the fastest-growing areas in the nation (Bureau of Reclamation 2005, 2012; GAO 2003), with projected water deficits in coming decades (Bureau of Reclamation 2012; CWCB 2014). Water shortages may be exacerbated, as climate change predictions suggest drying trends for this already mostly arid region (U.S. EPA 2013a; Bureau of Reclamation 2012; CWCB 2014).

In 1922, the states of the Colorado River Basin signed the Colorado River Compact. The pact defined the upper and lower basins of the river and apportioned 7.5 million acre-feet of water per year to each. Most of the water originates in the upper basin states of Colorado, Utah, Wyoming, and New Mexico. The Colorado River is managed and operated under numerous compacts, federal laws, court decisions and decrees, contracts, and regulatory guidelines, collectively known as the "Law of the River" (Bureau of Reclamation 2012). This collection of documents apportions the water and manages use of the Colorado River among the seven basin states and Mexico. There are increasing concerns that the pact cannot be met, as the agreed-on water volumes were set at what history would prove to be a high point in streamflow and low point in population (Bureau of Reclamation 2012).

An important source of water in the Colorado River system is the Upper Colorado River Basin (UCRB) (Fig. 5-5). The river originates in the rugged mountains of the Southern Rockies in Colorado that reach elevations of 10,000+ feet. The mountains capture precipitation as snow in what is otherwise a semi-arid climatic region (Spahr *et al.* 2000). The snowpack fuels a robust recreation-based economy in the headwaters. More importantly, it produces most of the water used by Colorado's population and satisfies a significant portion of the needs of the lower basin states. With dependence on snowmelt, natural streamflow is strongly seasonal. Some of the snowmelt flows directly downstream, while some is captured in large federal Bureau of Reclamation and smaller reservoirs in the headwaters for later release. Water naturally flows westward but some water is also piped through the mountains for use by more than one million people living in the cities of the eastern slopes of the Rockies (Bureau of Reclamation 2012; CWCB 2011; Spahr *et al.* 2000).

Figure 5-4. The hydrologic boundaries of the Colorado River Basin within the United States, plus the adjacent areas of the basin states that receive Colorado River water. (Map source: Bureau of Reclamation 2012.)

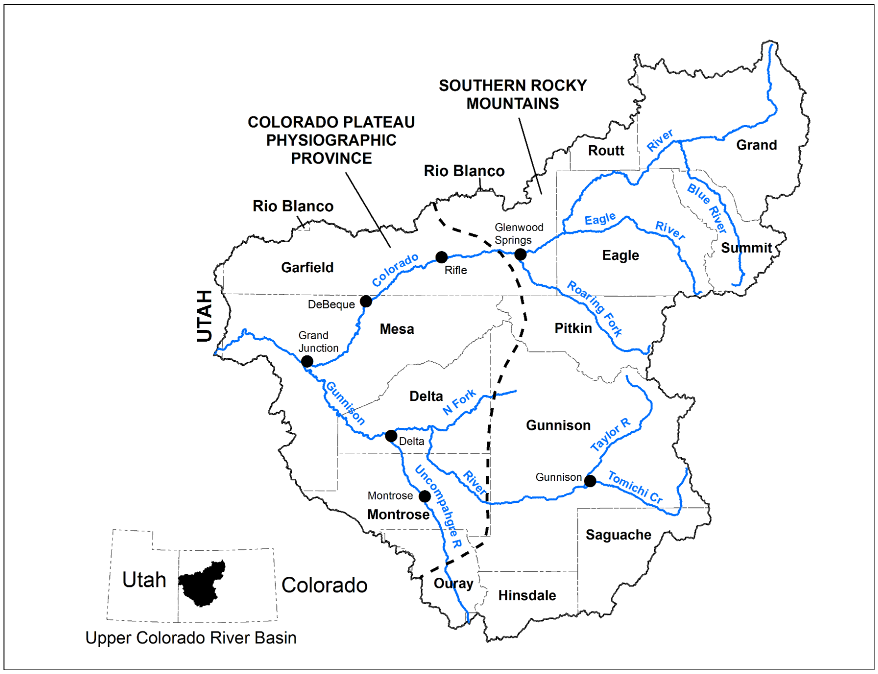


**Figure 5-5. The Upper Colorado River Basin in Colorado below Grand Junction, where the Upper Colorado River joins the Gunnison River. Counties, major towns, and physiographic provinces are shown. (Map modified from Spahr *et al.* 2000.)**

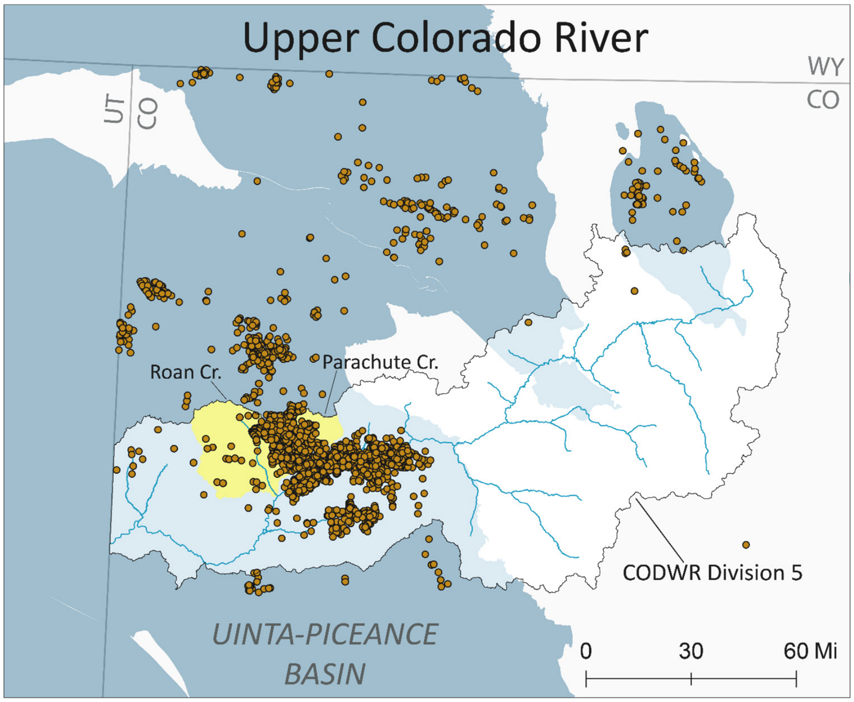


**Figure 5-6. Location of the Upper Colorado River and its basin above Grand Junction, where this project focused assessment of hydraulic fracturing water acquisition. The Uinta-Piceance structural basin is shown as blue/gray shading, with lighter shading where it intersects the Colorado River Basin. Hydraulic fracturing wells are shown as circles. Yellow designates Parachute and Roan Creek tributaries where the surface water use intensity is analyzed (Data source for well locations: FracTracker Alliance 2014.)**

The Upper Colorado River flows westward, descending from its alpine headwaters, and enters the Colorado Plateau physiographic province after it is joined by the Roaring Fork River near the town of Glenwood Springs (Fig. 5-5). This is the northeastern portion of the Colorado Plateau, which extends southward to Arizona and New Mexico and westward through Utah. The Piceance structural basin intersects the Upper Colorado River Basin in Colorado westward from approximately the town of Rifle to DeBeque (Fig.5-2 and Fig. 5-6).

The Colorado Plateau is characterized by structural geology consisting of the nearly horizontal sedimentary formations that have been uplifted thousands of feet since they were deposited in the Cretaceous period, as well as occasional igneous intrusions. The general surface of the plateau at the modern-day river valley is 5,000+ feet above sea level, and some of the uplifted plateaus reach nearly 10,000 feet (Hunt 1974). Within the UCRB, the Roan Plateau found on the north side of the Colorado River and west of the town of Rifle is one of those features. The top of the plateau is at 9,900 feet while the river base is at 6,500 feet (Fig. 5-7A). The drainage system is deeply incised and forms steep-walled canyons exposing the sedimentary strata (BLM 2006). The land surface on top of the plateau is relatively flat. The general position of the Roan Plateau is shown in Fig. 5-7.

### Hydraulic Fracturing Drilling Activity.

Hydraulic fracturing drilling activity within the river basin has mostly occurred in the area bounded to the east by the town of Rifle and to the west where the river passes the Douglas Creek Arch (Fig 5-2). The gas-bearing Williams Fork formation illustrated in Fig. 5-3 is composed of horizontally discontinuous sand lenses within fluvial deposits that have been the primary target of directional drilling and hydraulic fracturing (Fig. 5-7 upper panel). Increasingly, O&G companies have been horizontally drilling into the Mancos Shale formation below the Williams Fork. Hydraulic fracturing wells have been drilled in the alluvial valleys of the Colorado River and its tributaries and on top of the Roan Plateau.

The kerogen-rich oil shale deposits are found in the Green River formation in the uppermost strata exposed in the Roan Plateau cliffs and forms steep, 500-to-1,000 ft cliffs and slopes (BLM 2006) (Figs. 5-7 lower panel and 5-8A, B). The oil shale deposit extends northward into the White River basin in Rio Blanco County (Fig. 5-2).

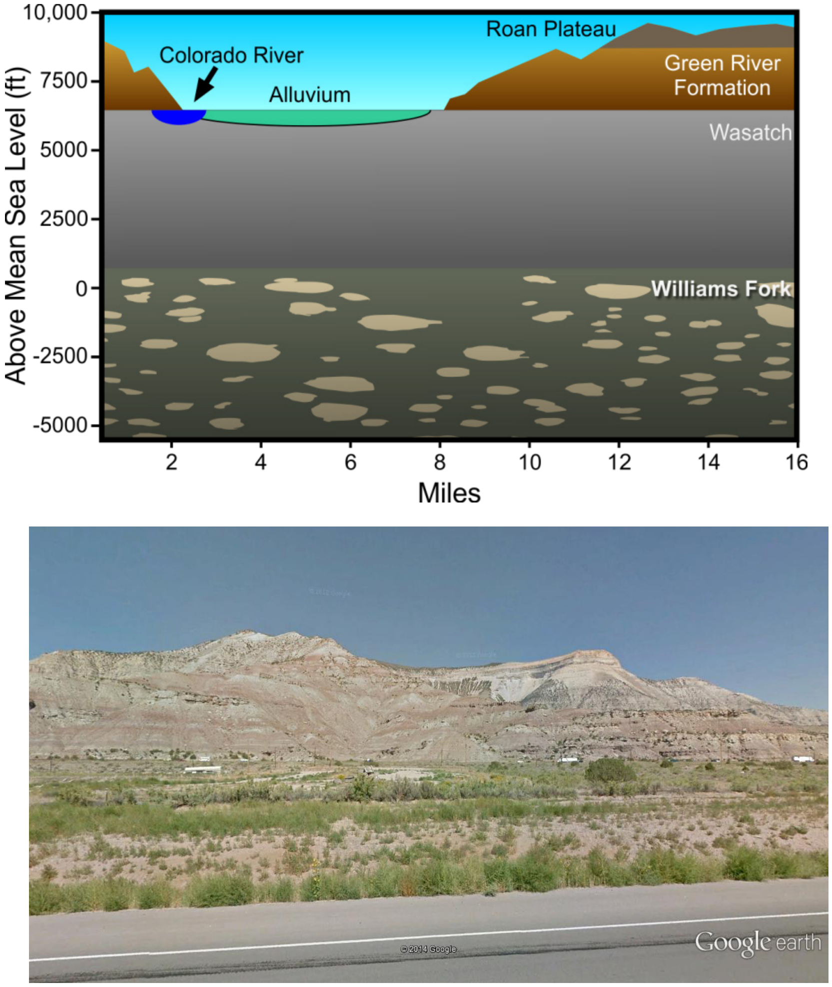


**Figure 5-7. Geologic strata in Garfield County. Upper Panel: Schematic of Garfield County's surficial geology and the recoverable gas formations of the Williams Fork formation below the current valley surface, as well as the exposed Green River formation, which bears kerogen-rich sedimentary deposits. Lower Panel: Photograph of the Green River formation. (Schematic after Dennison 2005; photo from Google Earth.)**

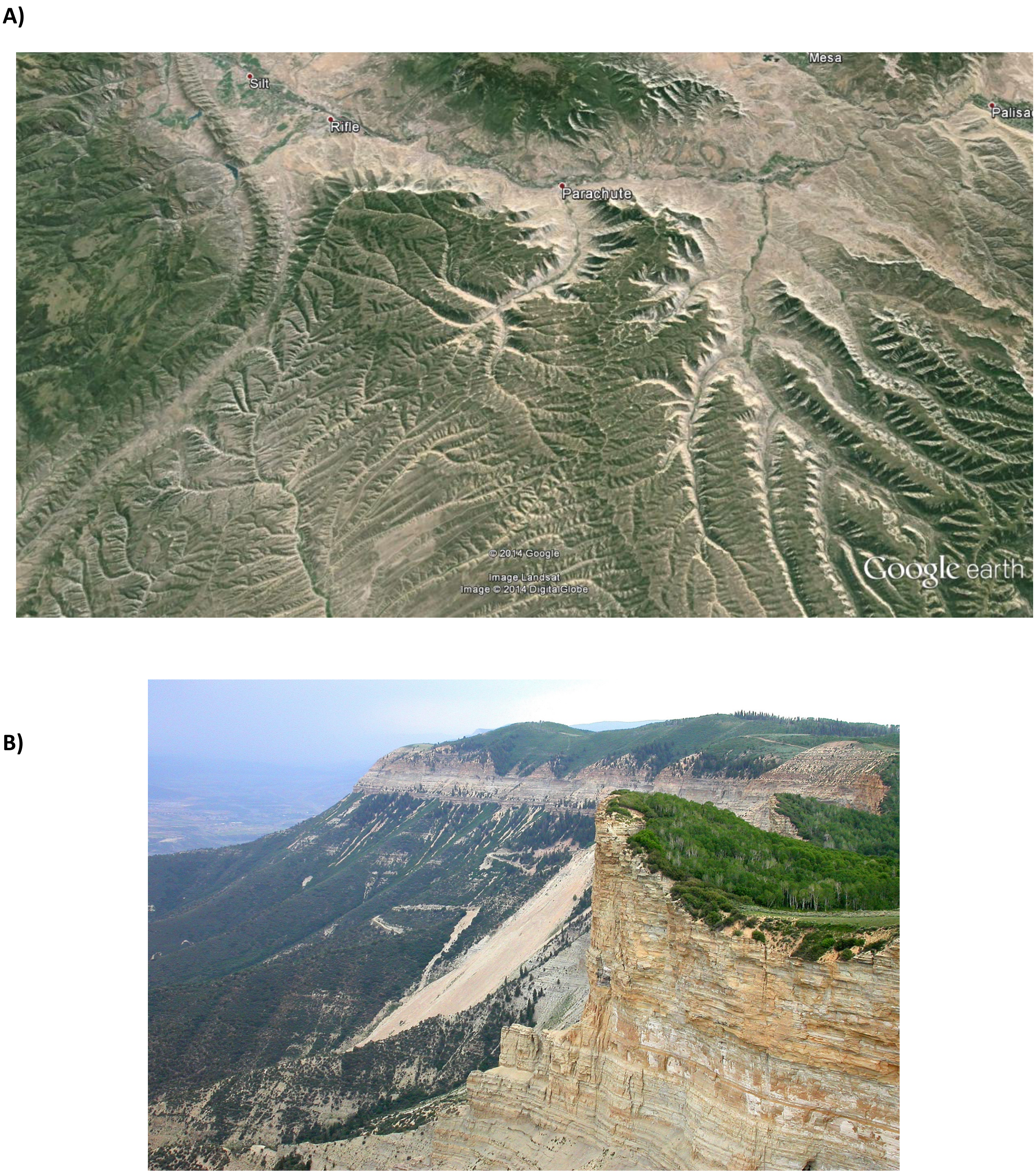


**Figure 5-8. Roan Creek Plateau. A) Aerial view of the Roan Plateau looking south across the top of the plateau to the Colorado River and alluvial plain at the top of the photograph. The photograph looks into the Parachute Creek subbasin, which joins the Colorado River in the upper right. The Grand Hogback monocline, a prominent northwest trending feature that separates the Colorado Plateau from the White River Plateau, is in the upper left. (Image from Google Earth; Landsat; ©Digital Globe.) B) Exposed bedrock outcrops on the southeast rim include the upper portion of the Piceance Basin sequence, including the Green River formation. (Image from Miamifittv.com.)**

**Hydrology, Climate, and Land Use.** The climate of the Colorado Plateau is semi-arid to arid and there is a general shortage of water (Bureau of Reclamation 2012; CWCB 2007; GAO 2003; Hunt 1974). This area has annual precipitation that ranges from 10 inches at lower elevations in the valley (which has little or no snow accumulation) to approximately 25 inches atop the plateau, where enough snowpack develops to sustain a spring snowmelt season in the tributaries (BLM 2006). Most of the population lives in towns in the alluvial valley along the UCRB and relies on the river and its upstream reservoirs for its water supply (Fig. 5-9). The upper elevations of the plateau are managed primarily by the Bureau of Land Management. Water from the river is withdrawn for municipal supplies and is also shunted through natural and engineered structures, such as ditches and pipelines that route it to irrigated farmlands on the mainstem and tributary valleys. River flow is highly seasonal, depending on snowmelt with occasional summer storms

The shallow rock aquifers of the area are capable of yielding sufficient supplies for agricultural or domestic use, but the water quality is variable (Robson and Banta 1995) and withdrawals within the Piceance Basin appear to be minimal (Colorado Geological Survey 2003), although several thousand households in Garfield County have private drinking water systems. Most municipal groundwater wells are located in the valleys and alluvium of the Colorado River and its tributaries. The primary water use is irrigated agriculture within Garfield County, where most hydraulic fracturing occurs.

**Figure 5-9. Colorado River alluvial valley bottom in the Garfield County along the Interstate 70 corridor between Rifle and Glenwood Springs. Irrigated agriculture is the dominant water use throughout the region. Many of the semi-regularly distributed white dots are hydraulic fracturing well pads. (Image from Google Earth 2014.)**

The Upper Colorado River flows 230 miles from its headwaters to the Utah border, encompassing a land area of 17,800 mi$^2$. Interstate 70 traces its path along most of the river's length in this area. The counties most dependent on the river—and at the same time experiencing hydraulic fracturing resource extraction—are Garfield County, with a population of about 56,000, and Mesa County, with a population of 146,000 (including Grand Junction, the largest city in western Colorado). Water must be passed downriver through Garfield County to other users, including Grand Junction, for municipal and agricultural use, low-head hydropower and endangered species habitat (CWCB 2007; Bureau of Reclamation 2012). Total daily water use for the UCRB from headwaters to Grand Junction (Division 5) is shown in Fig. 5-10. By far the largest users are irrigation, power generation from a low-head dam that does not consume water, and transfer of water to the east slope cities. Most of the O&G resource extraction occurs in the Colorado River valley and on the Roan Plateau on the north side of the river; some occurs on the south side of the river (Fig. 5-6).

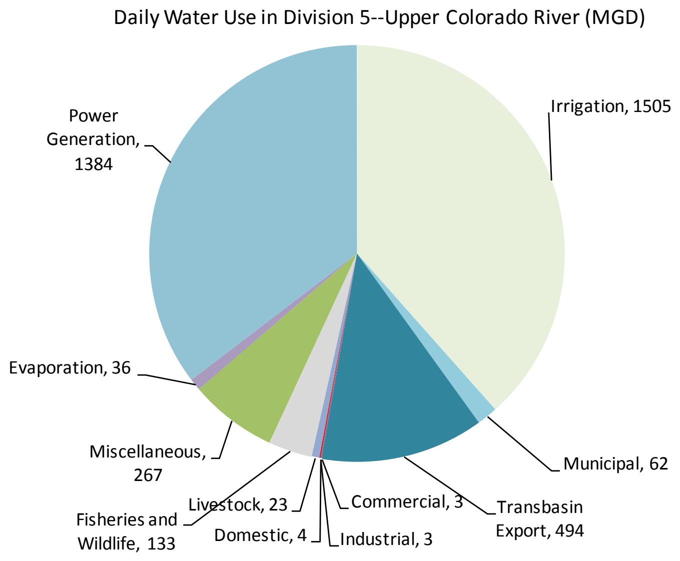


**Figure 5-10. Upper Colorado River (District 5) daily water use by sector in 2012. A number of categories were grouped in the "Miscellaneous" category. (Data source: CODWR 2012.)**

**Water Allocation and Regulation.** The Colorado Water Courts allocate water based on a prior appropriations doctrine and water is managed by the State Engineer in the Department of Water Resources (CODWR) in the Colorado Department of Natural Resources (Grantham 2011; CWCB 2014). The Colorado Water Conservation Board (CWCB) is an agency with responsibilities for water conservation, flood mitigation, watershed protection, stream restoration, and water supply planning. Courts decree a water right to an applicant for specified beneficial use(s) and volume. Priority is awarded based on date of appropriation. Later rights are junior to earlier rights and may not receive their appropriation in times of shortage until senior needs are filled. A water right can be transferred to another owner maintaining the original priority. Users include irrigation, municipal supplies, hydropower, livestock, industrial, commercial and endangered species. Municipalities hold rights like other users and may also augment supplies from the Bureau of Reclamation reservoirs by reserving volumes through contract.

Fresh surface water used by the hydraulic fracturing industry can be obtained from allocations on the mainstem Colorado River or its tributaries. Water can be purchased from large federal reservoirs and delivered via the Colorado River to a collection depot, from where it is transported to its final destination. This transaction may occur through a third party such as state-sanctioned water conservancy districts or private owners, as long as industrial use is defined as a use at the withdrawal point (a "diversion" structure). Since the 1980s, O&G companies have collectively acquired access to large allocated volumes of water and contracts held throughout the Piceance play (URS 2008). In this engineered system, water can be reallocated within the infrastructure among local and distant sources, allocated back and forth between tributaries, the river, and small private reservoirs distributed throughout the region, or transferred from structure to structure.

Irrigation has historically been the largest water user in this basin and throughout Colorado (Fig. 5-10). Withdrawal reporting at most structures occurs only during the irrigation period (mid-April to end of October) when the water is used. Some structures such as municipal structures report use year-round. Water used for hydraulic fracturing is not separated from other industrial uses.

**Data Sources.** CODWR tracks water use at the structures where water is taken. There are more than 18,000 active acquisition locations (structures) in the upper Colorado River basin. Every use location is identified, no matter how small. CODWR generates water use records on a daily, monthly, or annual basis (dependent on source) (CODWR 2014a). The CODWR online database was accessed for information on water allocation and use throughout Divisions 4, 5, and 6, with a focus on subbasins and the Upper Colorado River (Division 5) within Garfield County where hydraulic fracturing has been most active (CODWR 2014b,c,d). Individual database queries are listed in Table 5-2. The water acquisition system and the CODWR database that tracks it are very complex, and there are challenges to quantifying O&G industry water acquisition. Some of the structures where water is acquired are owned by O&G companies and can be identified in the data system, while others sourced from contract purchases cannot be readily identified. The O&G industry is designated as industrial use the same as other industries. Primary data sources for water use and hydraulic fracturing wells are listed in Table 5-2.

Well drilling practices are regulated by the Colorado Oil and Gas Conservation Commission (COGCC). The agency also monitors O&G resource production and well status. Since 2010, COGCC has required the O&G industry to report injection volume and chemicals used at individual wells in the FracFocus chemical disclosure database (COGCC 2012; FracFocus 2014). Well counts and produced water volumes were obtained from COGCC. Well fluid volume use was obtained from the FracFocus database (FracFocus 2014).

**Table 5-2. Water use data sources for the Upper Colorado River Basin.**

| Agency/Organization | Description | Source/Query | Data Use |
|---|---|---|---|
| Colorado Division of Water Resources (CODWR 2014) | b. Water rights information | http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx | Priority, decreed use |
| | c. Structure information | http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx | Locations, history, ownership |
| | d. Structure water use | http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx<br>(query structures for diversion reports) | Daily, monthly, annual volumes used |
| | e. StateMod water planning program | http://cdss.state.co.us/Modeling/Pages/SurfaceWaterStateMod.aspx | Scenario analysis of use and structure priority |
| Colorado Oil and Gas Conservation Commission (COGCC 2014) | a. Well starts and completions | http://cogcc.state.co.us<br>Query: staff report | Well counts |
| | b. Produced Water | http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyWaterProdByCounty | Estimates of hydraulic fracturing wastewater reuse |
| FracFocus (2014) | Well fluid volumes | http://www.fracfocusdata.org/DisclosureSearch/<br>(query by county, look at individual well reports) | Total well consumption, counts, timing |

## Sources of Freshwater for Hydraulic Fracturing

Development of unconventional gas reserves in the Piceance has been ongoing for almost two decades, but the pace has increased rapidly since 2000 (Hill 2013). Gas extraction using hydraulic fracturing has occurred in CODWR Division 5 (the Upper Colorado River from headwaters to Grand Junction), Division 4 (the Gunnison River basin), and Division 6 (the Yampa/White Rivers primarily in Rio Blanco County). Eighty-five percent of the wells have been drilled in Garfield County and Mesa County within about 30 miles north and south of the Upper Colorado River. Well starts by year are shown in Table 5-3 based on data provided by COGCC (2014a). Hydraulic fracturing has also been active in the While River Basin in Rio Blanco County in CODWR Division 6.

Annual hydraulic fracturing activity increased steadily in this area after 2000, peaking in 2008 when 1,688 wells were started in Garfield County (Fig. 5-11). The drilling rate has recently declined to only 390 in 2013. This decrease coincided with a shift in drilling from dry gas to liquid-rich reservoirs in central and eastern Colorado and a relative increase in the price of oil compared to the price of natural gas during this period (U.S. EIA 2013b).

**Table 5-3. Hydraulic fracturing well starts by county. (Data source: COGCC 2014a.)**

| County | CODWR Division | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Garfield** | **5** | 190 | 251 | 245 | 417 | 585 | 799 | 1,005 | 1,304 | 1,688 | 768 | 904 | **879** | **495** | **392** |
| **Mesa** | **5** | 2 | 12 | 12 | 13 | 25 | 89 | 156 | 209 | 222 | 14 | 1 | 39 | 4 | 6 |
| **Routt** | **4** | 5 | 12 | 1 | 0 | 1 | 6 | 3 | 2 | 0 | 2 | 1 | 2 | 4 | 2 |
| **Gunnison** | **5** | 0 | 0 | 1 | 0 | 1 | 1 | 9 | 5 | 1 | 4 | 5 | 2 | 4 | 1 |
| **Delta** | **4** | 0 | 0 | 0 | 5 | 4 | 6 | 5 | 2 | 0 | 0 | 4 | 1 | 6 | 0 |
| **Montrose** | **4** | 0 | 3 | 0 | 2 | 1 | 0 | 0 | 1 | 2 | 0 | 1 | 0 | 0 | 0 |
| **Rio Blanco** | **6** | 51 | 82 | 47 | 83 | 92 | 95 | 107 | 95 | 203 | 116 | 107 | 72 | 53 | 36 |

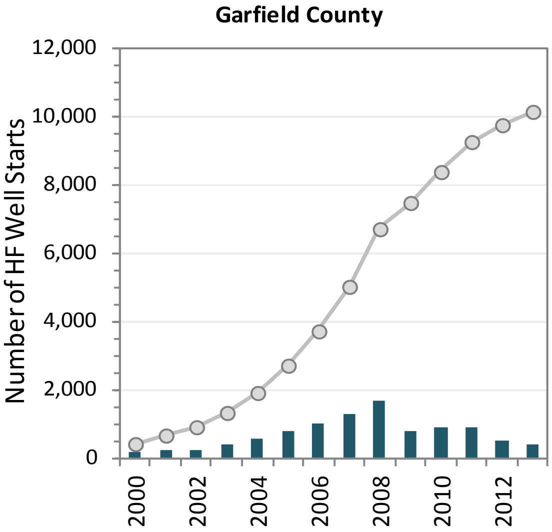


**Figure 5-11. Annual and cumulative hydraulic fracturing well starts in Garfield County since 2000. (Data source: COGCC 2014a.)**

This project focused analysis where hydraulic fracturing activity is centered in the UCRB (Division 5) and Garfield County within the division, where almost 10,000 wells have been drilled; see Figs. 5-6 and 5-11. However, data were examined from other water divisions in the Piceance in Colorado and are discussed as relevant.

## Water Used For Fracturing Wells

There is no direct reporting of how much freshwater is used for hydraulic fracturing gas wells in either oil and gas or water use databases managed by the state of Colorado (Table 5-2), although these data sources could be used to estimate the freshwater consumption for hydraulic fracturing activity. These estimates were supplemented by information provided by oil and gas operators to federal agencies in this area (USFWS 2008), including interviews conducted for this project. We use the term "freshwater" to distinguish from hydraulic fracturing wastewater. The term "freshwater" does not infer that water obtained from local supplies is of drinking water quality and may include untreated, brackish, saline, or contaminated water.

O&G companies have reported that 100% of the water used in the hydraulic fracturing process to stimulate gas wells in this area is hydraulic fracturing wastewater (BLM 2006; USFWS 2008). Freshwater is only used for drilling and associated activities. High reuse rates are possible because nearly all of the hydraulic fracturing fluid (80% to 100%) injected into directionally drilled tight gas wells in the Williams Fork formation returns to the surface within the first few months after fracturing, according to local operators and agencies (BLM 2006; USFWS 2008; WPX Energy, onsite interview, January 8, 2014). Returned hydraulic fracturing wastewater is of relatively good quality for industrial use and the industry captures, treats, and reuses it in other wells. In addition, the Piceance tight sands have naturally high water content (Johnson 1989) and formation water continues to flow from each producing well over time. COGCC tracks volumes of produced water; we queried COGCC (2014b) by county to quantify this volume. Each producing well in Garfield County returns approximately 140,000 gallons per year (0.43 ac-ft).

The freshwater volume needed for hydraulic fracturing in Garfield County was estimated with well counts and a set of assumptions on required injection volumes and water available for reuse as reported by the industry. Given the reported high reuse rate, we start from the assumption that all wells are fractured with reused hydraulic fracturing wastewater if it is available. Any shortfall in water needed for hydraulic fracturing must be supplied from freshwater sources. We quantify water use for hydraulic fracturing based on the following data and assumptions.

**Injection Fluid Volume Needed for Hydraulic Fracturing.** The volume of water needed for hydraulic fracturing depends on the number of directional and horizontal wells and the average volume used per well. For the latter, there is variability depending on each company's drilling strategies (targeted formation, depth, and so on.)

- *Injection volume:* Data obtained from FracFocus 1.0 disclosures (U.S. EPA 2015) was used to determine fluid injection volume per well for wells drilled from 2011 to 2013 in Garfield County. FracFocus 2.0 was directly accessed by this project for wells drilled in 2010. We assumed that numbers reported from 2010 to 2013 were representative of prior years. The injection volume generally ranged from 2 to 3 MG (6.1 to 9.2 ac-ft), averaging 2.4 MG (7.37 ac-ft).
- *Number of wells:* For the number of wells hydraulically fractured each year, we used well starts provided by COGCC (2014a), as listed in Table 5-3.

**Available Hydraulic Fracturing Wastewater.** The available hydraulic fracturing wastewater for Garfield County as a whole was computed as the sum of flowback and produced water. Any surplus was carried over to the next year.

Operators report that drilling directional wells and associated development activities use 0.25 MG (0.77 ac-ft) (BLM 2006; USFWS 2008; URS 2008). WPX Energy has started to drill horizontal wells into the Mancos Shale in recent years—they report that 1.05 MG (3.2 ac-ft) are needed for drilling these deeper and longer wells (WPX Energy, onsite interview, January 8, 2014).

- Flowback water: We computed the pool of flowback water available each year by assuming a proportion of flowback per well (80% to 100%) multiplied by the number of wells drilled that year. In the calculation, we offset this volume by six months to allow time for treatment. We did not know the exact length of time wastewater spends in storage, but this assumption somewhat improved our fit to observed data. Assumed percentage was 70% until 2002, 80% in 2003, 90% in 2004, and 100% thereafter to reflect improving technology and infrastructure development.
- Produced water: Produced water volume was reported by COGCC for Garfield County (COGCC 2014b). This number represents the cumulative number of producing wells in the county and grows each year. The volume available in 2000 was 26 MG (80ac-ft), climbing to 1,700 MG (5,200 ac-ft) by 2013.

**Freshwater Volume Needed for Hydraulic Fracturing.** The necessary volume of freshwater was the sum of water used for hydraulic fracturing and the water used for drilling and associated activities.

- *Hydraulic fracturing injected freshwater:* Each year, the required volume of injection fluid needed was computed from well count and average total injection volume. The volume of available hydraulic fracturing wastewater was computed based on well count and produced and flowback water volume. In the calculation, the wastewater was put into the wells first. Any deficit between required volume and wastewater was fulfilled with freshwater.
- *Drilling and associated activities:* All drilling and associated activities required freshwater of 0.25 MG (0.77 ac-ft) for each directional well and 1.05 MG (3.2 acre-feet) for each horizontal well as reported by O&G companies.

We combined these factors to estimate the total volume of hydraulic fracturing wastewater and freshwater used in Garfield County annually; results are shown in Fig. 5-12. Total annual injection volume at the peak of drilling in 2008 was almost 4,500 MG (14,000 ac-ft); freshwater was a small part of the total. Freshwater was needed for hydraulic fracturing until 2005, when a surplus of hydraulic fracturing wastewater developed (resulting from the cumulative increase in wells producing hydraulic fracturing formation water, combined with the large volume of flowback). There seems to have been enough hydraulic fracturing wastewater to accommodate the high drilling rates in 2008. Surpluses have continued to grow as drilling rates have declined. Freshwater has made up less than 10% of the annual volume of fluids used to drill and fracture primarily directional wells and has been used only for drilling since 2006. This project did not determine whether more freshwater will be needed for horizontal drilling into shales due to any technological differences other than longer wellbores. These estimates indicated how much freshwater must be acquired from local sources.

### *Water Acquired for Hydraulic Fracturing*

We determined the volume of water acquired by the O&G industry for hydraulic fracturing by querying the CODWR structure database (CODWR 2012b, 2012c). Each structure has a water rights allocation, a history of activity pertinent to the allocation, and data on water use at the structure. Each structure has an owner and one or more rights allocation with one or more designated uses and a daily or annual volume limit. This system is highly complex; only the most salient elements of use designation and allocation were used and discussed in this report. CODWR maintains a database of water taken from each structure that can be accessed using the “structure” query. Beginning there, we iteratively queried the database looking for water supplied to industrial users (the category to which use by the O&G industry is assigned) and/or owners that could be identified as an O&G company or provider by name. Eventually the search widened to other areas and structure ownership; water was not transported between major river basins at present as trans-basin transfers are also tracked. Note that water acquired at an O&G-owned structure is not necessarily used for hydraulic fracturing. Many of these structures are still used for irrigation.

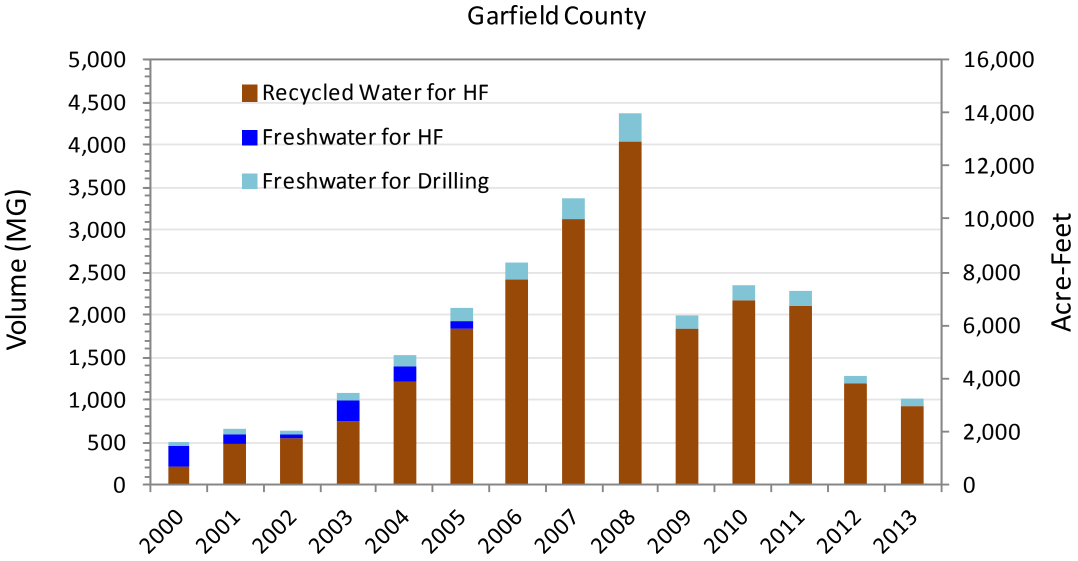


**Figure 5-12. Estimated use of water for hydraulic fracturing natural gas extraction in Garfield County. The total includes reused hydraulic fracturing fluid and freshwater used for hydraulic fracturing and for drilling. (Data sources: COGCC 2014a, 2014b; FracFocus 2014 for individual well injection volume.)**

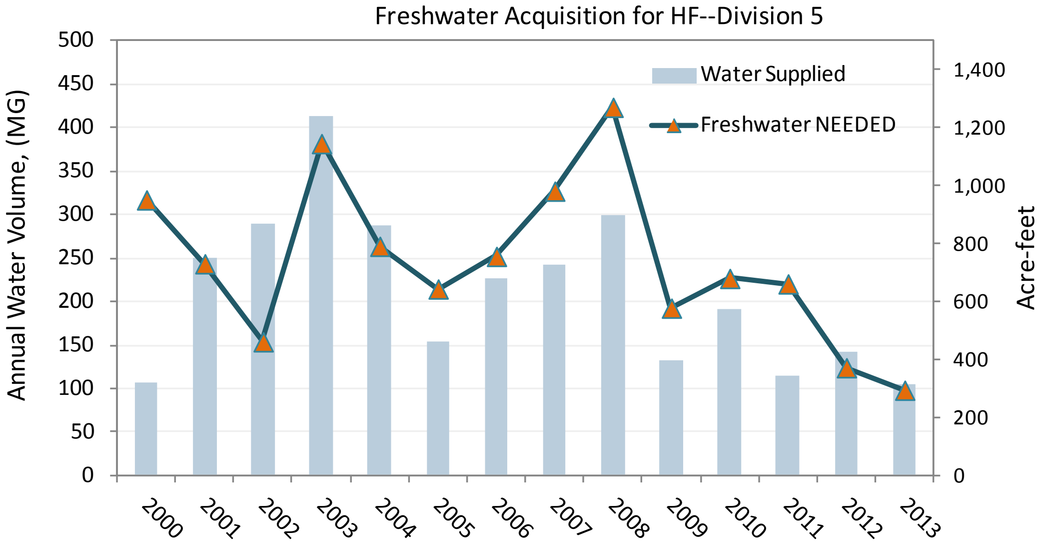


**Figure 5-13. Estimated freshwater use in Upper Colorado River Division 5. Water supplied was the freshwater volume accounted for in the Colorado Division of Water Resources structure use monitoring database. Water needed was the total volume of freshwater estimated in Fig. 5-12 as blue portions of the bars. (Data source: CODWR 2014d.)**

Later sections of this report analyze hydraulic fracturing water withdrawals in more detail; here, we characterize the total volume of freshwater acquired for hydraulic fracturing within the search area. Fig. 5-13 shows volumes of freshwater accounted for at withdrawal location and volumes needed for hydraulic fracturing activities (blue areas at the top of the bar chart in Fig. 5-12). We were able to account for a volume of water each year that was close to hypothesized based on the assumptions of hydraulic fracturing wastewater reuse as reported by hydraulic fracturing operators (Fig. 5-13). The accounting was better in some years than others, disagreeing by more than 50% in 2000 and 2002. Water can be obtained from third party contracts such as with the Conservancy Districts that acquire water reserved in the BLM reservoirs. This water is not tracked by individual users in the Colorado Water Resources database (CODWR 2014d) and any water supplied from these sources would contributed to differences between estimated water supplied and needed in Figure 5-13. Some water from this source was accounted for based on documents available at http://www.wdwcd.org/content/library. . For the 14-year period as a whole, 86% of the freshwater demand for hydraulic fracturing wells was accounted for at water withdrawal locations. These results support industry reports that 100% of the hydraulic fracturing injection fluid is reused hydraulic fracturing wastewater.

Note, however, that we generally have less confidence in the O&G water need and acquisition estimates in this case study area. Uncertainty is greater due to lack of direct data on freshwater use in hydraulic fracturing wells, as well as inclusion of hydraulic fracturing water with all other industrial uses in the CODWR water use data. Estimates appear to be the right order of magnitude, but may be biased low. Average annual freshwater acquisition by the O&G industry from 2000 to 2013 was 200 MG per year (600 ac-ft). In the peak year 330 MG (1000 ac-ft) were acquired in Division 5. This value is low relative to shale plays and compared to irrigated agriculture in the area where most of the O&G water is acquired.

### *Freshwater Sources for Hydraulic Fracturing*

The Piceance gas fields within the UCRB are found mostly within 20 miles north and south of the Colorado River (Fig 1, upper panel and Fig. 5-14) as it flows westward between Glenwood Springs and Grand Junction. Much of the hydraulic fracturing activity in Garfield County occurs within the northern tributaries including Parachute and Roan Creeks that together comprise an area of about 800 mi$^2$. These subbasins also contain rich oil shale deposits in the Piceance formations overlying the deeper unconventional gas reservoirs currently under development.

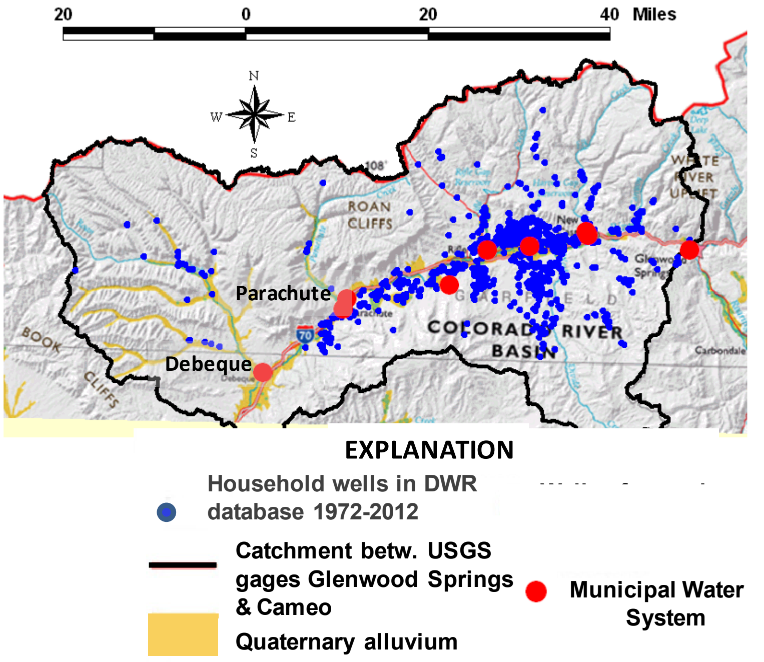


**Figure 5-14. Location of drinking water sources including public water supplies and private groundwater wells in the Upper Colorado River Basin between Glenwood Springs and Cameo west of DeBeque (CODWR 2014f) and municipal wells (U.S. EPA 2012c) in the area of primary hydraulic fracturing drilling activity. (Base map from CGS 2003).**

Land use in the alluvial valleys along the Colorado River and its tributaries has traditionally been irrigated agriculture, as continues today in Roan Creek. Parachute Creek has become a hub for natural gas extraction with numerous well pads and wastewater treatment facilities now intermixed with agricultural lands. Water sources in Garfield County, where hydraulic fracturing is most active, are the Colorado River and its major tributaries—mainly on the north side of the river draining the Roan Plateau (Fig. 5-14). Groundwater resources are primarily found in the alluvial valleys associated with the rivers and streams. Public water supplies are taken from the Colorado River for the most part, where they may also pick up reservoir water. The

O&G industry primarily self-supplies freshwater from a mixture of surface water and groundwater sources.

The alluvium of the Colorado River between Glenwood Springs and Cameo, where most of the population in Garfield County lives, is a primary groundwater source. There are many private and a few municipal groundwater wells that are not used for drinking water supply (Fig. 5-14). Just one municipal system pumps 0.9 MGD of groundwater from the alluvium of the Colorado River at 64% of facility pumping capacity (Hill 2013), but this water is not used for drinking water supplies. Some of the private wells are industrial gravel pits that fill with water seepage between the river and alluvium. The water allocation system treats a gravel pit as a groundwater tributary to the Colorado River, so water diverted for the O&G industry require plans for replacement of any depletion to river flow through augmentation plans (COGCC 2012). Gravel pits are designated for industrial use and any sales to O&G from these are not separately documented. We received anecdotal information from operators that some water has been obtained from one or more of these gravel pits, but we were unable to discern hydraulic fracturing use from CODWR use records.

**Public Water Supplies.** It appears from the CODWR database that hydraulic fracturing operators do not obtain water from public water suppliers. Consequently, the discussion of public water supplies and drinking water sources in this area is brief. Municipalities hold rights for water withdrawals from structures having designated beneficial uses, priority, and volume limits like all other users. They often have allocations at more than one location to supply water for a variety of municipal, commercial, and industrial uses. Many have water reserved in the Bureau of Reclamation reservoirs to augment supplies during shortages. We focus on the small municipalities of Parachute (pop. 1,095) and Battlement Mesa (pop. 4,500), which are co-located at the confluence of the Colorado River and Parachute Creek, while DeBeque (pop. 500) is located at the confluence with Roan Creek (Fig. 5-14). Each of these towns has one structure that appears dedicated primarily to drinking water supply: each draws from the Colorado River. The town of Parachute also augments its total supply from springs (Hill 2013).

The combined annual water intake for the three municipal suppliers is shown in Fig. 5-15. Water supply to these three municipal structures was sufficient to provide for domestic water use (100 to 200 gallons per person per day); augmentation from the reservoir was needed during the dry period in 2012–2013 when flow in the Colorado River in 2012 was the third lowest since records began in 1936. The reservoirs were generally called on to augment water supplies for many users throughout the region, including 25% to 44% of the annual use for these municipalities. These observations demonstrate the importance of the reservoir system, which was designed to sustain water supplies, especially during drier periods. According to records, none of the three municipal drinking supply structures provided water for hydraulic fracturing industrial operations during the study period.

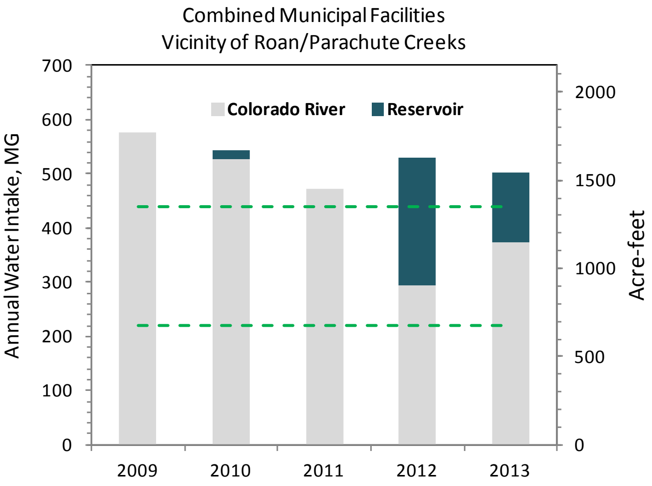


**Figure 5-15. Annual water volume acquired for drinking water at three municipal public water systems in the vicinity of Parachute and Roan Creeks, where current hydraulic fracturing drilling activity is focused. Water was obtained from the Upper Colorado River or augmented from Bureau of Reclamation reservoirs during low flow in 2012 and 2013 to satisfy per capita demands (shown as dotted horizontal lines set at 100 and 200 gallons per day). There was no acquisition of water by O&G at these municipal water supply structures.**

**Self-Supplied Sources.** CODWR structure records in Divisions 4, 5, and 6 were searched to identify locations with industrial use (use 4 in the CODWR system). In doing so, we found that a number of O&G companies collectively have rights to a sizable volume of water at 449 structures within the Piceance structural basin that includes Divisions 5 (Colorado River basin) and 6 (Yampa River Basin). Many are found in Parachute and Roan Creeks tributaries coincident with the Parachute gas field where much of the hydraulic fracturing is ongoing (Figs. 5-6 and 5-16). O&G water allocations were acquired in the late 1970s and 1980s to supply the large volumes of water necessary to extract the oil from kerogen in the oil shale deposits (AMEC 2011; URS 2008), the richest of which are in the Green River formation within the Roan Plateau (BLM 2006). These water allocations were acquired to supply projected water needs for oil shale extraction that could reach high end projections of

40,000 to 123,000 MG (120,000 to 399,000 ac-ft) per year, depending on scale of operations and technology advances (AMEC 2011; URS 2008).

Hydraulic fracturing operators obtain water at various locations along the Colorado River. Acquisition sites include structures with O&G owners,as well as collection sites shared among multiple users and where obtained by contract from organizations such as the West Conservancy District (WCD). The conservancy districts are Colorado governmental entities whose primary service is to provide water right augmentation within their service areas from supplies reserved in the upstream reservoirs for this purpose. They help those without access to enough water in the water allocation system to obtain supplies. Some of this water is picked up at five water depots that draw from the Colorado River, distributed along Interstate 70 interchanges in Garfield and Mesa Counties. Hydraulic fracturing operators and trucking companies have obtained water through this source. We included estimates of water supplied through contracts based on archived materials from the WCD website (http://www.wdwcd.org/), although we were not able to obtain this data directly. In general, water withdrawn from the Colorado River was more difficult to track, because it generally is acquired through various third party sources. As planned within the system, the volume of water from the Colorado River would have come from the reservoirs and was insignificant relative to the volume of water in the river.

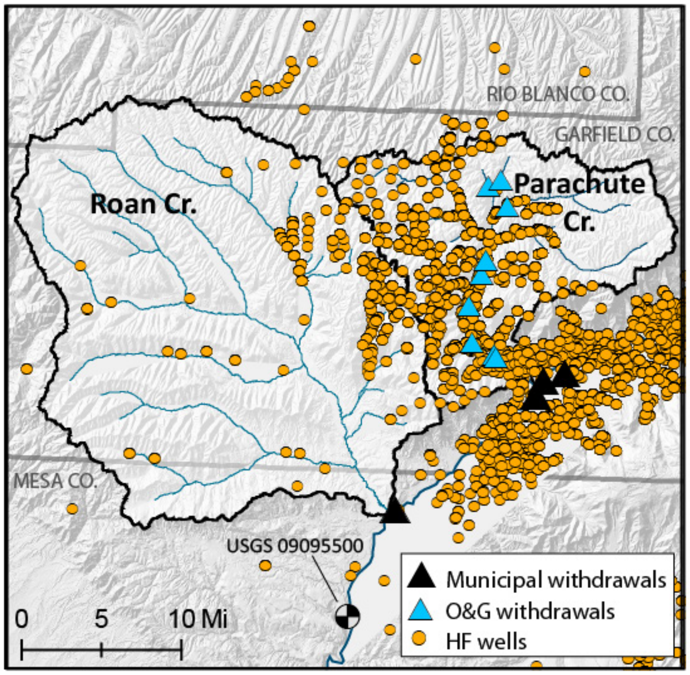


**Figure 5-16. Parachute and Roan Creek watersheds. Completed gas wells and oil and gas water withdrawal locations are shown. The location of the municipal public water systems discussed relative to Fig. 5-15 are also shown but note that they are not used as a water source for hydraulic fracturing. (Data source: gas wells from FracTracker Alliance 2014; water acquisition locations from CODWR 2014b, 2014c.)**

The CODWR water use data reports the volume of water taken for the designated uses at each structure separately. Each structure with assigned industrial use was examined for records of withdrawals. It appeared that irrigators and municipal suppliers provide little water, if any, to hydraulic fracturing operators, as their monitoring records showed no industrial use.

Although hydraulic fracturing activity was distributed throughout Garfield County, 50% or more of the freshwater was obtained from tributary streams and groundwater wells within the Parachute Creek watershed (198 mi$^2$) (Fig. 5-17). The location of Parachute and Roan Creeks within the UCRB is shown in Figs 5-6 and 5-14, and the distribution of hydraulic fracturing wells and withdrawal locations is shown in Fig. 5-16. Water acquired in Parachute Creek is taken from O&G owned structures. However, a very small fraction of O&G allocated water is withdrawn relative to rights, and a handful of structures are used by hydraulic fracturing operators. It appeared that Parachute Creek was used steadily, while the Colorado River was tapped more heavily when drilling rates were higher. There has been no industrial use of water in the Roan Creek watershed to date, although structures there are also part of the oil shale water delivery system (Stantec 2013).

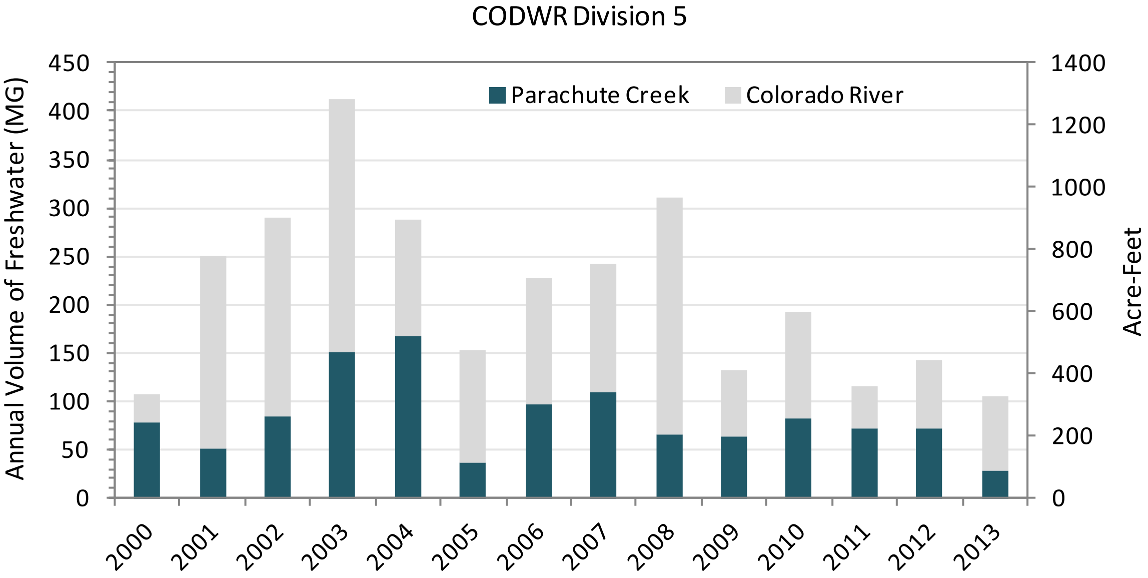


**Figure 5-17. Sources of freshwater acquired for the oil and gas industry in the Upper Colorado River Basin. All water was acquired in Garfield and Mesa Counties from miscellaneous distributed sites on the Colorado River mainstem or from structures within the Parachute Creek watershed. (Data source: CODWR 2014d.)**

**Parachute Creek Water Use.** Land use in the alluvial valleys along the Colorado River and its tributaries has traditionally been irrigated agriculture; this continues today in Roan Creek. While irrigated agriculture is still active in the Parachute Creek valley, this area has also become a hub for hydraulic fracturing drilling, industrial operations, and water acquisition within Garfield County and the Piceance Basin (Fig. 5-18). The O&G industry has built water treatment facilities to clean hydraulic fracturing wastewater for reuse in hydraulic fracturing wells. There are also groundwater well complexes, especially in the middle and upper reaches of the valley. At the same time, irrigation farming remains active in the lower valley.

Water acquisition sites, including irrigation ditches and reservoirs, are pictured in Fig. 5-18. The O&G industry primarily takes water from several small reservoirs that intercept the main tributaries in the upper valley with about 850 MG (2,600 ac-ft) of storage capacity, and from a groundwater well midway up the valley within the industrial complex shown in Fig. 5-18C, located above most irrigation. There are nearly 100 more O&G-owned small instream locations in the Parachute Creek headwaters; it is unknown if any hydraulic fracturing operators have obtained water from them, as use is not tracked in the CODWR database.

Most of the water in Parachute Creek is diverted from the stream into ditches and used for irrigation (Fig. 5-18A). Only a small fraction of the water that could be taken from O&G-owned diversion structures in Parachute Creek has been used for hydraulic fracturing (Fig. 5-19).

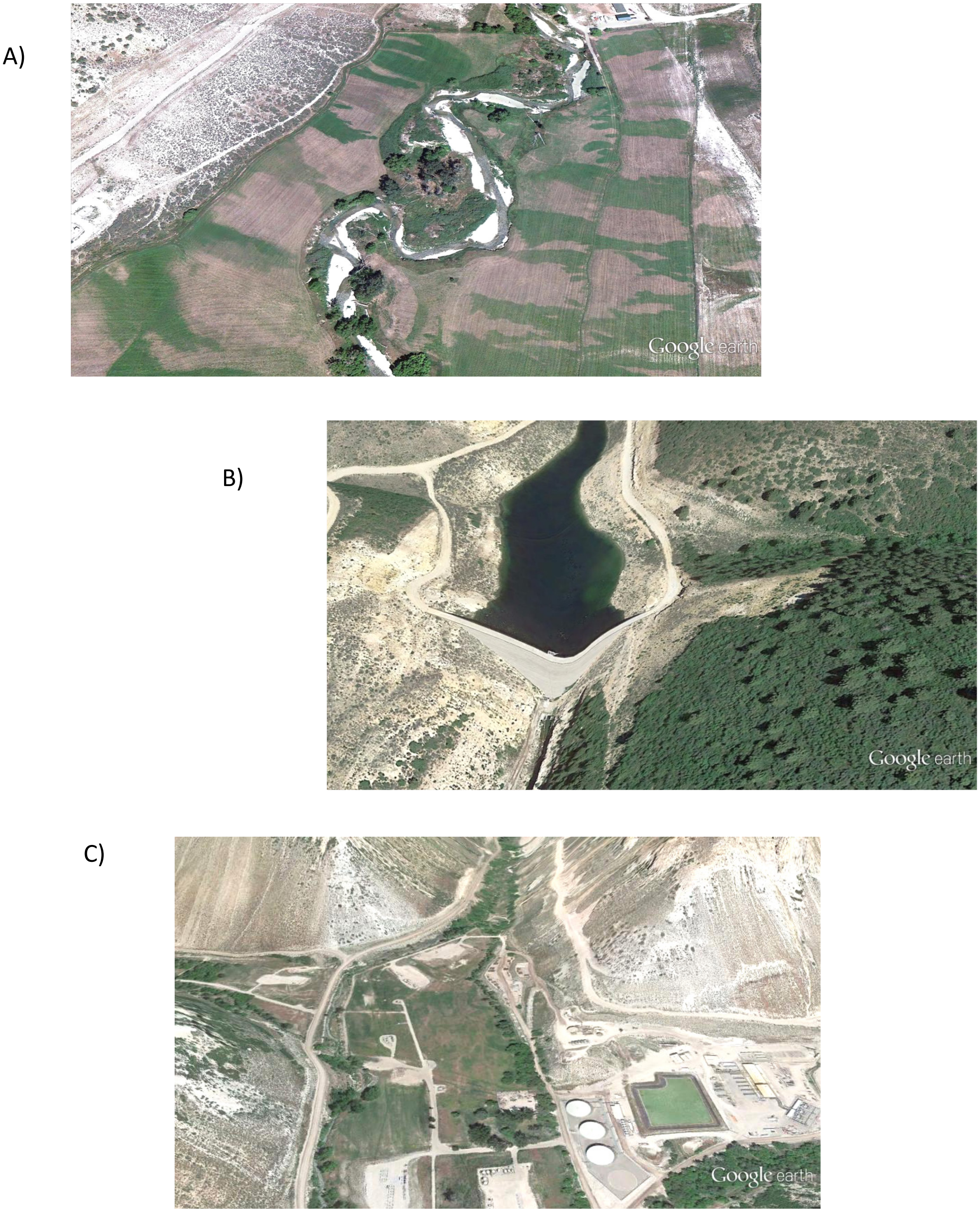


**Figure 5-18. Parachute Creek water acquisition sites. A) Irrigators divert water from the mainstem of Parachute Creek through headgates into ditches that carry it along the sides of the valley on each site of the stream. B) Small reservoirs in the upper valley store water from the main tributaries of Parachute Creek. C) A groundwater wellfield and reservoir complex in the upper valley at the junction of three main tributaries provides most of the water for hydraulic fracturing. (Images from Google Earth.)**

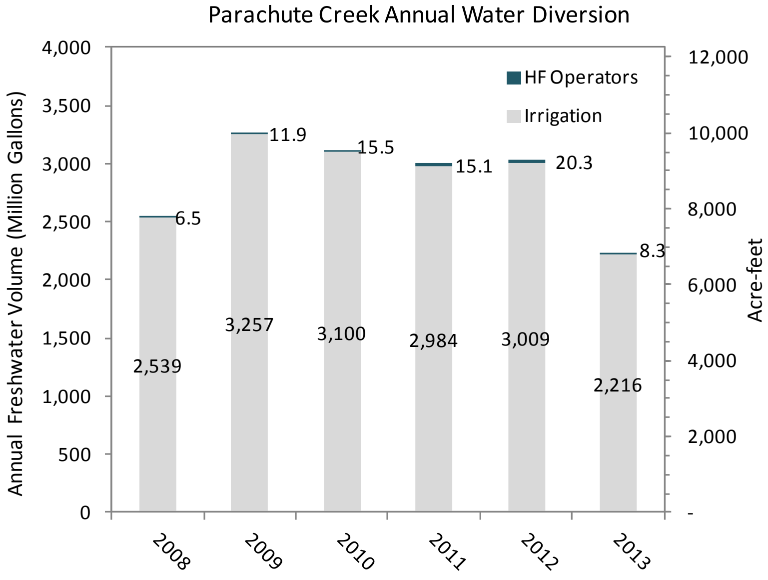


**Figure 5-19. Annual water withdrawn from surface waters in Parachute Creek for irrigation and for hydraulic fracturing by the oil and gas industry. (Data source: CODWR 2014d.)**

**Parachute Creek Water Availability.** Streamflow was not measured in Parachute or Roan Creeks on a consistent basis. Daily streamflow was estimated using a combination of HSPF modeling and empirical extrapolation from gaged locations. The USGS gage on the White River at Meeker, CO (09304500) (760 mi$^2$) was deemed the better choice for calibration among the few available gages in this area that had a sufficiently long record of flow. The calibration gage is 30 miles from the study area, and the watershed area is somewhat larger than Roan Creek. Results were cross-validated with two Colorado River gages at Glenwood Springs and Cameo west of the town of DeBeque. Modeling was informed by precipitation measured at five locations in the White River, Roan Creek, and the Colorado River valley at relatively lower elevations. The parameter set that produced the best model fit was used to estimate flow in Parachute and Roan Creeks. The streamflow modeling replicated the daily flow fluctuations at Meeker reasonably well (Weighted Nash Sutcliffe Score = 0.75). Streamflow was simulated from 1987 to 2012.

The SUI calculation required a “natural flow” record so that we did not overestimate withdrawal impacts. Existing stream gage records are affected by the large irrigation diversions each year. Some of the water taken at the irrigation structures is consumed by crops, but much is also lost back to the river system through leakage and structure delivery inefficiencies. The combined crop and structure loss has been quantified by Leonard Rice Engineers (2009) for use in the CODWR StateMod water rights planning tool (CODWR 2014e). We adjusted the calibrated record by the monthly structure delivery inefficiencies, which were generally about 70% of structure withdrawals. This adjusted streamflow record was assumed to be free of irrigation effects and to correctly reflect day-to-day streamflow fluctuations. The structure inefficiency factors were also used to modify the irrigation volumes.

The streamflow in Parachute Creek had been measured episodically for a total of 22 years within the period 1921 to 1982 (USGS site 09093500). Modeled Parachute Creek flow was summarized as monthly averages and compared to the observed monthly data. The fit was quite good for the summer and fall months (July through November), but flow was significantly underestimated during the spring snowmelt and somewhat overestimated during the winter months. We hypothesize that the precipitation records from lower elevations did not adequately address snow accumulation at the high elevations on the Roan Plateau, where annual precipitation is 2.5 times greater (BLM 2006). We empirically adjusted the daily simulated flow by applying monthly factors computed from the observed record. The final streamflow record matched monthly highs and low and daily fluctuations. (See Appendix B for a more comprehensive discussion of the methods for deriving the streamflow record in Parachute and Roan Creeks and calibration results.) This adjustment assured that the range of flows observed in each month matched the range of observed streamflow. In summary, the final natural streamflow record was 1) constrained to fall within flow volumes observed in Parachute Creek with daily fluctuations matching the calibration watershed, and 2) was free of irrigation-related removals and losses. This record was considered adequate for computing SUI, but had uncertainties due to these adjustments. The natural streamflow record from 2008 to 2012 and daily withdrawals summed for all structures in Parachute Creek are shown in Fig. 5-20.

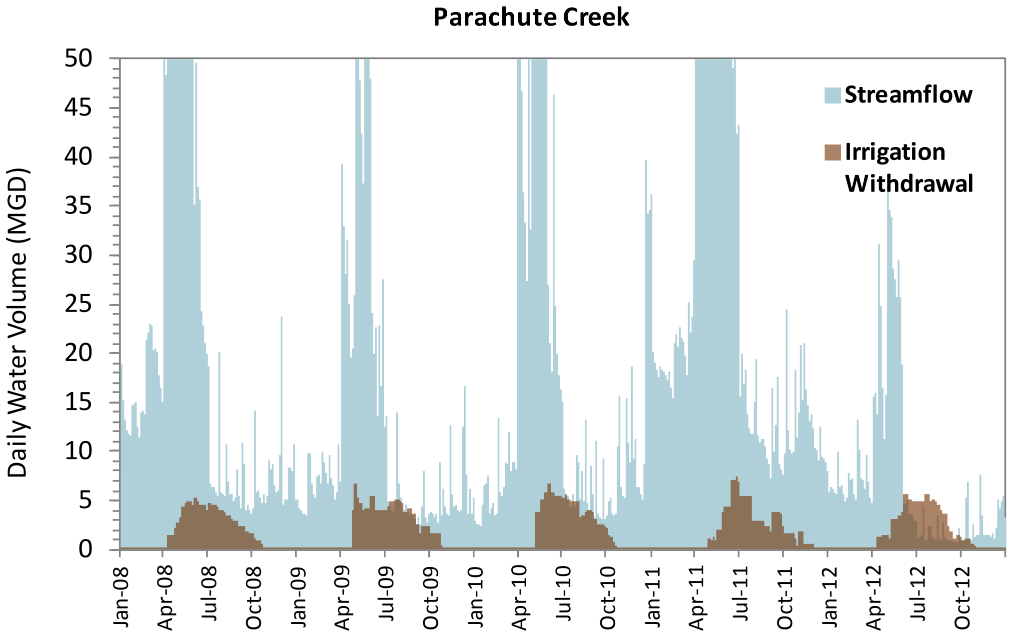


**Figure 5-20. Daily streamflow and collective withdrawal volume summing 29 structures withdrawing water from surface water structures in Parachute Creek. Streamflow was estimated using HSPF model, with empirical fitting to observed streamflow. The vertical axis is truncated to emphasize low flows. (Data source for water withdrawals: CODWR 2014d.)**

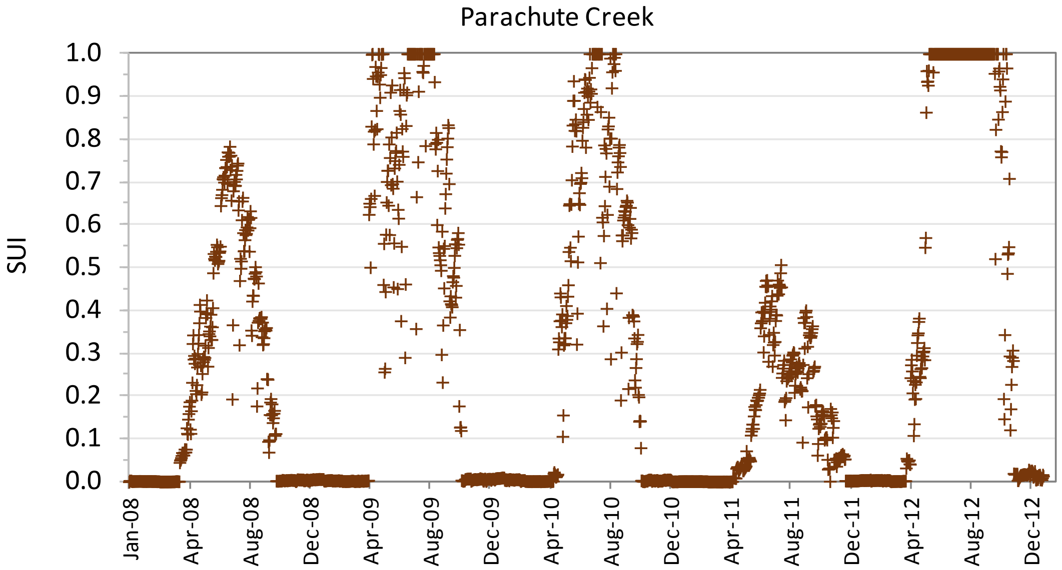


**Figure 5-21. Surface water use intensity index, SUI for combined withdrawals at 29 primary ditch sites in Parachute Creek. Most water is used for irrigation. (Data source: CODWR 2014d.)**

### Water Use Intensity Analysis at Self-supplied Sites

During the spring snowmelt, streamflow peak ranged from 350 MGD (540 cfs) in the very wet year of 2011 to a low of 35 to 37 MGD (77 cfs) during the very dry year of 2012. Streamflow descended to just 0.7 MGD (1 cfs) by October (Fig. 5-20). Total basin withdrawals accounting for structure efficiencies peaked at about 6 MGD and exceeded streamflow at times. While there was abundant water during the winter and spring months, shortages develop during most summers, at times taking much of the streamflow as shown by the SUI for this period (Fig. 5-21). In 2012, withdrawals exceeded streamflow, and records show that water supplies were imported into the subbasin from Ruedi Reservoir via the Colorado River.

SUI values computed from daily records at each surface water withdrawal structure are shown in Fig. 5-22. Three structures supply water to hydraulic fracturing, including two sites at the left of the figure (orange shaded boxes) and one in the upper valley at about 20 mi$^2$ (small range bar between sites at 14 and 34 in Fig. 5-22).These three hydraulic fracturing withdrawal sites are small reservoirs located in the Parachute Creek valley upstream of irrigators (Fig. 5-18B and C). SUI at irrigation withdrawal sites ranged from about 0.01 to 1.0, with a median of 0.05. SUI did not decrease with basin area (as observed in the Susquehanna River Basin), because withdrawal tends to be greater in the lower portions of the watershed and withdrawals increase faster than streamflow accumulates downstream. Median SUI in the reservoirs in the upper part of the basin used for hydraulic fracturing water supply ranged from 0.01 to 0.25, calculated as withdrawal relative to inflow to the reservoir and not accounting for the storage that mitigates effects. Counts by SUI category on all withdrawal days for all structures combined from 2008 to 2013 are provided in Table 5-4: 55% were less than 0.1 while 16% of sites exceeded 0.4 and 3.1% were near 1.

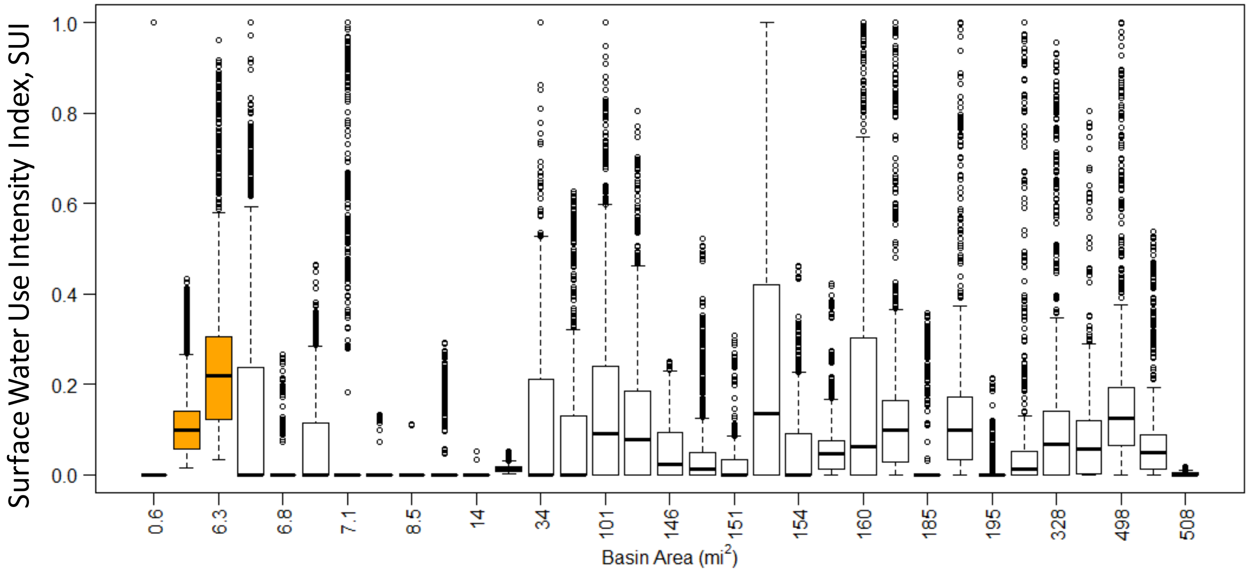


**Figure 5-22. Estimated surface water use intensity index (SUI) calculations at individual withdrawal sites (structures) in Parachute Creek. Sites represented by colored boxes (two on left and one at about 20 mi$^2$ that falls between 14 and 34 mi$^2$) provided water for hydraulic fracturing activities. The remaining sites were used for irrigation. (Data source: CODWR 2014d.)**

**Table 5-4. Count of daily surface water use intensity index at active Parachute Creek withdrawal structures from 2008 to 2013 (n = 16,012). Most withdrawals are for irrigation.**

| Surface Water Use Intensity Index (SUI) | N | % Observations |
|---|---|---|
| 0-0-0.10 | 8,825 | 55.1% |
| 0.11-0.20 | 3,381 | 21.1% |
| 0.21-0.30 | 1,263 | 7.9% |
| 0.31-0.40 | 639 | 4.0% |
| 0.41-0.50 | 536 | 3.3% |
| 0.50-0.6 | 300 | 1.9% |
| 0.61-0.70 | 263 | 1.6% |
| 0.71-0.80 | 155 | 1.0% |
| 0.81-0.90 | 161 | 1.0% |
| 0.91-1.0 | 489 | 3.1% |

**Groundwater Well Analysis.** About 40% of the freshwater obtained in Parachute Creek is taken from a groundwater wellfield located at the confluence of the west, middle, and east forks of Parachute Creek (Fig. 5-18C). Well Number 1 (structure 395298) was active for 2007–2010, and Well Number 1A (structure 395301) was pumped from 2011–2012. The driller's logs report that the pumps were rated at 236 gallons per minute (124 MG per year), and the wells were drilled to a depth of 57 feet. The structure permit capacity (decreed) is 80 MG per year (246 ac-ft).

The pumping wellfield receives its water from the outwash aquifer and the nearby creeks. The state of Colorado considers this a tributary wellfield of Parachute Creek and ultimately of the Colorado River, and thus under prior appropriation (Grantham 2011). The groundwater use intensity index (GUI) based on pumping capacity for this well varied from 0.5 to 0.7 in most years (Fig. 5-23). The groundwater modeling (GFLOW) and mapping (Surfer™) technology were used to calculate and map the cone of depression and the streamflow capture about the pumping center (Fig. 5-24), as performed in the SRB. The building of the GFLOW model for the Parachute Creek confluence is described in detail in Appendix C. The GFLOW model was parameterized to represent water balance using an estimation of baseflow and regional recharge. GFLOW evaluated the transmissivity of alluvium and rock needed to support the maximum rated pumping at the O&G private wellfield.

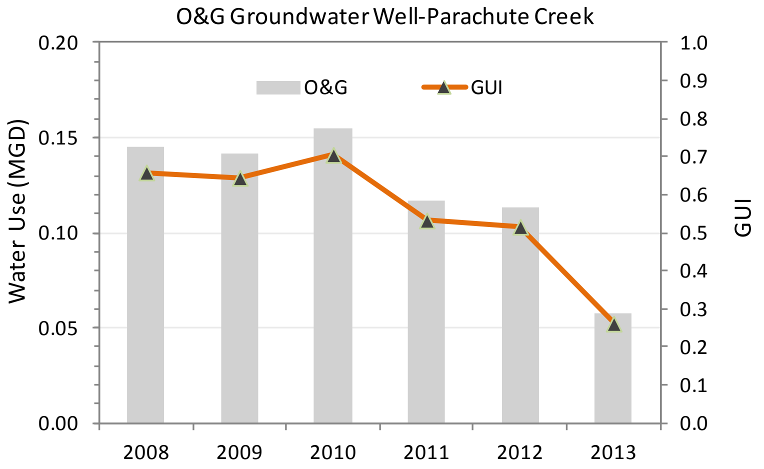


**Figure 5-23. Annual water pumping and groundwater use intensity index (GUI) at the groundwater wellfield, including wells 1 (structure 39-5298) and 1a (structure 39-5301). Structure capacity (water allocation) is 124 million gallons per year (380 ac-ft). (Data sources: CODWR 2014b, 2014d.)**

The zone of capture is illustrated using GFLOW and mapping of streamlines, as shown in Fig. 5-24B and D. Under average observed pumping, the wellfield captures about 6% of available baseflow, for a SUI of 0.06. The wellfield captures about 9.4% of available baseflow under maximum rated pumping, for a SUI of 0.09. The drawdown for the maximum pumping scenario was about 13 feet to the base of the aquifer. There were no domestic groundwater wells in the area of potential impact of the O&G well.

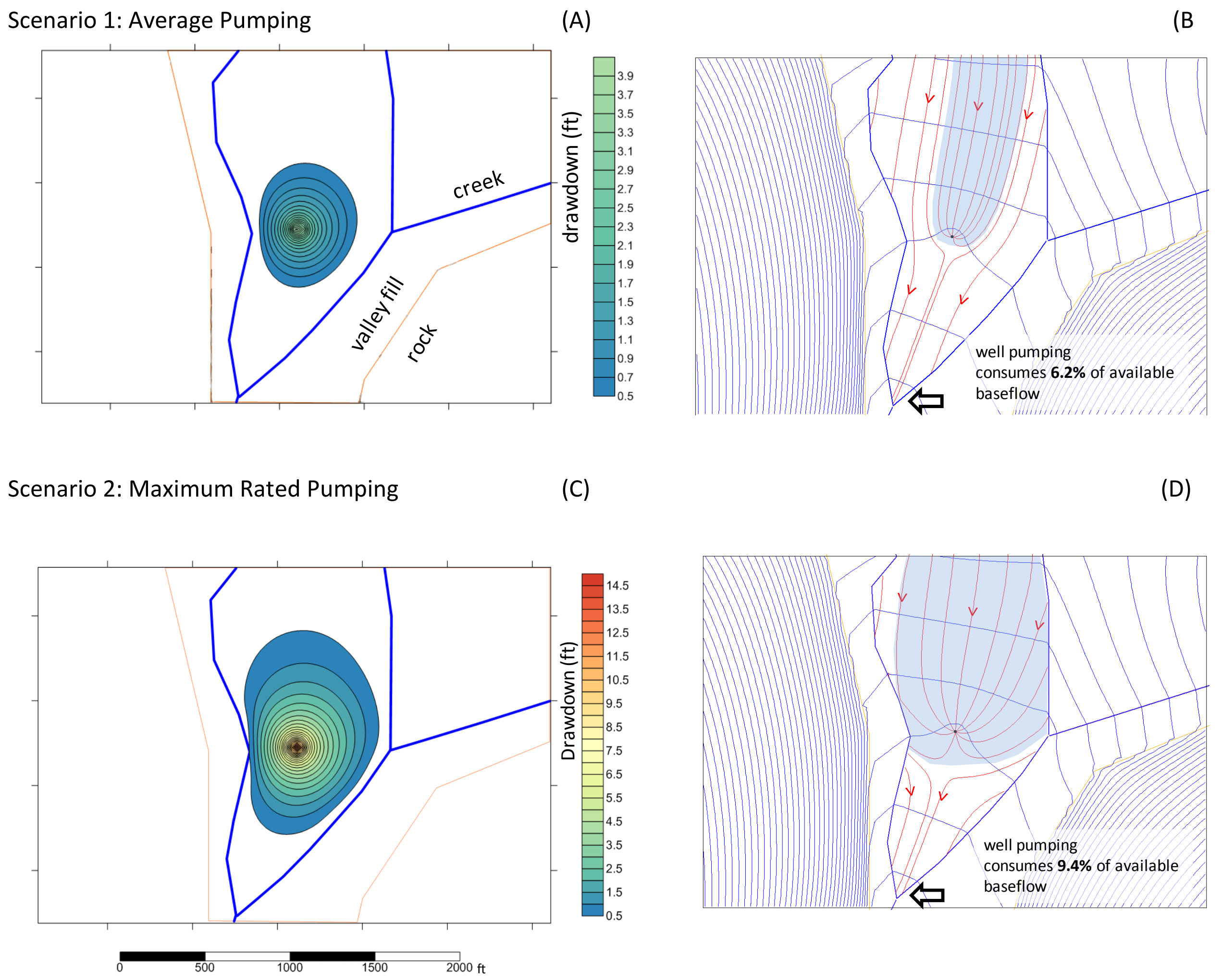


**Figure 5-24. Parachute Creek confluence self-supplied groundwater wellfield for oil and gas, showing area of potential impact and surface water zone of capture for two scenarios based on GFLOW simulations assuming averaged geohydrologic conditions (2007–2012). Scenario 1 was based on the average annual observed pumping rate; A) shows the cone of depression (drawdown in feet) associated with a groundwater stress index of 0.34, and B) shows the associated baseflow capture of 6.2% from the nearby creeks and surface water use intensity index of 0.06. Scenario 2 is based on maximum rated pumping; C) shows the drawdown to the base of the aquifer and a groundwater use intensity index of 1.0, and D) shows the baseflow capture of 9.4% of available and a surface water use intensity index of 0.09. (Water use data source: CODWR 2014d.)**

### Vulnerability of Streams to Depletions

Water from Parachute Creek is heavily used for 6 to 7 months of the year for irrigation. The O&G industry currently uses a small amount of water throughout the year to support hydraulic fracturing drilling. Hydraulic fracturing drilling peaked in 2008 at a relatively high rate of drilling compared to current activity. Therefore, we assume that peak well drilling rates are represented in the observed records and base scenario water requirements on 2008. Not well represented in observations to date are withdrawals from very small streams, withdrawals from flows not influenced heavily by irrigation, and volumes needed for horizontal wells that require more freshwater. Scenarios were applied to address these considerations.

The same techniques for defining subbasins and applying scenarios used in the SRB were used in Parachute (198 mi$^2$) and Roan Creeks (509 mi$^2$), but with different hydraulic fracturing use assumptions. Although most withdrawals currently occur in Parachute Creek, Roan Creek was included to increase the sample size for small streams and because it could be used for O&G water needs in the future. The watersheds were divided into a number of smaller subbasins by stream ordering marked by a stream prediction point. There were 47 subbasins, ranging in area from 4.4 to 509 mi$^2$. Streamflow was estimated from the simulated daily flow record at Parachute Creek based on watershed area. The scenario withdrawals were performed daily at each site. Acknowledging the highly managed nature of water withdrawals via water rights during the irrigation period (mid-April through October), and the abundant information already provided on large volumes of water use during this period, SUI were only computed from November through mid-April (the "free river" period). The streamflow determined for Roan and Parachute Creeks from 1986 to 2012 as described earlier was used for this analysis.

Hydraulic fracturing water use scenarios represented current and maximum observed drilling rate, and either all directional or all horizontal wells. They assumed that freshwater was used only for drilling, and that all hydraulic fracturing fluid was reused hydraulic fracturing wastewater. These scenarios enveloped the likely hydraulic fracturing water use in this subbasin, assuming that enough hydraulic fracturing wastewater was available to supply 100% of hydraulic fracturing injection fluid as currently occurs. To obtain daily water demand from Parachute Creek, we applied the following assumptions:

- The current rate of drilling is 600 hydraulic fracturing wells per year in Garfield County (average from 2011 to 2013). At the peak rate of drilling in 2008, 1,700 wells were drilled.
- Parachute Creek has typically provided about 50% of the hydraulic fracturing freshwater needs in Garfield County, and therefore would continue to supply 50% of the water for the number of wells for the current and peak scenarios.
- The groundwater wellfield routinely supplies 41 MG of water per year, which was subtracted from the total required of Parachute Creek before computing the required amount from surface waters.
- Directional and horizontal wells require 0.25 MG and 1.05 MG respectively. The groundwater wellfield could therefore supply 164 directional or 40 horizontal wells. The remainder is supplied from each of the streamflow prediction locations.

The daily water demand for the four scenarios is listed in Table 5-5.

**Table 5-5. Water withdrawal volume for hydraulic fracturing withdrawal scenarios applied to 26 years of streamflow (1987–2012) in subbasins of Parachute and Roan Creeks in Garfield County. Background use was obtained from the USGS water use census (Ivahnenko and Flynn 2010).**

| Scenario ID | Parachute and Roan Creek Withdrawal Scenarios for Surface Water Use Intensity Index Analysis | | | |
|---|---|---|---|---|
| | Water Demands | Hydraulic Fracturing Demand Assumptions | MGD | cfs |
| Current drilling—directional | 34.0 MG per year (104 ac-ft) | 136 directional wells per year<br>0.25 MG (0.77 ac-ft) per well | 0.10 | 0.14 |
| Current drilling—horizontal | 273 MG per year (838 ac-ft) | 261 horizontal wells per year<br>1.05 MG (3.22 ac-ft) per well | 0.75 | 1.16 |
| Peak drilling—directional | 172 MG per year (528 ac-ft) | 686 directional wells per year<br>0.25 MG (0.77 ac-ft) per well | 0.47 | 0.73 |
| Peak drilling—horizontal | 850 MG per year (2,609 ac-ft) | 811 horizontal wells per year<br>1.05 MG (3.22 ac-ft) per well | 2.33 | 3.01 |
| Background | Unmeasured background water use by other users | Domestic residential, livestock, assuming rates based on county-scale water use assessment | 0.38 | 0.54 |

Daily withdrawals ranged from 0.01 to 2.3 MGD, well within the range currently allowed at the 29 main structures. As in the SRB, background consumption was added to account for domestic and livestock use based on USGS water use census data for Garfield County (Ivahnenko and Flynn 2010). See Appendix D for additional information on scenario assumptions.

The SUI distribution of withdrawal locations for the current-drilling directional wells scenario is shown in Fig. 5-25. Water demand in this scenario was most similar to current use. The scenarios withdrew more from small streams than probably actually occurs, and withdrew less from the primary structures discussed previously than actually occurs. SUI declined in the scenario analysis with increasing basin area and streamflow. Median SUI was less than 0.1 and the 95th percentile was less than 0.6 in subbasins of approximately 20 mi$^2$ for the current drilling directional scenario. All subbasins less than 6 mi$^2$ routinely had simulated SUI greater than 0.5. Simulated SUI in subbasins larger than 100 mi$^2$ were similar to observed data.

The small to moderate-sized streams in the UCRB are vulnerable to withdrawals of relatively moderate volume. The median (50th percentile) and 95th percentiles of the SUI for all four scenarios are shown in Fig. 5-26. The approximate basin area where SUI declined below 0.4, as one example reference point, is provided in Table 5-6 for each of the scenario withdrawals. The basin area threshold where median SUI was less than 0.4 increased from 6 mi$^2$ to 150 mi$^2$ with increasing withdrawal rates. The 95th percentile figures indicate that higher SUI can occur with moderate withdrawals up to several hundred square miles.

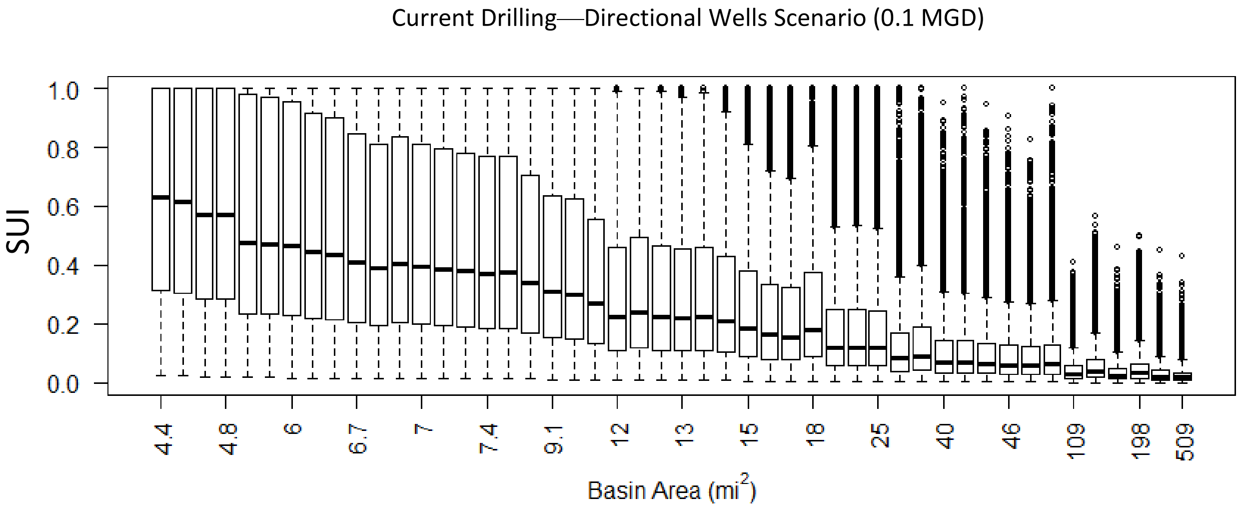
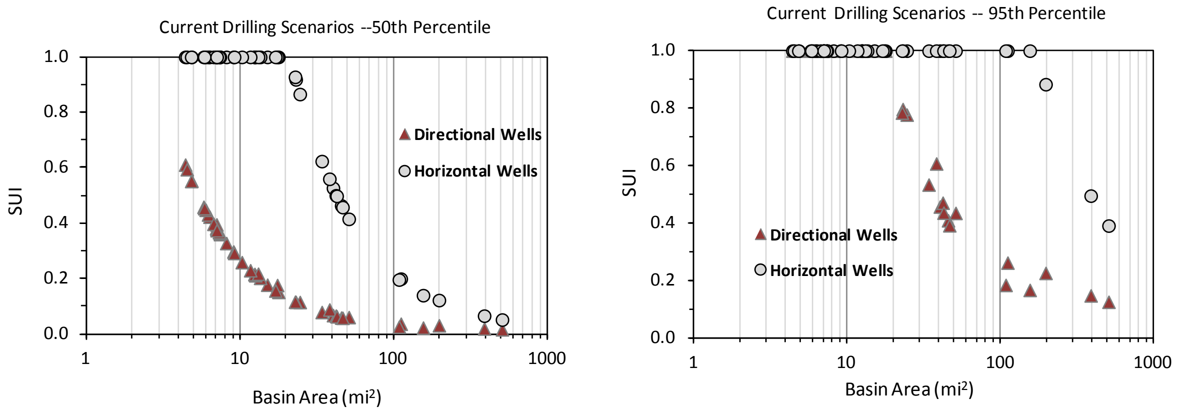


**Figure 5-25. Distribution of surface water use intensity index (SUI) at streamflow prediction locations in Parachute and Roan Creek for the current drilling-directional wells scenario, modeled from 2008 to 2013. Hydraulic fracturing withdrawal was 0.1 MGD. This scenario best represents current water volume used in Parachute Creek. Boxes envelop the 25th and 75th percentiles of the distribution, dotted lines extend to the 5th and 95th percentiles, and dots are the remainder of the observations (n = 4,325).**

A) Directional withdrawal = 0.10 MGD
Horizontal withdrawal = 0.75 MGD

B) Directional withdrawal = 0.10 MGD
Horizontal withdrawal = 0.75 MGD



C) Directional withdrawal = 0.47 MGD
Horizontal withdrawal = 2.33 MGD

D) Directional withdrawal = 0.47 MGD
Horizontal withdrawal = 2.33 MGD

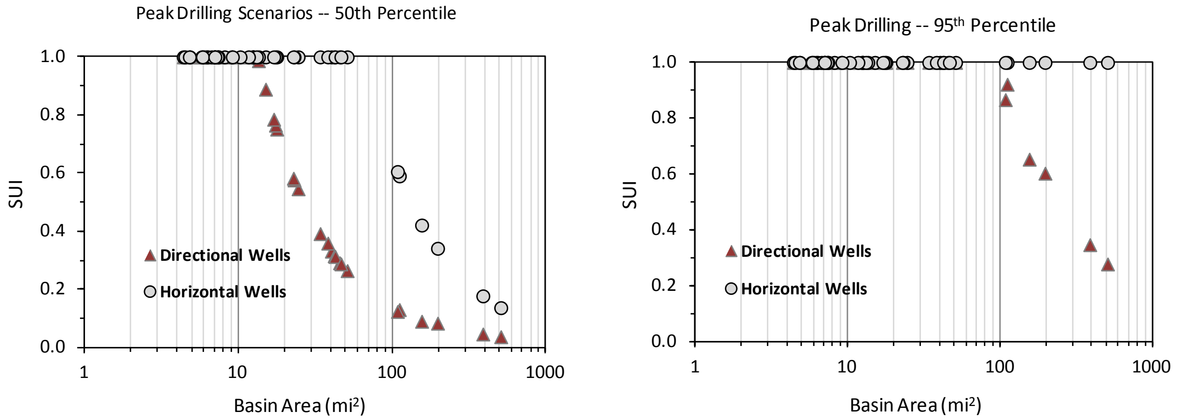


**Figure 5-26. Surface water use intensity indices (SUI) for drilling scenarios using current and peak drilling rates. Scenario SUI analysis covered subbasins in Parachute and Roan Creeks ranging from 4.4 to 509 mi$^2$; both directional and horizontal wells were investigated in each scenario. See Table 5-5 for withdrawal rates and assumptions. Computations were for November through April (n = 4,325). A) 50th percentile of SUI observations for current drilling scenarios. B) 95th percentile of SUI observations for current drilling scenarios. C) 50th percentile of SUI observations for peak drilling scenarios. D) 95th percentile of SUI observations for peak drilling scenario.**

**Table 5-6. Approximate basin area threshold for median and 95th percentiles of the surface water use intensity index (SUI) below 0.4 from 2008 to 2013, including wet and dry years at each streamflow prediction point. The full range of SUI for each scenario is shown in Fig. 5-26.**

| Scenario | Hydraulic Fracturing Withdraw Rate (MGD) | Basin Area ($mi^2$) | |
|---|---|---|---|
| | | Median SUI <0.4 | 95th percentile SUI <0.4 |
| Current—directional wells | 0.10 | 7 | 50 |
| Current—horizontal wells | 0.75 | 50 | 500 |
| Peak drilling—directional wells | 1.97 | 35 | 150 |
| Peak drilling—horizontal wells | 2.33 | 150 | >1,000 |

## UCRB Synopsis

The UCRB is located in a semi-arid climate and water shortages can occur at various spatial scales. Most of the water within the basin where hydraulic fracturing is ongoing is used for irrigation. Regional infrastructure is able to supplement water needs for users including municipal water suppliers, who hold reservoir contracts, but that capacity is diminishing as population grows and reservoir water is increasingly committed (CWCB 2011, 2007, 2014).

The region is rich in a variety of hydrocarbon reserves, and several of these can require larger quantities of water to extract. Water supplies accessed to meet energy extraction demands are concentrated in Garfield County. Existing water use by various user sectors in Garfield County and existing water use (Ivahnenko and Flynn 2010) and potential water demand from energy extraction in the UCRB (AMEC 2011) are summarized in Fig. 5-27. Freshwater use for hydraulic fracturing is small, because the industry is able to reuse hydraulic fracturing wastewater for nearly all needs. Most of the freshwater used for hydraulic fracturing is taken from the Upper Colorado River and from surface water and groundwater in Parachute Creek, a 198 $mi^2$ tributary to the Upper Colorado River that is centrally located at the Parachute gas field. The O&G industry assembled an extensive water supply system in the 1970s, anticipating the need for large water volumes to support oil shale resource extraction. Gas extraction currently taps a small portion of those allocations. Hydraulic fracturing operators have flexibility to purchase water from conservancy districts or other water rights holders with access to Colorado River water. We did not find any records that indicated that municipalities supplied water for hydraulic fracturing from their primary drinking water sources or other municipal supplies.

The volume of freshwater used for hydraulic fracturing is small (427 MG per year) despite high drilling rates during the past decade (Fig. 5-27). By accounting for how water is generally used in this basin for hydraulic fracturing, this study was able to indirectly confirm what is commonly reported that the water used for injection into wells is 100% reused wastewater from prior operations. Freshwater is only used for drilling and associated activities. The large quantities of water returned as flowback and produced water that are treated by the industry for reuse minimize the need for freshwater and impact on water supplies.

To date, most wells have been directionally drilled (s-shaped) into the tight sand formations. O&G companies have started to drill into the Mancos Shale underlying the Williams Fork formation and to shift to horizontal drilling, which will increase annual water use accordingly. Drilling into the Mancos Shale will increase water use per well by about 4 times (up to 1,600 MG per year) (URS 2008, WPX Energy, onsite interview, Jan 8, 2014). However, even with this increase, total hydraulic fracturing water use in Garfield County will remain relatively small at 1,800 MG year and relative to other uses, and is not likely to impact drinking water supplies.

Due to the high rate of hydraulic fracturing wastewater reuse by the O&G industry, we did not find any locations in the Piceance play where unconventional gas development contributed to locally high water use intensity at current levels of freshwater use. We also found no evidence that the O&G industry acquires water from municipal or domestic supplies. We are not aware of any reports of impact on drinking water availability in groundwater aquifers due to groundwater acquisition for hydraulic fracturing tight gas in the UCRB.

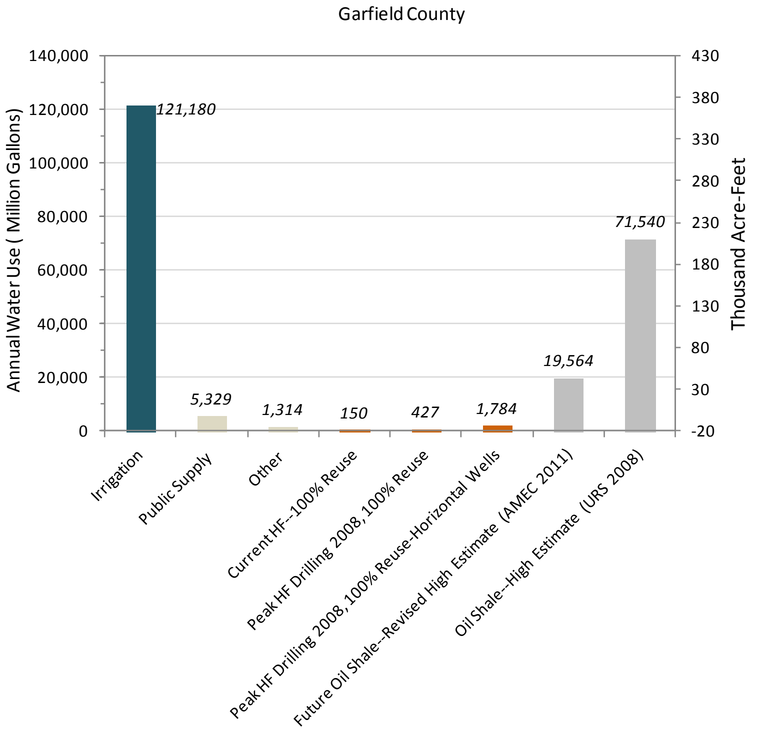


**Figure 5-27. Overview of current water use in Garfield County and existing or potential use to support oil and gas development with hydraulic fracturing and oil shale extraction. Water use by irrigators, municipalities, and other non-energy sectors was obtained from U.S. Geological Survey water census data for Garfield County (Ivahnenko and Flynn 2010). Hydraulic fracturing water use was determined in this study. Horizontal wells were assumed to require about 4 times more water than vertical wells (URS 2008) and the projection assumed all wells drilled in the county would be horizontal. Projections of potential future water use for oil shale development were taken from URS (2008) and AMEC (2011). Values shown for oil shale are 50% of total Piceance estimates, applying volumes equally to Garfield and Rio Blanco Counties.**

Greater water demand for energy extraction could occur should the far more water-intensive oil shale extraction ramp up in coming decades in the Colorado River and White/Yampa River basins (CWCB 2014). The O&G industry may likely exercise its water rights to a greater extent to meet the high water demands of petroleum extraction from oil shales (URS 2008; AMEC 2011). Although pilot oil shale projects have been undertaken in the area, current technology for obtaining oil from kerogen is costly, and extraction is not currently pursued commercially (U.S. EIA 2014d).

Two projected oil shale high-use water demand scenarios provided by URS (2008) and AMEC (2011) are shown in Fig. 5-27, varying with assumptions of the scale of operations and energy extraction technology eventually deployed. Values shown represent 50% of the total water estimate, assigning 50% to Garfield County and 50% to Rio Blanco County. Depending on projections, oil shale development could increase water use for energy extraction in Garfield and Rio Blanco Counties.

The Upper Colorado River—in terms of the population it serves throughout the Colorado River Basin and east of the Rocky Mountains—is one the fastest-growing regions in the nation (GAO 2003). Gaps between water supply and demand are expected in the UCRB and elsewhere throughout the southwestern states by 2050 with population growth and potential climate change (Bureau of Reclamation 2012; CWCB 2014; CWCB 2011; CWCB 2007; GAO 2003). Existing trends in warming were confirmed by Lukas *et al.* (2014). Fig. 5-28 shows Bureau of Reclamation (2012) estimates of past and projected use relative to water supply in the entire Colorado River Basin through 2050. Water use and supply have already come to the crossroads of supply and demand, and the gap will likely widen in the future (Bureau of Reclamation 2012). Water use in this region has been and will continue to be an important topic for public resource planning at the local, state, and federal level CWCB (2014).

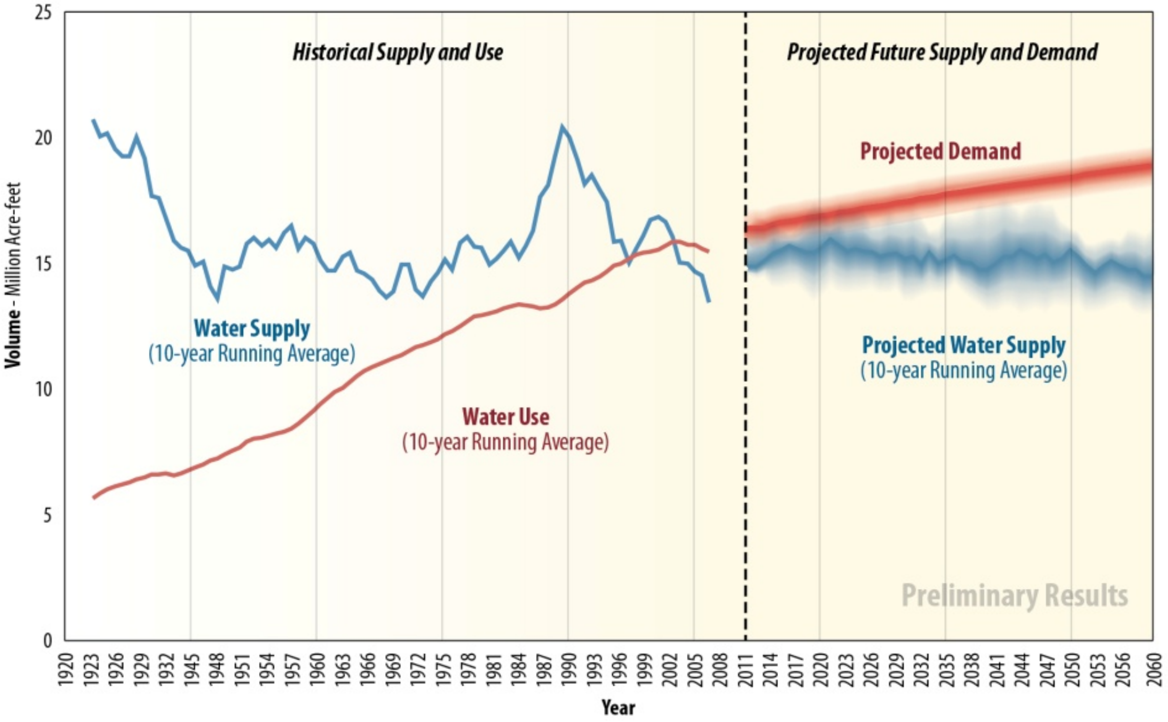


**Figure 5-28. Projected water supply and use in the Colorado River Basin with growing population in the next decades. (From Bureau of Reclamation 2012.)**

# 6. SYNTHESIS AND SUMMARY

Whether hydraulic fracturing water demand affects water resources and other users depends on how much freshwater is used and where water is acquired, especially in areas with water shortages due to population, climate, or drought. Hydraulic fracturing has different water use requirements than most other industries—it needs large quantities of water episodically and for short duration in many different places spread over wide areas. The volumes of water needed for hydraulic fracturing and the fast-paced expansion of hydraulic fracturing development in many areas of the country have raised concerns about the potential impact on local water supplies and users.

Hydraulic fracturing energy development in the United States operates within a variable overlay of water resources, climate, population centers, energy networks, ancient geologic formations, and water management, creating a mosaic of natural and operational situations that define water use and supplies. The options for acquiring water depend on volume and water quality requirements for a given hydraulic fracturing play, water availability, competing uses, and permitting constraints. These large-scale factors influence how much water is needed, who has access to it, and how it is shared. Not all water sourcing options are available to the oil and gas industry in all situations (API 2010).

At the state scale, assessments of hydraulic fracturing water use lack the granularity necessary to predict local effects on water resources, drinking water supplies, or other users. This project studied how the O&G industry acquires water for hydraulic fracturing in two large river basins that reflect the wide variability in contributing factors that exist nationally. The two study areas included the Susquehanna River Basin (SRB), located in the eastern United States (humid climate) and overlying the Marcellus Shale gas reservoir; and the Upper Colorado River Basin in Colorado (UCRB), located in the western United States (semi-arid climate) and overlying the Piceance structural basin with a total petroleum system that includes coal bed methane, shale and tight gas reservoirs, and oil shale.

The study areas were similar in some ways. Each has large hydrocarbon reserves, an active hydraulic fracturing industry, and productive natural gas wells with an anticipated long-term future of energy extraction. National assessments of the potential impacts of water use for hydraulic fracturing identified counties within each basin as areas of concern, based largely on their rate of drilling activity (Freyman 2014). In each basin, hydraulic fracturing activities are concentrated in largely rural areas, but within large river basins that generate water to support large populations that are remote from drilling and water use. There are also many differences between the watersheds in the factors that were ultimately important to whether hydraulic fracturing impacted availability of water resources. These included: (1) the dominant water users, 2) inherent availability of water; (3) water allocation and management oversight; and (4) geologic characteristics that influenced the gas development technologies and the amount of water needed for hydraulic fracturing.

The project gathered detailed information on where and how water is acquired in each study basin by querying publicly available databases from state, regional government, and federal data sources. The two basins each had state/regional agency databases that track water use, and our research could not have examined water acquired for hydraulic fracturing at the local scale without them. The Susquehanna River Basin Commission (SRBC) and Pennsylvania Department of Environmental Protection (PADEP) data systems specifically tracked water used for hydraulic fracturing in both public water supplier and self-supplied permitting systems. The complexity of the water allocation system in Colorado was reflected in their water use data system; freshwater used for hydraulic fracturing was more difficult to identify because O&G use is not separated from other industries, although considerable useful information was available that allowed the picture of water use for hydraulic fracturing to emerge. The most useful data included daily withdrawal volumes from individual water sources along with any allocation limits. We did not find the additional complexity of tracing water from source to specific gas well to be necessary for this project. We were able to examine water use at every local site where water was acquired in each area with these data.

This chapter summarizes and synthesizes the results described in earlier chapters dedicated to each river basin. It is organized to address the project framing questions on the potential impacts to drinking water resources of water acquisition to support hydraulic fracturing.

## How much freshwater is used in hydraulic fracturing operations?

The volume of hydraulic fracturing fluid that must be acquired each year depends on the drilling rate in the basin and the volume needed to drill and fracture each well. How much freshwater must be acquired depends on how much hydraulic fracturing wastewater is available and has been prepared for reuse. The characteristics of the rock formations targeted for resource extraction determine the volumes of flowback and produced water returned to surface from the formations, and whether it is economical to treat and reuse. Characteristics of well drilling and water use in the peak drilling year in each basin are summarized in Table 6-1. The two study areas varied significantly in geologic formation characteristics and total freshwater use.

In the SRB, O&G wells are horizontally drilled into the Marcellus Shale at a depth of about 7,000 ft. The drilling and development of each well requires 4.3 MG of fluid on average, most of which is freshwater. The Marcellus Shale returns a low percentage of hydraulic fracturing fluid of relatively poor quality as flowback, constraining the industry to substitute reused water up to 13% of the total water needed for hydraulic fracturing. This reuse rate is similar to those reported from other shale formations (Vengosh *et al*. 2014). About 3,350 million gallons of freshwater were needed in the SRB during the peak drilling year of 2012 (Fig. 6-1). Drilling rates in the Marcellus are expected to increase in the next decades, depending on economics, and could reach as high as 2,000 wells per year (Johnson 2010) raising potential water needs to 11,000 MG per year (Beauduy 2009).

In the Upper Colorado River Basin (UCRB), wells are primarily directionally drilled (S-shaped) into the Mesaverde sandstones in the Piceance basin to an average depth of about 8,000 ft. The average well uses 2.5 million gallons of fluid. The Williams Fork tight sand formation—the current target of exploration—returns most of the hydraulic fracturing fluid of relatively good quality. In addition, gas wells continue to bring formation water to the surface during their producing life. The industry captures, treats, and reuses the hydraulic fracturing wastewater, reducing the need for freshwater to 10% of total water per well and within the region as a whole.

**Table 6-1. Characteristics of well drilling and water use in the Susquehanna River Basin in (SRB, 2012) and Upper Colorado River Basin (UCRB, 2008) during the peak year of drilling in each area.**

| Factor | Parameter | Susquehanna River Basin (SRB) | Upper Colorado River Basin (UCRB) |
|---|---|---|---|
| **Geologic Characteristics** | Formation | Marcellus | Piceance Total Petroleum System |
| | Material | Shale | Tight Sands predominantly (Williams Fork formation) |
| | Drilling Type | Horizontal | Directional |
| | Depth Below Surface | ~7,000 ft | ~8,000 ft |
| | Maximum Drilling Rate (wells per year) | 836 (2012) | 1,688 (2008) |
| | Likely future drilling | ↑ | ↓ |
| | Flowback Returned | 7.3% | 100% + |
| **Water Use Characteristics** | Average Fluid Volume Injected per Well | 4.3 Million Gallons | 2.5 Million Gallons |
| | Total Annual Water Use | 3,594 MG | 4,220 MG |
| | Freshwater Portion of Hydraulic Fracturing Fluid | ~87% | ~0% |
| | Wastewater Portion of Hydraulic Fracturing Fluid | ~13% | ~100% |
| | Total Annual Freshwater Use | 3,350 MG | 430 MG (drilling only) |
| **State water management** | Allocation controls | Permitting | Appropriation |

In the UCRB, freshwater was needed only for well drilling and dust abatement at the site. The ability to recycle hydraulic fracturing fluids substantially reduced the hydraulic fracturing impact in this generally water-stressed area. Compared to 3,350 MG of freshwater used in SRB, 430 million gallons of freshwater were needed in the UCRB in the peak drilling year 2008 (Fig. 6-1). Drilling rates in UCRB may not return to this high of a level in future years. However, should the O&G industry increase emphasis on drilling horizontal wells into the Mancos Shale beneath the tight sands, the longer wellbores and perhaps different technology requirements could translate to increased freshwater use. It is difficult to project future use with these uncertainties, but freshwater needs could increase up to 2,000 MG per year, based on company estimates (WPX Energy interview Jan 8, 2014).

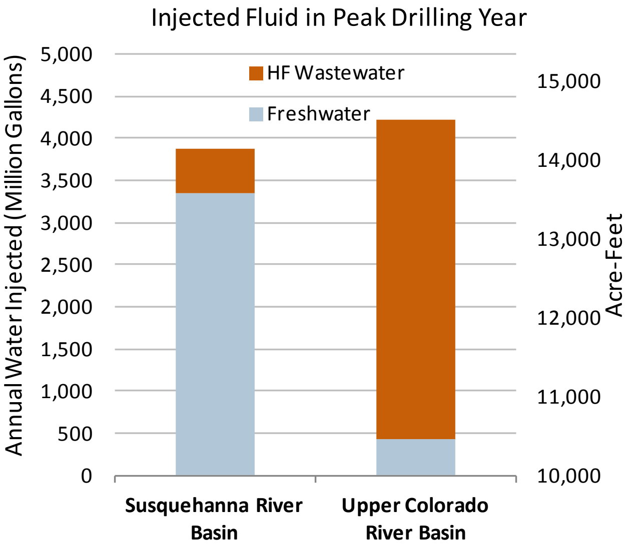


**Figure 6-1. Total fluid and freshwater use in the study basins in the peak year of drilling in each. Peak drilling occurred in 2012 in the Susquehanna River Basin (SRB) and 2008 in the Upper Colorado River Basin (UCRB).**

## What are the sources of water for hydraulic fracturing?

Securing a reliable water supply is of major operational importance to an oil and gas company when developing a play. Unlike many traditional water users that rely on stationary withdrawal points to serve stationary water uses, O&G activity involves multiple users crisscrossing an area withdrawing water from an increasing number of water sources, for use at increasing number of well drilling locations (Beauduy 2009). Oil and gas operators acquire water as close to the use point as possible, which could control trucking costs that are a significant portion of well development expense.

The O&G industry may purchase freshwater from either public water suppliers or other third parties, or operators may pump water directly (self-supply) from water sources. Throughout this report we use the term freshwater broadly to refer to any water used for hydraulic fracturing that is NOT hydraulic fracturing wastewater. It is typically not potable and may include untreated, brackish, saline, or contaminated water. We use the term "self-supplied" to refer to water obtained directly from a water body or aquifer by an oil and gas company or service provider, or obtained from a non-PWS third party provider. This latter group of water sources was the most difficult to quantify.

### *Public Water Supplies*

This study is particularly focused on the use of public drinking water supplies for hydraulic fracturing. Of the hundreds of public water suppliers in the SRB, 25 have sold water to the O&G industry for hydraulic fracturing at some time from 2008 to 2013. Municipal PWS provided 426 million gallons or about 20% of the water acquired for hydraulic fracturing in the peak year of 2011; that proportion declined to 7.5% by 2013. Most of the PWS water that is used for hydraulic fracturing in the SRB was obtained from groundwater sources. Nicot *et al.* (2014) observed a similar decreasing reliance on public water supplies over a decade of hydraulic fracturing development in the Barnett Shale in northern Texas as self-supplied infrastructure was developed. Municipal water suppliers in the SRB collectively provided 1.8 MGD for hydraulic fracturing in 2011, with a median of 0.62 MGD at individual facilities. Volumes taken at individual PWS facilities were not large enough to affect their ability to supply water to domestic or other customers.

None of the water used for hydraulic fracturing in the UCRB came from municipal supplies. We note that sales to O&G were not specifically tracked in water use records, but we are reasonably confident that the available water use records supplemented by discussions with district engineers from the Colorado Division of Water Resources (CODWR) support this conclusion.

### *Access to Freshwater for Self-Supply*

In both study areas, hydraulic fracturing operators as relatively “new” industrial water users have access to water on a site-by-site basis and are allowed to withdraw from water sources within constraints imposed by state and regional authorities. In the SRB, constraints are assigned in site permitting by the Susquehanna River Basin Commission (SRBC) (SRBC 2012) and by the water rights allocation system managed by the State Engineer and CODWR in the UCRB (Grantham 2011).

**Figure 6-2. Self-supplied water acquisition site on a river in the SRB.**

In the SRB, companies and operators gain access to water by requesting a permit at specific water sources from the SRBC. Most permitted sites draw water from rivers and streams. There were not many previous allocations to municipal or industrial users from surface water sources in the areas where hydraulic fracturing is most active. Groundwater resources are significant in the SRB, and they are the primary supply to many municipalities, other industrial users, and most of the private domestic users in much of the basin. Overall, SRBC permitting limits competition for available water among user sectors and largely separates domestic supplies from other self-supplied sites, including those used by the O&G industry.

**Figure 6-3. Trucking water to a hydraulic fracturing well site in Virginia (Photo from Virginia Dept. of Mines, Minerals and Energy.)**

In the SRB, the O&G industry can self-supply water at 140 permitted locations distributed throughout a 17 county area in Pennsylvania. One of these acquisition sites is shown in Fig. 6-2. Water is typically transported to gas wells via trucks (Fig. 6-3). Some permitted sites are used regularly while others are used infrequently or not at all.

SRBC has designed a system for hydraulic fracturing water acquisition by applying a number of specific measures that limit daily and seasonal withdrawals, including shutdown during low flows (Beauduy 2009). O&G operators could elect to use municipal water supplies during the shutdown periods.

In UCRB, the O&G industry acquires water within the Colorado water allocation system based on prior appropriations. Most available water is already allocated in the water rights system. During shortages, water is obtained in order of priority where the most senior (oldest) rights obtain water first. The O&G industry must obtain rights or purchase water from sources with existingappropriations.  Some water is available for purchase from state-sanctioned conservancy districts or the industry can buy water from rights holders as long as industrial use is assigned to their right.

Decades ago, individual O&G companies acquired many water right allocations in surface waters coincident with the Piceance structural basin anticipating oil shale development that requires large volumes of water to extract hydrocarbons with current known technologies (AMEC 2011; URS 2008). Many of these water sources serving the Parachute gas field (U.S. EIA. 2009) are spatially coincident with the oil shale deposits that are found in the same area. Ownership of water rights by the oil and gas industry in Colorado is currently unique to the Piceance structural basin. Acquisition of water for hydraulic fracturing in the UCRB is concentrated at a few of the O&G owned structures in Parachute Creek where the gas field is centered, including small private reservoirs and a groundwater well. The rest of the needed freshwater is obtained from the Colorado River through contracts.

Large regional high-yielding shallow groundwater aquifers are not available in either river basin. Shallow groundwater aquifers are ubiquitous in both study areas and many public and private water wells are strategically located in the highly permeable alluvial or valley-fill deposits of rivers and streams where the aquifers are in tight communication with rainfall recharge and surface water. Given the humid climate in the SRB, with over 40 inches per year of rainfall, the water replenishment rate tracks rainfall all year. Many of these river-adjacent aquifers are the source of municipal and domestic water supplies in the SRB.

Even though the O&G activity is concentrated in a semi-arid climate in the UCRB, the annual pulse of Colorado Rocky Mountain snowmelt supplies the Colorado River and its alluvium with significant annual recharge of freshwater. Due in part to poorer water quality, there are far fewer community drinking water wells in the Piceance overlapof the UCRB. In the UCRB, the wells are usually classified as tributary diversion structures and managed by the state appropriation laws, and the well pumping must be augmented through purchase and release of upstream reservoir storage water (Grantham 2011).

### *Volume of self-supplied freshwater used for hydraulic fracturing*

In the SRB, most freshwater is self-supplied from rivers and streams with basin areas ranging from 2 to 11,000 mi$^2$. A portion of the surface water comes from smaller rivers of sizes shown to be vulnerable to water use imbalance from over-withdrawal during low flow periods. The total annual volume that was self-supplied by hydraulic fracturing operators was 2,925 million gallons during the peak use year (2012), or 7.3 MGD and averaging 0.3 MGD at individual sites (Fig. 6-4). Site volumes are controlled by permit and vary significantly between sites. The largest daily withdrawals of 3.0 MGD are permitted in the Susquehanna River mainstem.

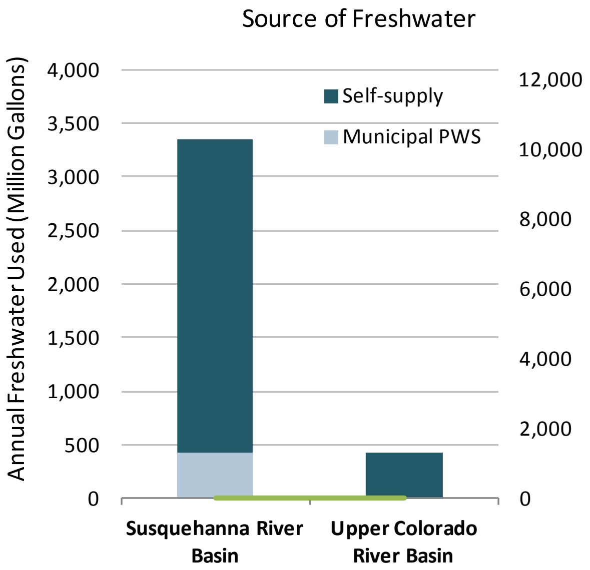


**Figure 6-4.Volume of water sourced from municipal public water suppliers and self-supplied by the oil and gas industry for hydraulic fracturing in the peak drilling year in each basin (Data sources: SRBC 2013a, CODWR 2014d).**

In the UCRB, 1.2 MGD of freshwater was obtained during the peak use year of 2008. Parachute Creek acquisition sites annually supply enough surface and low quality groundwater to supply about 50% of the freshwater used for hydraulic fracturing in Garfield County amounting to 430 million gallons (Fig. 6-5). Withdrawal of water from three small reservoirs and a tributary averaged 0.03 MGD. Hydraulic fracturing water use does not appear to interfere with downstream irrigation or municipal users, nor is it taken from drinking water supplies.

Shallow alluvial groundwater wells provided 20% to 25% of water used for hydraulic fracturing in both study areas. In the SRB, most of this water was self-supplied from a few commercial wells. Some water was taken from municipal supplies that relied on groundwater sources. Groundwater was also self-supplied in the UCRB from a single high-volume groundwater wellfield that produced 0.14 MGD. No direct impacts due to pumping drawdown at these groundwater wells were discovered in this study area.

## How might water withdrawals affect short- and long-term availability?

### *Intrinsic Vulnerability*

Regional or local water use imbalance from hydraulic fracturing water use may arise depending on the overall gas field development rate and individual well need, intrinsic water availability, and competition for water from other user sectors. Short-term and/or local water use imbalance depends on how much is withdrawn from a water source, how much is available at the source, and how fast water replenishes. Surface water flows and storage in human-engineered reservoirs are the dominant source of freshwater for hydraulic fracturing in the study areas, and these could be readily quantified.

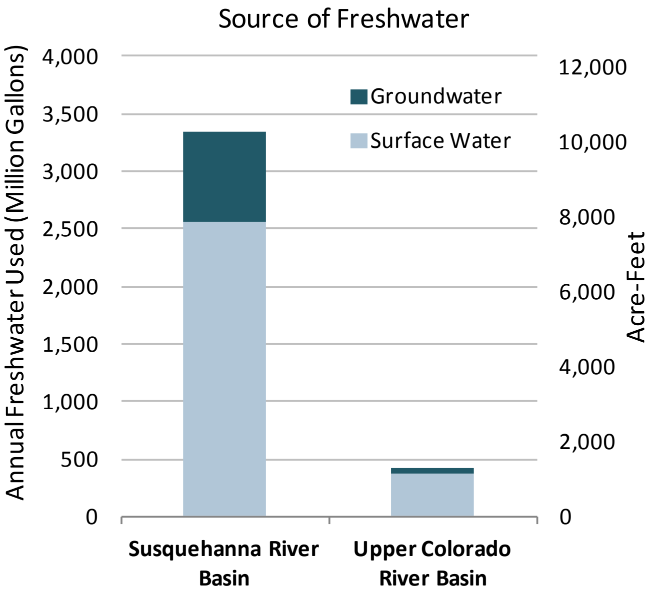


**Figure 6-5. Volume of water sourced from surface water and groundwater sources by the oil and gas industry for hydraulic fracturing in the peak drilling year in each basin (SRB 2012, UCRB 2008). (Data sources: SRBC 2013a, CODWR 2014d).**

With annual average precipitation over 40 inches distributed evenly through the year, the SRB has significant surface and groundwater resources. A relatively low population and rural economy where hydraulic fracturing is most active further minimizes competing demands. Shortages may develop during droughts, and low flow periods in the smaller streams, but intrinsic vulnerability to water shortages is generally relatively low. The population is not projected to increase substantially in this portion of the SRB (U.S. EPA 2013a).

The UCRB receives less than 20 inches of annual precipitation on average, and much of it occurs as snowfall on the western slope of the Colorado Rocky Mountains. The spring through summer snowmelt supplies streamflow in the Colorado River and tributaries. Some of the surplus streamflow is diverted into reservoirs for storage or transfer for use by communities and irrigators on both the west and the east sides of the Rocky Mountains. Surface water supplies are limited and in high demand in the UCRB. Under historic agricultural use, water shortages relative to demand evolve in many tributaries and the mainstem Colorado during the dry summer and early fall months. Regional infrastructure is able to supplement water needs with reservoir releases, but that capacity is diminishing as the population grows and reservoir water is increasingly committed (CWCB 2011). Water availability in the entire southwestern United States is dependent wholly or partially on water from the Upper Colorado River (Bureau of Reclamation 2012) and population growth is expected to significantly increase water demands at the same time that climate change is projected to decrease annual precipitation (CWCB 2011, 2014; GAO 2003, 2014). The region is thus intrinsically vulnerable to water shortages.

The volume of water needed for hydraulically fracturing at individual wells is large (2 to 4 million gallons) and the general rate of drilling can create a relatively high demand in an area. Nevertheless, the hydraulic fracturing demand will always be small compared to other users at the state and play spatial scales (e.g. Murray 2013, Nicot *et al*. 2014). Any imbalances that may arise between water supply and demand and competition among users are more likely to evolve at county or finer scales, especially at sources where water is actually acquired.

At the local level, whether withdrawals impose high use intensity on water resources depends on the withdrawal volume relative to the volume in the waterbody. This project quantified potential water imbalance using a simple water use intensity index (SUI and GUI) calculated as water volume withdrawn relative to available source volume on a daily basis. The index is a straightforward volumetric calculation that represents the proportion of water removed from the source in an immediate timeframe. The water use intensity index provided a quantitative scalar of potential imbalance and was used to represent vulnerability of local water sources to withdrawals for any use. No threshold values of concern were used in this study; others have used thresholds of 0.4 (Freyman 2014; Hurd *et al.* 1999) or 0.7 (Tidwell *et al.* 2012).

The study evaluated the effects of typical water withdrawal amounts for hydraulic fracturing on the water use intensity over a range of stream sizes and streamflow conditions in each basin, largely using hydrologic models and/or scenario modeling. A given withdrawal volume compared to a given flow volume produces a specific value of the use intensity index (SUI). Rivers and streams vary in the probability of observing low volume flow, dependent largely on contributing watershed area, and reflecting the climate in each location. At the same rate of withdrawal, a smaller stream is more likely to have a higher use intensity index than a larger river, as the former experiences smaller flow volumes during a greater part of the year.

Analysis in both study areas showed that smaller streams (watershed areas <10 mi$^2$) are vulnerable to typical hydraulic fracturing withdrawals 0.1 to 1.0 million gallons per day (higher SUI or proportion of water removed) most of the time. In general, three times more watershed area was needed to support typical hydraulic fracturing withdrawals in the semi-arid UCRB. However, the analysis also revealed that surprisingly large rivers in humid areas are vulnerable to typical hydraulic fracturing withdrawals during infrequent low flows that occur during infrequent regional droughts. Rivers draining watersheds up to 600 square miles were shown to be potentially vulnerable to hydraulic fracturing withdrawals (experience high SUI) in the SRB despite the abundance of water resources and humid climate.

### *Current and Potential Future Water Use Intensity*

The potential for cumulative impact associated with pumping groundwater sources for O&G water needs on drinking water supply is low in the SRB. However, there is the potential for localized effects on household or community drinking water wells in the drawdown of the hydraulic fracturing water-supplying wells. If the induced drawdown lowers the water table below the screen interval of a household or community well, the well could go dry. However, no effects were discovered at the few public and private groundwater sources that supply relatively larger volumes of water for hydraulic fracturing in the SRB. Groundwater wells located in alluvium and valley-fill can draw a part of their source water from nearby streams. In a limited investigation of SRB and UCRB study areas, this use was estimated to be less than 10% of the available annual baseflow. The SRBC manages streamflow depletion from groundwater pumping through the passby flow program.

At the local level, and reflecting the water management systems in place, water use for hydraulic fracturing is currently low relative to water availability at all but a few local sites in both basins. Despite the potential for higher water use intensity, we found no impacts of hydraulic fracturing water acquisition in either case study area, expressed in terms of the proportion of water withdrawn from the water body or PWS facility relative to the volume of freshwater available at each location. We identified no shortages or hardships imposed on other users or at public water suppliers by hydraulic fracturing in the two study areas. Many natural climatic and hydrologic differences between the Susquehanna River and Upper Colorado River basins influence water availability, but other factors related to water management influenced consumption patterns and contributed substantially to outcomes. Differences in water demands and water management factors in these two regions resulted in the same outcome of no adverse effect on water supply.

In the SRB, the industry trend is to widely distribute acquisition sites within the region and to locate them primarily in rivers and streams that are not extensively used by others. The rate and timing of withdrawals are managed by permit to protect other users and aquatic life. Although the rate of hydraulic fracturing activity is likely to increase in the future, there is currently enough capacity in the self-supplied permitting system to accommodate future hydraulic fracturing water needs from rivers and streams without the need for significant contributions from public water suppliers. Furthermore, O&G companies and hydraulic fracturing service companies in both areas are increasingly building piping infrastructure to move water, and have built numerous small impoundments distributed around the landscape to store water. There is currently sufficient storage in the SRB to supply freshwater for hydraulic fracturing for a year at current drilling rates, further reducing the need for public water supplies during low flow shutdowns that typically occur seven or more days each year.

Water use intensity is already high in the semi-arid Colorado River basin, primarily due to large irrigation withdrawals, but the contribution to this use intensity from hydraulic fracturing withdrawals is very low. The favorable geologic characteristics that return large volumes of reusable hydraulic fracturing fluids currently minimize the use of freshwater by the O&G industry. Freshwater usage for hydraulic fracturing will increase with development of the Mancos Shale below the tight sands with horizontal drilling, due in part to longer wellbores. These additional demands should be within historical scope and should not significantly impact water availability in the area given available water sources that do not conflict with other users. Extraction of energy from oil shales may require the O&G industry to use as much as 50 times more water than hydraulic fracturing demands (CWCB 2011; AMEC 2011; URS 2008). Thus, significantly greater water demand would emerge should the far more water-intensive oil shale extraction ramp up in future decades when the economics of resource extraction make extraction more feasible.

### What are the potential impacts of hydraulic fracturing water withdrawals on water quality of source waters?

A preliminary exploration was conducted on the potential impact of hydraulic fracturing withdrawals on water quality in streams. Water quality is determined by the concentration of chemical stressors within a volume of water. Hydraulic fracturing withdrawals reduce water volume and thus have the potential to increase chemical concentration if taken upstream of discharge points or a chemical spill site. In this case, the chemical concentration would be magnified in proportion to the water withdrawal volume. The SUI index used for this study could be mathematically reformulated to determine the concentration magnification of given withdrawal rates, and was applied to the observed withdrawal data in the SRB assuming all sites were affected by point source discharges. In the SRB, concentration magnification was mostly less than 10% but could range as high as 30%. Because SUI and concentration magnification are mathematically related, the same factors that influenced SUI influence the magnitude of water quality response.

- A combination of factors determine whether hydraulic fracturing introduces imbalance in the relationship between water supply and demand in a region, including drinking water resources. These factors include available water resources and their capacity to yield water, industry needs influenced by geologic characteristics of rocks in each play, other user demands, and permitting or allocation controls.

- No significant negative impacts to past or present drinking water supplies or other water users resulting from hydraulic fracturing water acquisition were found in either study basin due to unique combinations of these factors in each area.

- In the Susquehanna River Basin in Pennsylvania (SRB), there is little use of public water supplies (currently <8%) because water resources are well distributed and available year round and hydraulic fracturing operators have been able to develop unallocated sources. In SRB, there are times or locations when water sources can be stressed, but water is managed to prevent overuse and minimize risk at individual sources.

- Water in the Upper Colorado River Basin in Colorado (UCRB) is strongly seasonal and over-allocated, but unconventional gas production requires little freshwater as the industry is able to reuse large volumes of flowback and produced water instead. No municipal drinking water supplies are used for hydraulic fracturing in the areas studied within the UCRB.

### Study Conclusions

We studied the potential impact on drinking water resources of water acquisition for hydraulic fracturing by the unconventional oil and gas industry, with particular focus on the implications of hydraulic fracturing for natural gas in tight/shale formations. We focused our study on two large river basins where significant O&G activity has occurred and is predicted to continue in the future: (1) the Susquehanna River basin, which overlies the Marcellus shale; and (2) the Upper Colorado River basin of Colorado, which overlies the Piceance structural basin. No significant negative impacts to past or current drinking water supplies or other water users resulting from hydraulic fracturing water acquisition were found in either of the study basins. However, this underscores the importance of careful planning and management to protect water resources. This conclusion is based on data on both available water and water volumes obtained at local sources on fine temporal scales. A combination of geology, industry practices, state allocation and management, and other factors, in each study basin reduced the actualization of impact. The potential for future impact was explored by distributing hypothetical point withdrawals within representative sub-watersheds. Results showed that unmanaged withdrawals in small streams (watershed area <10 $mi^2$) have the potential for frequently large impact. Since multiple local factors must be understood to anticipate the effects of water acquisition on drinking water supplies, generalization to other plays and regions is not possible. The study only involved two large river basins. Other areas with active hydraulic fracturing will likely have a unique combination of the important driving factors that determine water balance that could result in adverse impacts that were not observed in the two study basins.

Several recent national scale studies have used downscaling techniques based on water census and hydraulic fracturing activity and other data to predict areas of potential water use imbalance or high use intensity at the county level throughout the United States (e.g. Freyman 2014). Where our study basins overlapped these national studies, data at the local scale did not identify any impacts on water availability for other users in several counties highlighted in the national assessments. This underscores a need for integrating the array of key factors that influence water use and water availability when assessing the likely effects of water acquisition for hydraulic fracturing on water resources and drinking water supplies in a local area.

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# REFERENCES

AMEC. 2011. Energy development water needs assessment Phase II. Prepared for the Colorado River Basin Roundtable and Yampa/White Basin Roundtable.

API (American Petroleum Institute). 2010. Water management associated with hydraulic fracturing. API Guidance Document HF2. Available at: http://www.api.org/policy-and-issues/policy-items/hf/api_hf2_water_management.aspx

Arguez, A., I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. R. Heim, and T. W. Owen. 2012. NOAA's 1981–2010 U.S. climate normals: An overview. Bulletin of the American Meteorological Society 93(11): 1687-1697.

Arthur, J. D., M. Uretsky, and P. Wilson. 2010. Water resources and use for hydraulic fracturing in the Marcellus Shale region. ALL Consulting. Available at: http://www.all-llc.com/publicdownloads/WaterResourcePaperALLConsulting.pdf

Aydemir, A. 2012. Comparison of Mississippian Barnett Shale, northern-central Texas, USA and Silurian Dadas formation in southeast Turkey. Journal of Petroleum Science and Engineering 80(1): 81-93.

Beauduy, T. W. 2009. Accommodating a new straw in the water: Extracting natural gas from the Marcellus Shale in the Susquehanna River Basin. Susquehanna River Basin Commission, Harrisburg, PA.

Bicknell, B. R., J. C. Imhoff, J. L. Kittle Jr., A. S. Donigian Jr., and R. C. Johanson. 1997. Hydrological simulation program—FORTRAN: User's manual for version 11. EPA/600/SR-97/080. U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, GA. 755 pp.

BLM (Bureau of Land Management). 2006. Roan Plateau planning area proposed resource management plan amendment and environmental impact statement. U.S. Department of the Interior, Bureau of Land Management, Glenwood Springs, CO.

Brantley, S. L., D. Yoxtheimer, S. Arjmand, P. Grieve, R. Vidic, J. Pollak, G. T. Llewellyn, J. Abad, and C. Simon. 2014. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. International Journal of Coal Geology 126: 140-156.

Bredehoeft, J. D. 2002. The water budget myth revisited: Why hydrogeologists model. Ground Water 40(4): 340-345.

Bureau of Reclamation. 2005. Water 2025: Preventing crises and conflict in the West. U.S. Department of the Interior, Washington, D.C.

Bureau of Reclamation. 2012. Colorado River Basin water supply and demand study. U.S. Department of the Interior, Bureau of Reclamation. Available at: http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Executive%20Summary/Executive_Summary_FINAL_Dec2012.pdf).

CGS (Colorado Geological Survey). 2003. Ground water atlas of Colorado. Available at: http://coloradogeologicalsurvey.org/water/groundwater-atlas/

Clark, C. E., A. J. Burnham, C. B. Harto, and R. M. Horner. 2012. The technology and policy of hydraulic fracturing and potential impacts of shale gas development. Environmental Practice 14: 251-261.

Clark, C. E., R. M. Horner, and C. B. Harto. 2013. Life cycle water consumption for shale gas and conventional natural gas. Environmental Science and Technology 47: 11829-11836.

CODWR (Colorado Division of Water Resources). 2012. Cumulative statistics. Available at: http://water.state.co.us/DWRDocs/Reports/Pages/CumStats.aspx

CODWR (Colorado Division of Water Resources). 2014a. Data search. Available at: http://water.state.co.us/DataMaps/DataSearch/Pages/DataSearch.aspx#adminrpts

CODWR (Colorado Division of Water Resources). 2014b. Water rights. Available at: http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx

CODWR (Colorado Division of Water Resources). 2014c. Structures (diversions). Available at: http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx

CODWR (Colorado Division of Water Resources). 2014d. Structures (diversions). Available at: http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx. Query: individual structures for diversion reports.

CODWR (Colorado Division of Water Resources). 2014e. Surface water (StateMod). Available at: http://cdss.state.co.us/Modeling/Pages/SurfaceWaterStateMod.aspx

CODWR (Colorado Division of Water Resources). 2014f. Colorado's well permit search. Available at: http://www.dwr.state.co.us/WellPermitSearch/default.aspx

COGCC (Colorado Oil and Gas Conservation Commission). 2012. COGCC hydraulic fracturing rules: Rule 205A Disclosure. Available at: http://cogcc.state.co.us/Announcements/Hot_Topics/Hydraulic_Fracturing/COGCC%20Hydraulic%20Fracturing%20Rules.htm

COGCC (Colorado Oil and Gas Conservation Commission). 2013. COGCC GIS online. Available at: http://cogcc.state.co.us/Home/gismain.cfm

COGCC (Colorado Oil and Gas Conservation Commission). 2014a. Annual well starts by county. Oil & Gas Staff Report (July 28, 2014): 21. Available at: http://cogcc.state.co.us. Query: Staff reports (Staff RPT).

COGCC (Colorado Oil and Gas Conservation Commission). 2014b. COGCC reports portal. Available at: http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyWaterProdByCounty,

Colorado Geological Survey. 2003. Ground water atlas of Colorado, Chapter 6.2 Piceance Basin. Special Publications 53. http://coloradogeologicalsurvey.org/water/groundwater-atlas/.

Cueto-Felgueroso, L., and R. Juanes. 2013. Forecasting long-term gas production from shale. Proceedings of the National Academy of Sciences 110(49): 19660-19661.

CWCB (Colorado Water Conservation Board). 2007. Colorado's water supply future. Statewide Water Supply Initiative-Phase 2. Available at: http://cwcb.state.co.us/public-information/publications/Documents/ReportsStudies/TechnicalRoundtableReportFinalDraft.pdf .

CWCB (Colorado Water Conservation Board). 2011. Colorado's Water Supply Future—Statewide Water Supply Initiative 2010. Available at: http://cwcb.state.co.us/water-management/water-supply-planning/pages/swsi2010.aspx

CWCB (Colorado Water Conservation Board), 2014. Colorado's Water Plan. Available at: https://www.colorado.gov/pacific/cowaterplan/framework-documents-and-draft-chapters.

Davis, C. 2012. The Politics of "Fracking": Regulating natural gas drilling practices in Colorado and Texas. Review of Policy Research 29 (2): 177-191.

Dennison, D. 2005. Drilling 101: Drilling of a natural gas well and natural gas production in the Piceance Basin. Garfield County Oil & Gas Liaison. Available at: http://www.garfield-county.com/oil-gas/documents/drilling_101.pdf

Dietrich, J. D., and R. C. Johnson. 2013. Simplified stratigraphic cross sections of the Eocene Green River formation in the Piceance Basin, Northwestern Colorado. U.S. Geological Survey Open-File Report 2013-1012. 23 pp.

Dott, R. H., Jr., and R. L. Batten. 1981. Evolution of the Earth. McGraw-Hill, New York. 579 pp.

Dripps, W. R., R. J. Hunt, and M. P. Anderson. 2006. Estimating recharge rates with analytic element models and parameter estimation. Ground Water 44(1): 47-55.

Dunlap, K. 2011. Shale gas production and water resources in the eastern United States. U.S. Senate Committee on Energy and Natural Resources Subcommittee on Water and Power.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Company, New York. 818 pp.

Eckhardt, K. 2008. A comparison of baseflow indices, which were calculated with seven different baseflow separation methods. Journal of Hydrology 352(1-2): 168-173.

Entrekin, S., M. Evans-White, B. Johnson, and E. Hagenbuch. 2011. Rapid expansion of natural gas development poses a threat to surface waters. Frontiers in Ecology and the Environment 9(9): 503-511.

Erenpreiss, M. S., L. H. Wickstrom, C. J. Perry, R. A. Riley, D. R. Martin, and others. 2011. Regional organic-thickness map of the Marcellus Shale with addition organic-rich shales beds in the Hamilton Group included for New York, Pennsylvania, and West Virginia. Ohio Department of Natural Resources, Division of Geological Survey.

FEMA (Federal Emergency Management Agency). 2014. Hydrologic models meeting the minimum requirement of National Flood Insurance Program: Current nationally accepted hydrologic models. Available at: http://www.fema.gov/national-flood-insurance-program-flood-hazard-mapping/hydrologic-models-meeting-minimum-requirement

FracFocus. 2014. Chemical disclosure registry. Available at: http://fracfocus.org/

FracTracker Alliance. 2014. Available at: http://www.fractracker.org/

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ. 604 pp.

Freyman, M.. 2014. Hydraulic fracturing & water stress: Water demand by the numbers—shareholder, lender, & operator guide to water sourcing. CERES. Available at: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers/

GAO (U.S. Government Accounting Office). 2003. Freshwater supply: States' view of how federal agencies could help them meet the challenges of expected shortages. GAO-03-514. Washington, DC.

GAO (U.S. Government Accountability Office). 2014. Freshwater: Supply concerns continue, and uncertainties complicate planning. GAO-14-430. Washington, DC.

Gilmore, K., R. Hupp, and J. Glathar. 2014. Transport of hydraulic fracturing water and wastes in the Susquehanna River Basin, Pennsylvania. Journal of Environmental Engineering 140(SPECIAL ISSUE: Environmental impacts of shale gas development).

Grantham, J. 2011. Synopsis of Colorado Water Law. Report for the Colorado Division of Water Resources. Available at: http://water.state.co.us/DWRIPub/DWR%20General%20Documents/SynopsisOfCOWaterLaw.pdf

Gregory, K. B., R. D. Vidic, and D. A. Dzombak. 2011. Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements 7: 181-186.

Grubb, R. G. 1986. Soil survey of Bradford and Sullivan Counties, Pennsylvania. U.S. Department of Agriculture, Soil Conservation Service. 135 pp.

GWPC (Groundwater Protection Council). 2009. State oil and natural gas regulations designed to protect water resources. U.S. Department of Energy, Office of Fossil Energy, Washington, DC.

Haitjema, H. M. 1995. Analytic element modeling of groundwater flow. Academic Press, Inc., San Diego, CA. 394 pp.

Hansen, E., D. Mulvaney, M. Betcher. 2013. Water resource reporting and water footprint from Marcellus Shale development in West Virginia and Pennsylvania. Earthworks Oil and Gas Accountability Project. 88 pp. Available at: http://www.downstreamstrategies.com/documents/reports_publication/marcellus_wv_pa.pdf

Heisig, P. M. 2012. Hydrogeology of the Susquehanna River valley-fill aquifer system and adjacent areas in eastern Broome and southeastern Chenango Counties, New York. U.S. Geological Survey Scientific Investigations Report 2012-5282. 19 pp.

Hettinger, R. D., and M. A. Kirschbaum. 2002. Stratigraphy of the Upper Cretaceous Mancos Shale (upper part) and Mesaverde Group in the southern part of the Uinta and Piceance basins, Utah and Colorado. U.S. Geological Survey Geological Investigations Series I-2764. 21 pp.

Hill, M. 2013. Source water protection of the Colorado River partnership: Source water protection plan Garfield County, Colorado. Colorado Rural Water Association. 87 pp.

Hunt, C. B. 1974. Natural regions of the United States and Canada. W. H. Freeman and Company, San Francisco, CA. 725 pp.

Hunt, R. J. 2006. Ground water modeling applications using the analytic element method. Ground Water 44(1): 5-15.

Hurd, B., N. Leary, R. Jones, and J. Smith. 1999. Relative regional vulnerability of water resources to climate change. Journal of the American Water Resources Association 35: 1399-1409.

Ivahnenko, T., and J. L. Flynn. 2010. Estimated withdrawals and use of water in Colorado, 2005. USGS Scientific Investigations Report 2010-5002. Reston, VA. 71 pp.

Johnson, C., and M. Mifflin. 2006. The AEM and regional carbonate aquifer modeling. Ground Water 44(1): 24-34.

Johnson, N. 2010. Pennsylvania energy impacts assessment report 1: Marcellus Shale: Natural Gas and Wind. The Nature Conservancy. Available at: http://www.nature.org/media/pa/tnc_energy_analysis.pdf

Johnson, R. C. 1989. Geologic history and hydrocarbon potential of Late Cretaceous-age, low-permeability reservoirs, Piceance Basin, western Colorado. U.S. Geological Survey Bulletin 1787-E. 51 pp.

Johnson, R. C., and S. B. Roberts. 2003. The Mesaverde total petroleum system, Uinta-Piceance Province, Utah and Colorado. U.S. Geological Survey Digital Data Series DDS-69-B. 68 pp.

Juckem, P. F., 2009. Simulation of the regional ground-water-flow system and ground-water/surface-water interaction in the Rock River Basin, Wisconsin. U.S. Geological Survey Scientific Investigations Report 2009-5094. 38 pp.

Kargbo, D. M., R. G. Wilhelm, and D. J. Campbell. 2010. Natural gas plays in the Marcellus Shale: Challenges and potential opportunities. Environmental Science and Technology 44: 5679-5684.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelance, and M. A. Maupin. 2009. Estimated use of water in the United States in 2005. U.S. Geological Survey Circular 1344. 52 pp. Available at: http://pubs.usgs.gov/circ/1344/.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel. 2006. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15(3): 259-263.

Leonard Rice Engineers. 2009. Historic crop consumptive use analysis, Colorado River Basin, final report. Prepared for the Colorado Water Conservation Board. 44 pp. Available at: http://cwcbweblink.state.co.us/WebLink/ElectronicFile.aspx?docid=146047&searchid=6a9fd4ff-d203-4864-a8f5-4f014c64994a&dbid=0

Lukas, J., J. Barsugli, N. Doesken, I. Rangwala, and K. Wolter. 2014. Climate change in Colorado—a synthesis to support water resources management and adaption. Prepared by the Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, for the Colorado Water Conservation Board. University of Colorado Boulder. 114 pp.

Maloney, K. O., and D. A. Yoxtheimer. 2012. Production and disposal of waste materials from gas and oil extraction from the Marcellus Shale play in Pennsylvania. Environmental Practice 14(4): 278-287.

Maupin, M.A., J.F. Kenny, S.S. Huston, J.K. Lovelace, N.L. Barber, and K.S. Linsey. 2014. Estimated water use in the United States in 2010. U.S. Geological Survey Circular 1405. 52 pp. Available at: http://dx.doi.org/10.3133/cir1405.

McGonigal, K. H. 2005. Nutrients and suspended sediment transported in the Susquehanna River Basin, 2004, and trends, January 1985 through December 2004. Publication 241. Available at: http://www.srbc.net/pubinfo/techdocs/Publication_241/techreport241.htm.

Milici, R. C., and C. S. Swezey. 2006. Assessment of Appalachian Basin oil and gas resources: Devonian Shale-Middle and Upper Paleozoic Total Petroleum System. U.S. Geological Survey Open-File Report 2006-1237. 70 pp. Available at: http://pubs.usgs.gov/of/2006/1237/

Mitchell, A. L., M. Small, and E. A. Casman. 2013. Surface water withdrawals for Marcellus Shale gas development: Performance of alternative regulatory approaches in the Upper Ohio River Basin. Environmental Science and Technology 47(22): 12669-12678.

Montgomery, C. T., and M. B. Smith. 2010. Hydraulic fracturing—history of an enduring technology. Journal of Petroleum Technology 62(12): 26-32.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50(3): 885-900.

Murray, K. E. 2013. State-scale perspective on water use and production associated with oil and gas operations, Oklahoma, U.S. Environmental Science and Technology 47(9): 4918-4925.

Narasimhan, B., R. Srinivasan, J. G. Arnold, and M. Di Luzio. 2005. Estimation of long-term soil moisture using a distributed parameter hydrologic model and verification using remotely sensed data. Transactions of the ASAE 48(3): 1101-1113.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models part I—a discussion of principles. Journal of Hydrology 10(3): 282-290.

Nicot, J.-P., and B. R. Scanlon. 2012. Water use for shale-gas production in Texas, U.S. Environmental Science and Technology 46: 3580-3586.

Nicot, J.-P., B. R. Scanlon, R. C. Reedy, and R. A. Costley. 2014. Source and fate of hydraulic fracturing water in the Barnett shale: A historical perspective. Environmental Science and Technology 48: 2464-2471.

NOAA (National Oceanic and Atmospheric Administration). 2013. Climate data online. Available at: http://www.ncdc.noaa.gov/cdo-web/

PADCNR (Pennsylvania Deptartment of Conservation and Natural Resources). 2014a. Pennsylvania Groundwater Information System (PaGWIS). Available at: http://www.dcnr.state.pa.us/topogeo/groundwater/pagwis/index.htm

PADCNR (Pennsylvania Deptartment of Conservation and Natural Resources). 2014b. Pennsylvania Internet Record Imaging System/Wells Information System (PA*IRIS/WIS): Gateway to detailed oil and gas well information data. Available at: http://www.dcnr.state.pa.us/topogeo/econresource/oilandgas/pa_iris_home/

PADEP (Pennsylvania Department of Environmental Protection). 2013a. Oil and gas reports. Available at: http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297.

PaDEP (Pennsylvania Department of Environmental Protection). 2013b. Marcellus Shale development. Fact Sheet 0100-FS-DEP4217. Available at: http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-97683/0100-FS-DEP4217.pdf.

PADEP (Pennsylvania Department of Environmental Protection). 2014a. State Water Plan. Available at: http://www.pawaterplan.dep.state.pa.us/StateWaterPlan/WaterDataExportTool/WaterExportTool.aspx. Query: Primary facility report by year and county.

PADEP (Pennsylvania Department of Environmental Protection). 2014b. State Water Plan. Available at: http://www.pawaterplan.dep.state.pa.us/StateWaterPlan/WaterDataExportTool/WaterExportTool.aspx. Query: Chapter 110 (Act 220) registration.

Padowski, J. C., and J. W. Jawitz. 2012. Water availability and vulnerability of 225 large cities in the United States. Water Resources Research 48(12):W12529.

Perrone, D., J. Murphy, and G. M. Hornberger. 2011. Gaining perspective on the water-energy nexus at the community scale. Environmental Science and Technology 45: 4228-4234.

Pranter, M. J., and N. K. Sommer. 2011. Static connectivity of fluvial sandstones in a lower coastal-plain setting: An example from the Upper Cretaceous lower Williams Fork formation, Piceance Basin, Colorado. AAPG Bulletin 95(6): 899-923.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rahm, B. G., and S. J. Riha. 2012. Toward strategic management of shale gas development: Regional, collective impacts on water resources. Environmental Science and Policy 17: 12-23.

Reeves, H.W. 2010. Water availability and use pilot—A multiscale assessment in the U.S. Great Lakes Basin. U.S. Geological Survey Professional Paper 1778, 105p.

Reilly, T. E., K. F. Dennehy, W. M. Alley, and W. L. Cunningham. 2008. Ground-water availability in the United States. U.S. Geological Circular 1323. 70 pp. Available at: http://pubs.usgs.gov/circ/1323/

Richardson, N., M. Gottlieb, A. Krupnick, and H. Wiseman. 2013. The state of state shale gas regulation. RFF Report (June 2013). Available at: http://www.rff.org/Publications/Pages/default.aspx

Richter, B. 2014. Chasing water. Island Press, Washington D.C.

Risser, D.W., R. W. Conger, J. E. Ulrich, and M. P. Asmussen. 2005. Estimates of ground-water recharge based on streamflow-hydrograph methods: Pennsylvania. U.S. Geological Survey Open-File Report 2005-1333. 30 pp.

Robson, S.G, and E.R. Banta. 1995. Groundwater atlas of the United States, Arizona, Colorado, New Mexico, Utah, Colorado Plateau aquifers. U.S. Geological Survey HA 730-C. http://pubs.usgs.gov/ha/ha730/ch_c/C-text8.html

Roy, S. B., P. F. Ricci, K. V. Summers, C.-F. Chung, and R. A. Goldstein. 2005. Evaluation of the sustainability of water withdrawals in the United States, 1995 to 2025. Journal of the American Water Resources Association 41(5): 1091-1108.

Rutledge, A. T. 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data—update. U.S. Geological Survey Water-Resources Investigations Report 98-4148. 43 pp.

Schlumberger 2014. Directional Drilling. Oilfield glossary. http://www.glossary.oilfield.slb.com/en/Terms/d/directional_drilling.aspx

Slonecker, E. T., L. E. Milheim, C. M. Roig-Silva, A. R. Malizia, D. A. Marr, and G. B. Fisher. 2012. Landscape consequences of natural gas extraction in Bradford and Washington Counties, Pennsylvania 2004-2010. U.S. Geological Survey Open-File Report 2012-1154. 36 pp.

Soeder, D. J., and W. M. Kappel. 2009. Water resources and natural gas production from the Marcellus Shale. U.S. Geological Survey Fact Sheet 2009-3032. West Trenton, NJ.

Spahr, N. E., L. E. Apodaca, J. R. Deacon, J. B. Bails, N. J. Bauch, C. M. Smith, and N. E. Driver. 2000. Water quality in the Upper Colorado River Basin, 1996-98. U.S. Geological Survey Circular 1214. Available at: http://pubs.usgs.gov/circ/circ1214/#pdf

SRBC (Susquehanna River Basin Commission). 2003. Guidelines for using and determining pass-by flows and conservation releases for surface-water and ground-water withdrawal approvals. Susquehanna River Basin Commission, Harrisburg, PA.

SRBC (Susquehanna River Basin Commission). 2005. Groundwater management plan for the Susquehanna River Basin. Publication No. 236.

SRBC (Susquehanna River Basin Commission). 2012. Technical guidance for low flow protection related to withdrawal approvals under Policy No. 2012-01. Susquehanna River Basin Commission, Harrisburg, PA. Available at: http://www.srbc.net/policies/lowflowpolicy.htm

SRBC (Susquehanna River Basin Commission). 2013a. Public information Available at: http://www.srbc.net/pubinfo/index.htm. Query water source acquisition volume.

SRBC (Susquehanna River Basin Commission). 2013b. Policies, guidances & regulations. Available at: http://www.srbc.net/policies/policies.htm

SRBC (Susquehanna River Basin Commission). 2013c. Water Resource Portal Overview. Available at: http://www.srbc.net/wrp/

SRBC (Susquehanna River Basin Commission). 2013d. Public information. Available at: http://www.srbc.net/pubinfo/index.htm. Query: Gas well consumptive use.

SRBC (Susquehanna River Basin Commission). 2013e. Natural gas well development in the Susquehanna River Basin. Susquehanna River Basin Commission Information Sheet. Available at: http://www.srbc.net/programs/docs/NaturalGasInfoSheetJan2013.PDF

SRBC (Susquehanna River Basin Commission). 2014. Approved water sources for natural gas development. Available at: http://www.srbc.net/wrp/ApprovedSourceListReport.aspx

Stantec. 2013. Evaluation of water yields of the Getty Oil Company water system water rights in the Colorado River Basin, Colorado. Prepared for Chevron U.S.A Inc. JN 87300002. Denver, CO.

Stuckey, M. H. 2006. Low-flow, base-flow, and mean-flow regression equations for Pennsylvania streams. USGS Scientific Investigations Report 2006-5130. 84 pp.

Tidwell, V. C., P. H. Kobos, L. A. Malczynski, G. Klise, and C. R. Castillo. 2012. Exploring the water-thermoelectric power nexus. Journal Water Resources Planning and Management 138(5): 491-501.

URS. 2008. Energy development water needs assessment (Phase 1 Report). Prepared for the Colorado,Yampa, and White River Basin Roundtables. Glenwood Springs, CO.

U.S. Census Bureau. 2010. 2010 Census home. Available at: http://www.census.gov/2010census/

U.S. EIA (Energy Information Administration). 2009. U.S. crude oil, natural gas, and natural gas liquids proved reserves, 2009. Available at: http://www.eia.gov/pub/oil_gas/natural_gas/data_publications/crude_oil_natural_gas_reserves/historical/2009/pdf/geodistribution.pdf

U.S. EIA (Energy Information Administration). 2011a. The geology of natural gas resources. Today in Energy (February 14). Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=110

U.S. EIA (Energy Information Administration). 2011b. North American shale plays. Available at: http://www.eia.gov/oil_gas/rpd/northamer_gas.jpg

U.S. EIA (Energy Information Administration). 2012. Annual energy outlook 2012. DOE/EIA-0383(2012). U.S. Department of Energy, Washington, DC. Available at: http://www.eia.gov/forecasts/aeo/

U.S. EIA (Energy Information Administration). 2013a. Annual energy outlook 2013. DOE/EIA-0383(2013). U.S. Department of Energy, Washington, DC. Available at: http://www.eia.gov/forecasts/aeo/

U.S. EIA (Energy Information Administration). 2013b. Drilling often results in both oil and gas production. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=13571#

U.S. EIA (Energy Information Administration). 2014a. Drilling productivity report. Available at: http://www.eia.gov/petroleum/drilling/. Query: Report data (aggregated by region); July 2014.

U.S. EIA (Energy Information Administration). 2014b. Data for the US shale plays map; Data for the tight gas plays map. Available at: http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm#field

U.S. EIA (Energy Information Administration). 2014c. Marcellus region production continues growth. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=17411

U.S. EIA (Energy Information Administration). 2014d. Colorado State energy profile. Available at: http://www.eia.gov/state/print.cfm?sid=co

U.S. EPA (Environmental Protection Agency). 2012a. Study of the potential impacts of hydraulic fracturing on drinking water resources: Progress report. EPA/601/R-12/011. Washington, DC. Available at: http://www2.epa.gov/sites/production/files/documents/hf-report20121214.pdf

U.S. EPA (Environmental Protection Agency). 2012b. Plan to study the impacts of hydraulic fracturing on drinking water resources, Quality Management Plan, Revision No. 1. Available at: http://www2.epa.gov/hfstudy/quality-management-plan-revision-no-1-plan-study-potential-impacts-hydraulic-fracturing

U.S. EPA (Environmental Protection Agency). 2012c. Safe Drinking Water Information System—federal version (SDWIS/FED). Available at: http://water.epa.gov/scitech/datait/databases/drink/sdwisfed/index.cfm

U.S. EPA (Environmental Protection Agency). 2013a. Watershed modeling to assess the sensitivity of streamflow, nutrient, and sediment loads to potential climate change and urban development in 20 U.S. watersheds. EPA/600/R-12/058F. Washington, DC.

U.S. EPA (Environmental Protection Agency). 2013b. Modeling the impact of hydraulic fracturing on drinking water resources based on water acquisition scenarios: Phase 2, EPA hydraulic fracturing study quality assurance project plan (QAPP). Athens, GA. Available at: http://www2.epa.gov/hfstudy/qapp-modeling-impact-hydraulic-fracturing-drinking-water-resources-based-water-acquisition

U.S. EPA (Environmental Protection Agency). 2014. Study of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources, Quality Management Plan, Revision No. 2.

U.S. EPA (Environmental Protection Agency). 2015. Analysis of hydraulic fracturing fluid data from the FracFocus Chemical Disclosure Registry 1.0. Office of Research and Development, Washington D.C. EPA/601/R-14/003.

USFWS (U.S. Fish and Wildlife Service). 2008. Programmatic biological opinion for water depletions associated with Bureau of Land Management's Fluid Mineral Program within the Upper Colorado River Basin in Colorado. December 19. Grand Junction, CO.

USGS (U.S. Geological Survey). 1982. Guidelines for determining flood flow frequency. Bulletin #17B. U.S. Geological Survey, Office of Water Data Coordination, Reston, VA. Available at: http://water.usgs.gov/osw/bulletin17b/dl_flow.pdf

USGS (U.S. Geological Survey). 2003. Aquifers. National Atlas of the Unites States, Map Maker. Retrieved September 16, 2014 from http://www.nationalatlas.gov/mapmaker

USGS (U.S. Geological Survey). 2014a. USGS water use data for the nation. Available at: http://waterdata.usgs.gov/nwis/wu

USGS (U.S. Geological Survey). 2014b. U.S. Geological Survey surface-water use data for the nation. Available at: http://waterdata.usgs.gov/nwis/sw

USGS (U.S. Geological Survey). 2014c. WaterWatch. Available at: http://waterwatch.usgs.gov

USGS Uinta-Piceance Assessment Team. 2003. Executive summary—assessment of undiscovered oil and gas resources of the Uinta-Piceance Province of Utah and Colorado, 2002. U.S. Geological Survey Digital Data Series DDS-69-B.

Vengosh, A., R. B. Jackson, N. Warner, T. H. Darrah, and A. Kondash. 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environmental Science and Technology 48(15): 8334-8348.

Weiskel, P.K. R.M. Vogel, P.A. Steeves, P.J. Zarriello, L.A. DeSimone, and K.G. Ries III. 2007. Water use regimes: Characterizing direct human interaction with hydrologic systems. Water Resources Research 43: doi:10.1029/2006WR005062

Williams, J. H., L. E. Taylor, and D. J. Law. 1998. Hydrogeology and groundwater quality of the glaciated valleys of Bradford, Tioga, and Potter Counties, Pennsylvania. Pennsylvania Geological Survey, 4th ser, Water Resource Report 68. 89 pp.

Wilson, J. M., and J. M. VanBriesen. 2012. Oil and gas produced water management and surface drinking water sources in Pennsylvania. Environmental Practice 14: 288-300.

Yager, R. M., and C. J. Neville. 2002. GFLOW 2000: An analytic element ground water flow modeling system. Ground Water 40(6): 574-576.

Zhou, Y. 2009. A critical review of groundwater budget myth, safe yield and sustainability. Journal of Hydrology 370: 207-213.

# GLOSSARY

(numbers in parentheses are references at end of glossary)

**Acid mine drainage:** Drainage of water from areas that have been mined for coal of other mineral ores. The water has a low pH because of its contact with sulfur-bearing material and is harmful to aquatic organisms. (2)

**Analysis of existing data:** The process of gathering and summarizing existing data from various sources to provide current information on hydraulic fracturing activities. (8)

**API number:** A unique identifying number for each oil/gas well drilled in the United States. The system was developed by the American Petroleum Institute. (1)

**Aquifer:** An underground geological formation, or group of formations, containing water. A source of groundwater for wells and springs. (2)

**Consumptive use:** The part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment. Consumptive-use estimates were included in some previous water use U.S. Geological Survey circulars, but were omitted beginning in 2000. Also referred to as water consumed. (6)

**Contaminant:** A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful (adverse) health effects. (2)

**Conventional reservoir:** A reservoir in which buoyant forces keep hydrocarbons in place below a sealing caprock. Reservoir and fluid characteristics of conventional reservoirs typically permit oil or natural gas to flow readily into wellbores. The term is used to make a distinction from shale and other unconventional reservoirs, in which gas might be distributed throughout the reservoir at the basin scale, and in which buoyant forces or the influence of a water column on the location of hydrocarbons within the reservoir are not significant. (5)

**Conveyance loss:** Water lost in transit from a pipe, canal, conduit, or ditch by leakage or evaporation. Generally, the water is not available for further use; however, leakage (e.g., from an irrigation ditch) may percolate to a groundwater source and be available for further use. (6)

**Domestic water use:** Water used for indoor household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and outdoor purposes such as watering lawns and gardens. Domestic water use includes water provided to households by a public water supply (domestic deliveries) and self-supplied water. (6)

**Drinking water resource:** Any body of water, ground or surface, that could (now or in the future) serve as a source of drinking water for public or private water supplies. (8)

**Flowback:** After the hydraulic fracturing procedure is completed and pressure is released, the direction of fluid flow reverses, and water and excess proppant flow up through the wellbore to the surface. (3)

**Fluid formulation:** The entire suite of products and carrier fluid injected into a well during hydraulic fracturing. (8)

**Formation:** A geological formation is a body of earth material with distinctive and characteristic properties and a degree of homogeneity in its physical properties. (2)

**Formation water:** Water that occurs naturally within the pores of rock. (5)

**FracFocus:** National registry for chemicals used in hydraulic fracturing, jointly developed by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission. Serves as an online repository where oil and gas well operators can upload information about the chemical compositions of hydraulic fracturing fluids used in specific oil and gas production wells. Also contains spatial information for well locations and information on well depth and water use. (8)

**Freshwater:** Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids. Generally, water with more than 500 mg/L of dissolved solids is undesirable for drinking and many industrial uses. (6)

**Geographic information system (GIS):** A computer system designed for storing, manipulating, analyzing, and displaying data in a geographic context, usually as maps. (2)

**Groundwater:** All water found beneath the surface of the land. Groundwater is the source of water found in wells and springs and is used frequently for drinking. (2)

**Horizontal drilling:** The intentional deviation of a wellbore from the path it would naturally take to a horizontal trajectory. A subset of the more general term "directional drilling," used where the departure of the wellbore from vertical exceeds about 80 degrees. Horizontal lateral sections can be designed to intersect natural fractures or simply to contact more of the productive formation. (5)

**Hydraulic fracturing:** The process of using high pressure to pump proppant (e.g. sand) along with a base (e.g. water) and other fluids into subsurface rock formations in order to improve flow of oil and gas into a wellbore. (8)

**Hydraulic fracturing fluid:** Specially engineered fluids containing chemical additives and proppant that are pumped under high pressure into the well to create and hold open fractures in the formation. (8)

**Hydraulic fracturing wastewater:** Flowback and produced water, where flowback is the fluid returned to the surface after hydraulic fracturing has occurred but before the well is placed into production and produced water is the fluid returned to the surface after the well has been placed into production. (8)

**Hydraulic fracturing water cycle:** The cycle of water in the hydraulic fracturing process, encompassing the acquisition of water, chemical mixing of the fracturing fluid, injection of the fluid into the formation, the production and management of flowback and produced water, and the ultimate treatment and disposal of hydraulic fracturing wastewaters. (8)

**Hydraulic gradient:** Slope of a water table or potentiometric surface. More specifically, change in the hydraulic head per unit of distance in the direction of the maximum rate of decrease. (2)

**Hydrocarbon:** An organic compound containing only hydrogen and carbon, often occurring in petroleum, natural gas, and coal. (2)

**Industrial water use:** Water used for fabrication, processing, washing, and cooling. Includes industries such as chemical and allied products, food, paper and allied products, petroleum refining, wood products, and steel. (6)

**Instream use:** Water that is used, but not withdrawn, from a surface water source for such purposes as hydroelectric power generation, navigation, water quality improvement, fish propagation, and recreation. (6)

**Irrigation water use:** Water that is applied by an irrigation system to assist crop and pasture growth, or to maintain vegetation on recreational lands such as parks and golf courses. Irrigation includes water that is applied for pre-irrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, leaching of salts from the root zone, and conveyance losses. (6)

Kerogen: The naturally occurring, solid, insoluble organic matter that occurs in source rocks and can yield oil upon heating. Kerogen is the portion of naturally occurring organic matter that is nonextractable using organic solvents. Typical organic constituents of kerogen are algae and woody plant material. (5)

**Livestock water use:** Water used for livestock watering, feedlots, dairy operations, and other on-farm needs. Types of livestock include dairy cows and heifers, beef cattle and calves, sheep and lambs, goats, hogs and pigs, horses and poultry. (6)

**Mining water use:** Water used for the extraction of naturally occurring minerals including solids (such as coal, sand, gravel, and other ores), liquids (such as crude petroleum), and gases (such as natural gas). Also includes uses associated with quarrying, milling, and other preparations customarily done at the mine site or as part of a mining activity according to the U.S. Geological Survey. Does not include water associated with dewatering of the aquifer that is not put to beneficial use. Also does not include water used in processing, such as smelting, refining petroleum, or slurry pipeline operations. The U.S. Geological Survey includes these processing uses in industrial water use. (6)

**Monte Carlo simulation:** A technique used to estimate the most probable outcomes from a model with uncertain input data and to estimate the validity of the simulated model. (8)

**Natural gas or gas**: A naturally occurring mixture of hydrocarbon and non-hydrocarbon gases in porous formations beneath the Earth's surface, often in association with petroleum. The principal constituent of natural gas is methane. (5)

**Permeability:** Ability of rock to transmit fluid through pore spaces. (1)

**Play:** A set of oil or gas accumulations sharing similar geologic and geographic properties, such as source rock, hydrocarbon type, and migration pathways. (1)

**Porosity:** Percentage of the rock volume that can be occupied by oil, gas, or water. (1)

**Produced water:** After the drilling and fracturing of the well are completed, water is produced along with the resource. Some of this water is returned fracturing fluid and some is natural formation water. These produced waters move back through the wellhead with the gas. (4)

**Proppant/propping agent:** A granular substance (sand grains, aluminum pellets, or other material) that is carried in suspension by the fracturing fluid and that serves to keep the fractures open when fracturing fluid is withdrawn after a fracture treatment. (8)

**Public supply water use:** Water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 connections. Public suppliers provide water for a variety of uses, such as domestic, commercial, industrial, thermoelectric power, and public water use. (6)

**Public supply deliveries:** Amount of water delivered from a public supplier to users for domestic, commercial, industrial, thermoelectric power, or public-use purposes. (6)

**Public water system (PWS):** A system that provides water to the public for human consumption through pipes or other constructed conveyances. A PWS, per EPA's definition, must have at least 15 service connections or regularly serve at least 25 people. (2)

**Public water use:** Water supplied from a public supplier and used for such purposes as firefighting, street washing, flushing of water lines, and maintaining municipal parks and swimming pools. Generally, public-use water is not billed by the public supplier. (6)

**$Q_{7,10}$:** The average minimum streamflow that can be expected for seven consecutive days once every 10 years, computed from measured flow records.

**Safe yield:** Commonly used in efforts to quantify sustainable groundwater development. The term should be used with respect to specific effects of pumping, such as water-level declines, reduced streamflow, and degradation of water quality. (7)

**Scenario evaluation:** Exploration of realistic, hypothetical scenarios related to hydraulic fracturing activities using computer models. Used to identify conditions under which hydraulic fracturing activities may adversely impact drinking water resources. (8)

**Science Advisory Board:** A federal advisory committee that provides a balanced, expert assessment of scientific matters relevant to EPA. An important function of the Science Advisory Board is to review EPA's technical programs and research plans. (2)

**Self-supplied water use:** Water withdrawn from a groundwater or surface water source by a user rather than being obtained from a public supply. (6)

**Service company:** A company that assists well operators by providing specialty services, including hydraulic fracturing. (8)

**Shale:** A fine-grained sedimentary rock composed mostly of consolidated clay or mud. Shale is the most frequently occurring sedimentary rock. (5)

**Source water:** Water withdrawn from surface or ground water, or purchased from suppliers, for hydraulic fracturing. (8)

**Statistical analysis:** Analyzing collected data for the purposes of summarizing information to make it more usable and/or making generalizations about a population based on a sample drawn from that population. (2)

**Surface water:** All water naturally open to the atmosphere (rivers, lakes, reservoirs, ponds, streams, impoundments, seas, estuaries). (2)

**Surfactant:** Used during the hydraulic fracturing process to decrease liquid surface tension and improve fluid passage through the pipes. (8)

**Tight sands:** A geological formation consisting of a matrix of typically impermeable, non-porous tight sands. (8)

**Total dissolved solids:** The quantity of dissolved material in a given volume of water. (2)

**Unconventional resource:** An umbrella term for oil and natural gas produced by means that do not meet the criteria for conventional production. What has qualified as unconventional at any particular time is a complex function of resource characteristics, the available exploration and production technologies, the economic environment, and the scale, frequency, and duration of production from the resource. Perceptions of these factors inevitably change over time and often differ between users of the term. At present, the term is used in reference to oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and carbonate reservoirs. Coalbed methane, gas hydrates, shale gas, fractured reservoirs, and tight gas sands are considered unconventional resources. (5)

**Water use:** Pertains to the interaction of humans with and influence on the hydrologic cycle; includes elements such as water withdrawal, delivery, consumptive use, wastewater release, reclaimed wastewater, return flow, and instream use. (6)

**Water withdrawal:** Water removed from the ground or diverted from a surface water source for use. (6).

**Well files:** Files that generally contain information on all activities conducted at an oil and gas production well. These files are created by oil and gas operators. (8)

**Well operator:** A company that ultimately controls and operates oil and gas wells. (8)

## Glossary References

1. Oil and Gas Mineral Services. 2010. Oil and gas terminology. Available at: http://www.mineralweb.com/library/oil-and-gas-terms/
2. U.S. Environmental Protection Agency. 2006. Terminology services: Terms and acronyms. Available at: http://iaspub.epa.gov/sor_internet/registry/termreg/home/overview/home.do
3. New York State Department of Environmental Conservation. 2011. Supplemental generic environmental impact statement on the Oil, Gas and Solution Mining Regulatory Program: Well permit issuance for horizontal drilling and high-volume hydraulic fracturing to develop the Marcellus Shale and other low-permeability gas reservoirs. Revised draft. Available at: ftp://ftp.dec.state.ny.us/dmn/download/OGdSGEISFull.pdf
4. Ground Water Protection Council and ALL Consulting. 2009. Modern shale gas development in the United States: A primer. Prepared for the U.S. Department of Energy. Available at: http://energy.gov/sites/prod/files/2013/03/f0/ShaleGasPrimer_Online_4-2009.pdf
5. Schlumberger. The oilfield glossary: Where the oilfield meets the dictionary. Available at: http://www.glossary.oilfield.slb.com/
6. Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelance, and M. A. Maupin. 2009. Estimated use of water in the United States in 2005. USGS Circular 1344. 52 pp. Available at: http://pubs.usgs.gov/circ/1344/
7. Reilly, T. E., K. F. Dennehy, W. M. Alley, and W. L. Cunningham. 2008. Ground-water availability in the United States. USGS Circular 1323. 70 pp. Available at: http://pubs.usgs.gov/circ/1323/
8. U.S. Environmental Protection Agency. 2012. Study of the potential impacts of hydraulic fracturing on drinking water resources: Progress Report. EPA/601/R-12/011. Available at: http://www2.epa.gov/sites/production/files/documents/hf-report20121214.pdf

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# Appendix A. Compendium of Data Sources

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Appendix A lists the data sources used in this study. The data sources have been organized into three tables. Table A-1 contains the national data sources used for one or both of the study areas. Table A-2 contains the data sources specific to the Colorado study site. Table A-3 contains the data sources specific to the Pennsylvania study area.

## Table A- 1. National Data Sources

| National Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **USGS National Water Information System (NWIS) Surface Water Data**<br>http://waterdata.usgs.gov/nwis/sw | 9/8/2014 | – location of stream gages in the Susquehanna River Basin (SRB) and the Upper Colorado River Basin (UCRB)<br>– streamflow time series for SRB and UCRB | – deterministic hydrologic modeling<br>– baseflow separation analysis<br>– area-weighted extrapolation to ungaged SRB withdrawal sites |
| **USGS National Water Information System (NWIS) Groundwater Data**<br>http://waterdata.usgs.gov/nwis/gw | 2/26/2014 | – location of water wells<br>– well depth and aquifer water level elevations in wells | – estimation of average thickness of drinking water aquifer in SRB and UCRB |
| **USGS National Water Information System (NWIS) Water Use Data**<br>http://waterdata.usgs.gov/nwis/wu | 3/14/2014 | – 2005 water use data by county | – county-level estimation of water use in SRB |
| **NOAA National Climatic Data Center (NCDC)**<br>http://www.ncdc.noaa.gov/cdo-web/ | 11/7/2013 | – location and elevation of weather stations in SRB and UCRB<br>– meteorological data (precipitation, air temperature, evapotranspiration) for SRB and UCRB | – deterministic hydrologic modeling<br>– input for SRB regional equations |
| **U.S. Energy Information Administration (EIA)**<br>http://www.eia.gov/ | 5/1/2014 | – location of shale and tight gas basins in the United States | – general reference; cartography |
| **U.S. Energy Information Administration (EIA)**<br>http://www.eia.gov/<br>as compiled by the U.S. EPA | 9/12/2012 | – projections of unconventional gas annual drilling rates generated with the National Energy Modeling System (NEMS)—Annual Energy Outlook 2012 (AEO2012) reference case | – hydraulic fracturing future drilling projections |
| **FracFocus Database**<br>as compiled by The Cadmus Group, Inc. for the U.S. EPA | 11/22/2013 | – data on total fluid volume used for O&G wells between January 2011 and February 2013 | – computation of average fluid volumes used per well for hydraulic fracturing in Garfield, Mesa, and Rio Grande Counties in Colorado |
| **FracFocus 2.0**<br>http://fracfocus.org/ | 5/31/2014 | – data on fluid volume in O&G wells fractured after 2010 (location of wells, fracture date, total fluid volume used) | – computation of average fluid volumes used per well for hydraulic fracturing in Garfield, Mesa, and Rio Grande Counties in Colorado<br>– well counts |
| **FracTracker Alliance**<br>http://www.fractracker.org/ | 2/21/2014 | – data on permitted oil and gas wells and drilled wells (date, location, and number of wells) | – mapping location of oil and gas activity in UCRB |
| **EPA Safe Drinking Water Information System-Federal version (SDWIS/FED)**<br>http://water.epa.gov/scitech/datait/databases/drink/sdwisfed/index.cfm | 6/1/2012 | – location of public drinking water systems in SRB | – mapping the general location of public water suppliers in SRB |

| National Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **USDA National Agricultural Statistics Service** http://www.nass.usda.gov/ | 2/1/2014 (provided by SRBC) | – 2010 crop-specific land cover data in raster format at 30 meters spatial resolution (2010 Cropland Data Layer)<br>– 2007 Census of Agriculture statistics<br>– 2008 Farm and Ranch Irrigation Survey data | – surface water use intensity index (SUI) calculations in SRB |
| **Multi-Resolution Land Characteristics Consortium (MRLC)** http://www.mrlc.gov/index.php | 8/22/2013 | – 2006 land cover classification in raster format at 30 meters spatial resolution (National Land Cover Database [NLCD] 2006) for SRB and UCRB | – deterministic hydrologic modeling<br>– input for SRB regional equations |
| **National Elevation Dataset (NED)** http://ned.usgs.gov/ | 3/31/2014 | – ground elevation data in raster format at 1/3 arc-second (about 10 meters) and 1 arc-second (about 30 meters) resolution for SRB and UCRB<br>– ground elevation data in raster format at 1/9 arc-second (approximately 3 meters) resolution for SRB | – deterministic hydrologic modeling<br>– input for SRB regional equations<br>– extraction of elevations for stream channels<br>– basemap for groundwater modeling<br>– cartography |
| **GeoCommunity** http://data.geocomm.com/catalog | 12/10/2013 | – medium resolution (1:100,000 scale) vector elevation contours (USGS Digital Line Graphs—Hypsography) for SRB and UCRB | – extraction of elevations for stream channels<br>– basemap for groundwater modeling |
| **USGS Historical Topographic Map Collection** http://nationalmap.gov/historical/index.html | 5/22/2014 | – drainage networks from digital version of historical topographic maps at 1:24,000 and 1:100,000 scale<br>– general site information | – evidence of perennial stream channels in SRB and UCRB |
| **National Hydrography Dataset (NHD)** http://nhd.usgs.gov/index.html | 9/6/2013 | – high-resolution (1:24,000 or larger scale) vector stream network for SRB and UCRB | – reference stream network when generating the ArcSWAT stream network |
| **EPA Center for Exposure Assessment Modeling (CEAM)** http://www2.epa.gov/exposure-assessment-models/whaem2000-bbm-files-us | 11/4/2013 | – medium-resolution (1:100,000 scale) vector surface hydrologic features (USGS Digital Line Graphs—Hydrography) in binary base map (BBM) format for SRB and UCRB | – basemap for groundwater modeling |
| **Better Assessment Science Integrating Point and Nonpoint Sources (BASINS)** http://water.epa.gov/scitech/datait/models/basins/index.cfm | 8/28/2012 | – low-resolution (1:500,000 scale) vector stream network—Reach File 1 (RF1) | – evidence of perennial stream channels in Colorado<br>– cartography |
| **USDA Natural Resources Conservation Service** http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053629 | 3/19/2014 (accessed directly through ArcSWAT) | – generalized (1:250,000 scale) polygon-based soils information (STATSGO2) for SRB and UCRB | – deterministic hydrologic modeling |

| National Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **United States Census Bureau**<br>http://www.census.gov/ | 11/13/2013 | – 2010 population data and census block shapefiles (TIGER/Line) for Bradford, Lycoming, Sullivan, and Tioga Counties in Pennsylvania and Garfield, Mesa, Pitkin, and Rio Blanco Counties in Colorado | – estimation of private water well use |
| | 2/1/2014 (provided by SRBC) | – 2010 population data and housing unit counts by census block (TIGER/Line shapefile) for Towanda Creek basin in Pennsylvania | – SUI calculations in SRB |
| **United States Census Bureau—American Factfinder**<br>http://factfinder2.census.gov/faces/nav/jsf/pages/community_facts.xhtml#none | 04/16/2014 | – 2012 population estimates for Colorado municipalities (Parachute and DeBeque); only 2010 data available for Battlement Mesa, Colorado | – reference |

## Table A- 2. Colorado Data Sources

| Colorado Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **Colorado's Decision Support Systems (CDSS)**<br>http://cdss.state.co.us/onlineTools/Pages/OnlineToolsHome.aspx | 4/19/2014 | – records of water rights and administrative structures in UCRB<br>– water withdrawal history from administrative structures in UCRB | – quantification of water use in various areas of UCRB; identification of administrative structures owned by oil and gas |
| **Colorado's Decision Support Systems (CDSS)**<br>http://cdss.state.co.us/GIS/Pages/GISDataHome.aspx | 3/25/2014 | – shapefiles of water structures and water management boundaries in UCRB | – reference; locate diversion structures in UCRB |
| **Colorado Municipal League**<br>Water & Wastewater Survey<br>http://www.cml.org/water-wastewater | 3/11/2014 | – information on selected Colorado public drinking water systems from 2012 water and wastewater survey | – background information |
| **Colorado Division of Water Resources (DWR)**<br>http://water.state.co.us/Home/Pages/default.aspx | 2/21/2014 | – Colorado water use yearly statistics by water division (roughly equivalent to a major river basin) | – SUI calculations in UCRB |
| | | – location of drilled household wells | – cartography |

| Colorado Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **Colorado Oil and Gas Conservation Commission (COGCC)**<br>http://cogcc.state.co.us/ | 6/4/2014 | – location of permitted oil and gas wells in UCRB<br>– number of well completions prior to 2010<br>– number of producing wells<br>– produced water volumes | – general analysis of hydraulic fracturing use metrics<br>– SUI calculations in UCRB<br>– cartography |
| | | – names of oil and gas operators in UCRB | – help identify administrative structures own by oil and gas in Garfield, Mesa, Rio Blanco, Moffat, Routt, and Jackson Counties in Colorado |
| | | – line shapefile representing directionally drilled oil and gas wells in Colorado | – mapping of well directional lines in Parachute Creek upper valley |
| **StreamStats (Colorado application)**<br>http://water.usgs.gov/osw/streamstats/colorado.html | 04/01/2014 | – drainage area delineations for selected water diversion structures in Parachute and Roan Creeks, Colorado | – area-weighted extrapolation to ungaged diversion structures in UCRB |

### Table A- 3. Pennsylvania Data Sources

| Pennsylvania Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **Susquehanna River Basin Commission (SRBC)**<br>Personal communication | 4/2/2014 | – well pad consumption volumes in SRB | – generate hydraulic fracturing use scenarios in SRB |
| | | – water withdrawal volumes and location of permitted SRB surface water withdrawal sites | – generate hydraulic fracturing use scenarios in SRB<br>– SUI calculations<br>– area-weighted extrapolation to ungaged SRB withdrawal sites |
| **SRBC River Basin Commission**<br>http://www.srbc.net/ | 2/4/2014 | – data on oil and gas withdrawal permits in SRB (permit requirements including passbys and capacity) | – general analysis of hydraulic fracturing use metrics in SRB |
| | | – location, total depth and pump ratings of permitted freshwater wells in SRB | – mapping of self-supplied well fields<br>– groundwater impact analysis |
| **Pennsylvania Department of Environmental Protection (PADEP) State Water Plan**<br>http://www.pawaterplan.dep.state.pa.us/StateWaterPlan/WaterDataExportTool/WaterExportTool.aspx | 4/15/2014 | – annual water use reports from public water systems in Pennsylvania, including amounts sold to the oil and gas industry | – quantification of water use in SRB by public water systems |

| Pennsylvania Data Source | Last Access Date | Information Obtained | Use in Report |
|---|---|---|---|
| **Pennsylvania Department of Environmental Protection (PADEP) North-Central Regional Office, Williamsport** | 1/20/2014 | – depth of fresh groundwater (DFGW) in oil and gas wells reported by industry (paper records) | – estimation of average thickness of fresh groundwater in SRB |
| **Pennsylvania Department of Environmental Protection (PADEP) Oil and Gas Reports**<br>http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297 | 7/29/2013 | – location of unconventional drilled hydraulic fracturing wells in Pennsylvania | – mapping of unconventional drilled hydraulic fracturing wells in Pennsylvania |
| **PADCNR—Pennsylvania Groundwater Information System (PaGWIS)**<br>http://www.dcnr.state.pa.us/topogeo/groundwater/pagwis/index.htm | 5/22/2014 | – drilled depth, static water elevations in water wells, pump ratings in SRB | – estimation of thickness of shallow aquifers<br>– groundwater modeling |
| **PADCNR—The Pennsylvania Internet Record Imaging System/Wells Information System (PA*IRIS/WIS)**<br>http://www.dcnr.state.pa.us/topogeo/econresource/oilandgas/pa_iris_home/ | 2/6/2014 | – DFGW in oil and gas wells in SRB | – estimation of average thickness of fresh groundwater in SRB |
| **StreamStats (Pennsylvania application)**<br>http://water.usgs.gov/osw/streamstats/pennsylvania.html | 02/07/2014 | – drainage area delineations for selected oil and gas withdrawal sites in SRB | – area-weighted extrapolation to ungaged SRB withdrawal sites |

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# Appendix B. Surface Water Hydrology

# Contents

## Overview

This research required measurements or estimates of streamflow at numerous points throughout the Pennsylvania and Colorado study areas. While all available U.S. Geological Survey (USGS) streamflow data in both locations were incorporated, active USGS gages tend to be located on streams and rivers draining larger watersheds, and there was limited data availability at oil and gas (O&G) water withdrawal sites, particularly on tributary streams. For quantification of water availability at und sites, a combination of empirical and deterministic modeling methods were implemented to generate estimates of daily streamflow (Booker and Woods 2014).

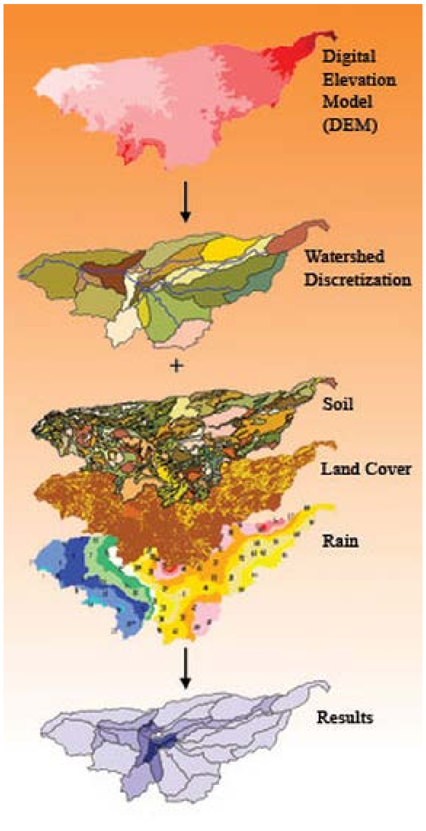


**Figure B-1. Mechanistic watershed modeling: General conceptual diagram (U.S. EPA 2011).**

Physically-based, deterministic watershed modeling relies on mathematical formulations of watershed processes within a given system. Deterministic models are typically complex software tools that reproduce key components of the hydrologic cycle, incorporating a combination of mathematical representations of watershed processes, along with varying degrees of locally-observed spatial and time series data (Fig. B-1). These models rely on observed streamflow data only to compare simulated flows for calibration and validation. Empirical hydrologic methods use recorded streamflow observations from local and regional hydrology to simulate streamflow. Typical empirical methods involve either direct extrapolation of data from gaged streams to ungaged streams, based on similarities in watershed characteristics, or statistical methods of varying sophistication. This project acquired streamflow data using all approaches depending on specific applications as discussed in this appendix and in the main body of the report. Generally, deterministic modeling generated longer-term records for surface water use intensity (SUI) calculations and scenario analysis.

## Deterministic Watershed Modeling

Analyses of SUI in Pennsylvania and Colorado required streamflow estimation at all permitted O&G water withdrawal sites within the Susquehanna River Basin (SRB). Additionally, streamflow was estimated at a large number of random locations within the focus study watersheds, including many very small subwatersheds. The watershed modeling approach used herein was designed for maximum repeatability— preference was given to commonly used and freely available technologies (Soil & Water Assessment Tool, or SWAT; and Hydrological Simulation Program—Fortran, or HSPF), while detailed, region-specific scenarios were avoided. While many of the same methodologies were implemented in both locations, pronounced regional differences in data availability dictated what methods could be used for extrapolating streamflow from gaged to ungaged locations in the individual study areas.

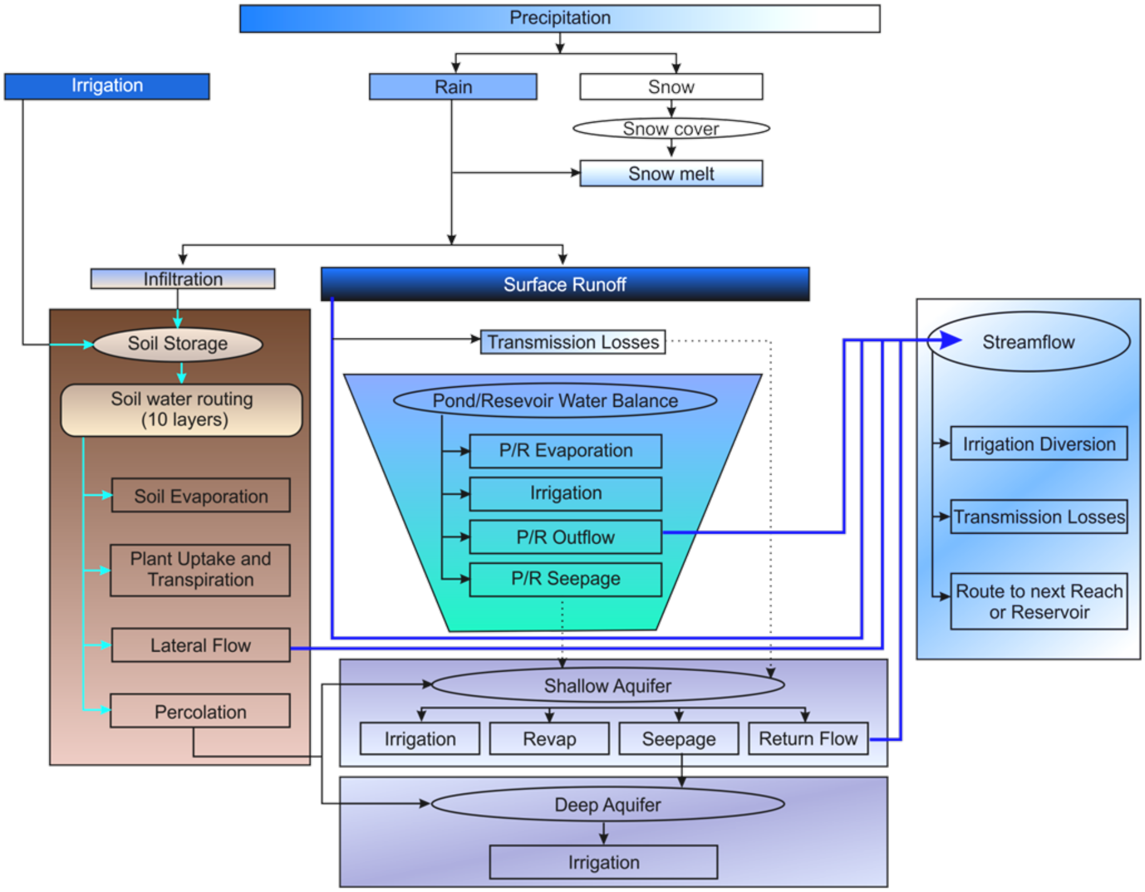


**Figure B-2. SWAT conceptual diagram (Reprinted with permission: Neitsch *et al.* 2011).**

**Table B-1. HSPF and SWAT input data requirements**

| Input | Format | HSPF | SWAT | Source* |
|---|---|---|---|---|
| Topography | spatial | DEM (30m) | DEM (30m) | National Elevation Dataset |
| Soils | spatial | - | STATSGO2 | Natural Resources Conservation Service |
| Land Use | spatial | NLCD (30m) | NLCD (30m) | Multi-Resolution Land Characteristics Consortium |
| Temperature | time series | max and min hourly | mean daily | NOAA National Climatic Data Center:<br>*USC00361212 (Canton PA), USC00368905 (Towanda PA), USC00050214 (Altenbern CO) ,USC00057031 (Rifle CO), USR0000CRIF (Rifle CO), USC00053359, (Glenwood Springs CO),Center:USS0007K02S (Burro Mountain CO), USC00055484 (Meeker CO), USS0007J05s (Ripple Creek CO)* |
| Precipitation | time series | hourly total | daily total | |

*see Appendix A for details on data sources

**SWAT** is a widely used, freely available, process-based, deterministic, semi-distributed watershed model, developed by Texas A&M University and the U. S. Department of Agriculture (Neitsch *et al.* 2011). Minimal model inputs include land use, topography, and soil coverages, along with daily mean temperature and total precipitation (Table B-1). Pre-processing of spatial data is most commonly performed using the ArcSWAT extension for ArcGIS (SWAT 2014). Details of specific pre-processing steps are presented in the following section. SWAT uses a semi-distributed approach to simulate water quantity and quality. Within each topographically defined subbasin, the following variables are lumped into discontiguous Hydrologic Response Units (HRUs): spatially explicit land use, topography, and soils data. Each HRU is composed of members sharing similar rainfall-runoff responses. These aggregation processes are user-guided, allowing some degree of control over the model's spatial resolution (Fig. B-2). SWAT is primarily an infiltration-excess flow model that separates precipitation into two components: that which infiltrates to shallow and deep subsurface storage, and that which occurs as overland flow. To partition runoff vs. non-runoff flow components, SWAT uses the SCS curve number II (Hawkins *et al.* 2009). SWAT has successfully been used to assess water quantity response to human watershed manipulation in many settings, across a range of watershed scales (Ahmad *et al.* 2012; Faramarzi *et al.* 2013; Gabriel *et al.* 2014; Price *et al.* 2014). SWAT's default operation uses a daily timestep.

**HSPF** is a widely used, freely available, process-based, deterministic, semi-distributed watershed model for streamflow and water quality simulation that is endorsed by the Federal Emergency Management Agency (Atkins *et al.* 2005; FEMA 2013; U.S. EPA 2013; Bicknell 1997). HSPF water balance processes distinguish between surface runoff, throughflow, and groundwater storage, which are determined by processes of infiltration, loss to deeper groundwater, and soil storage (Golden *et al.* 2014). The model inputs are digital representations of land use and topography, time series of meteorological data for simulation forcing, and observed streamflow time series for model calibration (Table B-1). HSPF is a "semi-distributed parameter" model, meaning there is limited spatial discretization of watershed processes (Johnson *et al.* 2003). It has been established as a reliable water quantity modeling tool for a wide range of settings and applications (Buchanan *et al.* 2013; He *et al.* 2013; Johnson *et al.* 2003; Kim and Chung 2014). Like SWAT, HSPF is primarily an infiltration-excess model that separates precipitation into infiltrated/non-infiltrated components, but HSPF uses the Philip method (Philip 1957) as opposed to curve number (Fig. B-3).The model works via three major modules: (1) PERLND, which simulates terrestrial processes on pervious land areas; (2) IMPLND, which simulates terrestrial processes on impervious surfaces; and (3) RCHRES, which simulates linkages between the stream network and terrestrial segments, and routes streamflow through water bodies (U.S. EPA 2013). This multi-module configuration is partitioned via area-weighting of watershed characteristics, but does not directly model watershed processes in a spatially explicit manner.

HSPF requires hourly maximum and minimum temperature and hourly precipitation totals, but this study used companion programs to disaggregate daily data to an hourly timestep. Preprocessing for HSPF is most commonly performed using BASINS, an open-source program that facilitates data acquisition and model setup for multiple models (U.S. EPA 2013). However, for the sake of consistency, this study used the processed spatial data from the SWAT preprocessing steps described herein to initialize HSPF.

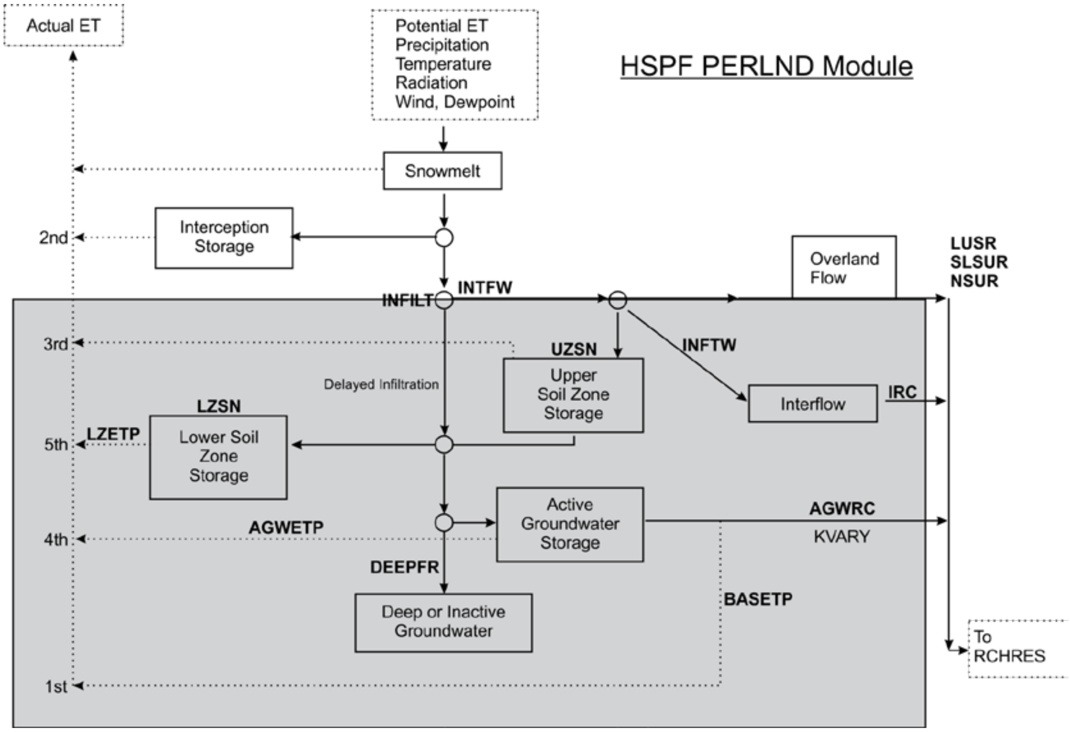


**Figure B-3. HSPF pervious surface conceptual diagram (Atkins *et al.* 2005)**

## Description of Modeling Steps

Of the seven steps detailed below, steps 1–4 were followed for setup and initialization of both SWAT and HSPF. After initializing both models, preliminary simulations and calibrations were performed using HSPF and SWAT, but detailed SUI analyses were ultimately performed using only HSPF due to significantly faster run times and slightly better simulation accuracy. All of the following steps (1–7) were followed for HSPF setup, calibration, and simulation, with details provided for each study area in subsequent sections of this appendix:

**1. Setup of Model Inputs:** Standard model inputs of topography, land cover, soils, meteorology, and observed streamflow were obtained for all study watersheds (Table B-1).

**2. Stream Network Definition and Subbasin Delineation:** All spatial preprocessing was performed using ArcSWAT, which provides a user-friendly environment for customized configuration of stream network and subbasin delineation. Equivalent tools are available for HSPF in BASINS (U.S. EPA 2013). Stream network definition is achieved by estimating a draining area threshold required for perennial streamflow, and subbasins are delineated upstream of every node in the stream network topology. Given the importance of low flows to these research objectives, establishment of a simulation stream network that closely approximated the actual perennial stream network was deemed essential. The National Hydrography Dataset (NHD) high-resolution network was used as a baseline, and any additional regionally available perennial streamflow data were incorporated. Stream networks were iteratively generated in ArcSWAT using a range of accumulation area thresholds, until a visual match between observed and generated networks was achieved. In ArcSWAT, subbasins are delineated upstream of every node in the stream network; changes to subbasin delineation alters the stream network and vice-versa, which is key for model operation of both HSPF and SWAT.

Of the seven steps detailed below, steps 1–4 were followed for setup and initialization of both SWAT and HSPF. After initializing both models, preliminary simulations and calibrations were performed using HSPF and SWAT, but detailed SUI analyses were ultimately performed using only HSPF due to drastically faster run times and slightly better simulation accuracy. All of the following steps (1–7) were followed for HSPF setup, calibration, and simulation, with details provided for each study area in subsequent sections of this appendix:

**3. Pour Point Designations**. SUI calculations were required across a wide range of watershed areas. Thus, subbasins were aggregated into a series of larger-order watersheds based on a Strahler ordering scheme performed on the ArcSWAT-delineated stream network. Most outlets of these aggregated streams were retained as simulation pour points ("pour point" is an ArcGIS term for the point of accumulated flow when delineating drainage basins using the Watershed tool, i.e., flow simulation locations at subbasin outlets). Subbasins were omitted as pour points if they (1) contained defined stream channel for less than 20% of basin length, (2) contained major ponds or impoundments proportional to watershed area, and (3) were tributary watersheds to other subbasins of the same order (i.e., did not flow directly into a subbasin of higher order).

**4. Sensitivity Analysis, Preliminary Calibration, and Watershed Model Selection.** Deterministic watershed models generally contain "free parameters," whose values can be mathematically optimized to best match observed streamflows. Automated parameter-fitting procedures are widely used to streamline the process of identifying the best combination of parameters. For example, streamflow simulation using SWAT allows for modification of 27 free parameters, whose values can be optimized to best match observed streamflows during a given period of record. Sensitivity analysis and preliminary calibration were performed in SWAT-CUP, a companion program to SWAT (Abbaspour 2009).

The drawback of automated procedures is that they may introduce physically unlikely parameter combinations among the multiple mathematical solutions that exist to optimize the parameter set. Such concerns are also known as equifinality and overfitting (Beven 2006; Matott et al. 2009). To minimize overfitting, we retained a small number of parameters for calibration: the most sensitive parameters, ranked by the amount of variability they explained, stopping once (1) 90% of total sensitivity was explained and (2) a minimum of six model parameters were included. These stopping rules represent a compromise between model parsimony and exploring the full calibration space among the models' available free parameters.

For HSPF, sensitivity was calculated with PEST, a model-independent parameter sensitivity and optimization program (Watermark Numerical Computing 2005). PEST uses a Jacobian matrix approach to sensitivity estimation, which is a vector calculus, partial-derivative determination approach. Sensitivity is quantified using the following equation:

$$s_i = \frac{(J^t QJ)_{ii}^{\frac{1}{2}}}{m} = \frac{\sqrt{\left(\frac{\partial M_1}{\partial x_i}\right)^2 + \left(\frac{\partial M_2}{\partial x_i}\right)^2 + \cdots + \left(\frac{\partial M_m}{\partial x_i}\right)^2}}{m}$$ **Equation B-1**

where, $s_i$ = composite sensitivity of $i$th parameter, $J$ = Jacobian matrix, $Q$ = diagonal matrix whose diagonal element is the square of the weight (all weight is unity in this case), $m$ = number of modeled value, $M_j$: $j$th modeled value, and $x_i$ = value of $i$th parameter.

For preliminary calibration and model selection, agreement was evaluated between simulated and observed streamflow using the standard Nash-Sutcliffe (Nash and Sutcliffe 1970) efficiency criterion (NS):

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$ **Equation B-2**

where *i* represents each timestep in the series, O = observed streamflow, and gages = simulated streamflow. While there are limits to implementation of NS, it is a widely used fit statistic and is available in both SWAT-CUP and PEST. For these preliminary analyses, a minimum of 500 Latin hypercube-derived parameter combinations were tested.

Simulations for the calibration period were more than 50 times longer with SWAT than HSPF (~45 minutes vs. < 1 minute per run), an impediment to using advanced calibration procedures, which require many thousands of runs for each watershed. The prohibitively long run times for calibrating SWAT using the Monte Carlo approach and somewhat greater simulation accuracy using HSPF (NS values of 0.75and 0.60 or HSPF and SWAT, respectively), lead the project to conclude that HSPF was the better alternative for deterministic modeling in this particular application (Price *et al.* in preparation).

**5. Calibration**. Next, the reduced parameter set was used for a rigorous calibration of HSPF to identify the optimized parameter set that best matched simulated and observed streamflow at the USGS-d outlets. The models were calibrated and validated using a standard split-sample approach (Andréassian *et al.* 2009), meaning that part of the observed record was reserved for independent model evaluation. From the total observed record of 1987–2012, the calibration period used was 1997–2012, while1987–1996 was withheld as a validation period.

While NS was well-suited toward preliminary model comparison, there were concerns about using NS for the model application itself, given its bias toward fitting flood peaks at the expense of low flows (Krause *et al.* 2005; Price *et al.* 2012). Taking the NS of log-transformed flow values ($NS_{\ln}$) is an established method of removing flood bias in model calibration. As it was desired to retain the influence of low flows, while not completely losing the water balance considerations associated with proper estimation of flood magnitudes, NS and $NS_{\ln}$ were combined to form a Weighted Nash Sutcliffe (WNS) fit criterion:

$$NS_{\ln} = 1 - \frac{\sum_{i=1}^{n}[\ln(O_i) - \ln(S_i)]^2}{\sum_{i=1}^{n}[\ln(O_i) - \ln(\bar{O})]^2}$$ **Equation B-3**

$$WNS = W_{NS} \cdot NS + (1 - W_{NS}) \cdot NS_{ln}$$ **Equation B-4**

where *i* represents each timestep in the series, O is the observed streamflow, gages is the simulated streamflow, and W is the weighting factor (determined *a posteriori* by minimizing the root-mean-square error, or RMSE, among weighting scenarios).

A Latin hypercube-derived Monte Carlo analysis (10,000 15-year simulations on a daily timestep) was used to identify the parameter sets associated with the highest WNS scores in each watershed. Additionally, calibrations were cross-validated by applying the parameterizations to simulate streamflow at a nearby USGS gaging station and evaluating model fit.

**6. Streamflow Simulation.** Once models were calibrated and parameter sets were established, streamflow was simulated across the full range of pour point drainage areas in each of the three study watersheds, Towanda Creek in the SRB and Parachute and Roan Creeks in the Upper Colorado River Basin (UCRB). The input parameters values of land use, vegetation and soils were tailored to each subbasin. Daily flows were simulated for the period spanning 1986-2012 because this water the period of available weather data. Simulations for 1986 were discarded as model spin-up, and 1987-2012 were retained for further analysis.

**7. Simulation Uncertainty.** Simulation uncertainty was characterized by identifying the range of flows and flow statistics in the subset of simulations that produced daily WNS of 0.3 or greater. Additionally, any simulations for which annual water yield (as mean streamflow) differed from observed by more than 15% were excluded.

# Pennsylvania: Susquehanna River and Towanda Creek

## Study Area Hydrometeorology

Bradford County and the Towanda Creek watershed lie entirely within Pleistocene glacial margins. This area is underlain by shales and sandstones, without significant occurrence of karst. Soils are primarily well-drained loamy inceptisols and entisols forming in glacial and alluvial parent material (Grubb 1986). Topographic relief in the Towanda Creek watershed is moderate, with elevations ranging from 770 feet above sea level (ASL) at the outlet, to 2436 feet ASL along the northwestern divide.

The climate of Bradford County is classified as "cold humid" (Df) in the revised Köppen-Geiger classification system (Kottek *et al.* 2006). Long-term (1981–2010) annual average precipitation is 35.7 inches in Towanda, PA (station ID = USC00368905; station elevation = 751 feet ASL), with the lowest monthly average (1.94 inches) occurring in February and highest monthly average (3.60 inches) occurring in July (Fig. B-4). Minimum and maximum monthly mean temperatures occur in January (24.8°F) and July (70.4°F), respectively (Arguez *et al.* 2012).

Towanda Creek above Monroeton, PA (USGS 01532000, 215 mi$^2$) consists of two watersheds and drains into the Susquehanna River in Towanda, PA. USGS-observed streamflow during the modeling and hydraulic fracturing activity periods demonstrate the absence of major snowpack/snowmelt cycles and general hydrological stationarity during the study period (Fig. B-5A). Lowest flows typically occur in late fall. Remnants of major Atlantic and Gulf storms occasionally affect the region during tropical storm season (NOAA Coastal Services Center 2014), but the influence of these is not frequent enough to substantially alter the low-flow season as a whole. Comparison of study-period streamflows with long-term records shows that the hydraulic fracturing analysis period includes one very wet year and one very dry year (Fig. B-5B).

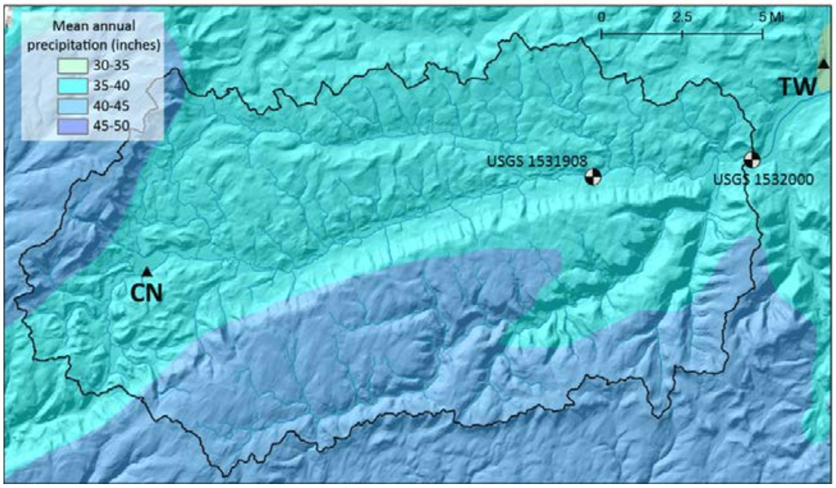


**Figure B-4. Towanda Creek watershed mean annual precipitation, 1981-2010 National Climatic Data Center gages are shown for reference as black triangles (CN = Canton; TW = Towanda 1 S). Precipitation interpolations shown were derived from PRISM data (PRISM Climate Group 2013)**

## Deterministic Watershed Modeling: Towanda Creek

Background and general explanations for each modeling step are provided in the Overview section above.

**1. Setup of Model Inputs.** Standard model inputs of land cover and topography were obtained for Towanda Creek (Table B-1). Two meteorology stations were available for model forcing data (Fig. B-6). One USGS streamflow gaging station was available for the entire calibration period (USGS 1532000, Towanda Creek at Monroeton, PA, 215 mi$^2$). A second site with a shorter period of record was available internal to the Monroeton (Fig. B-6).

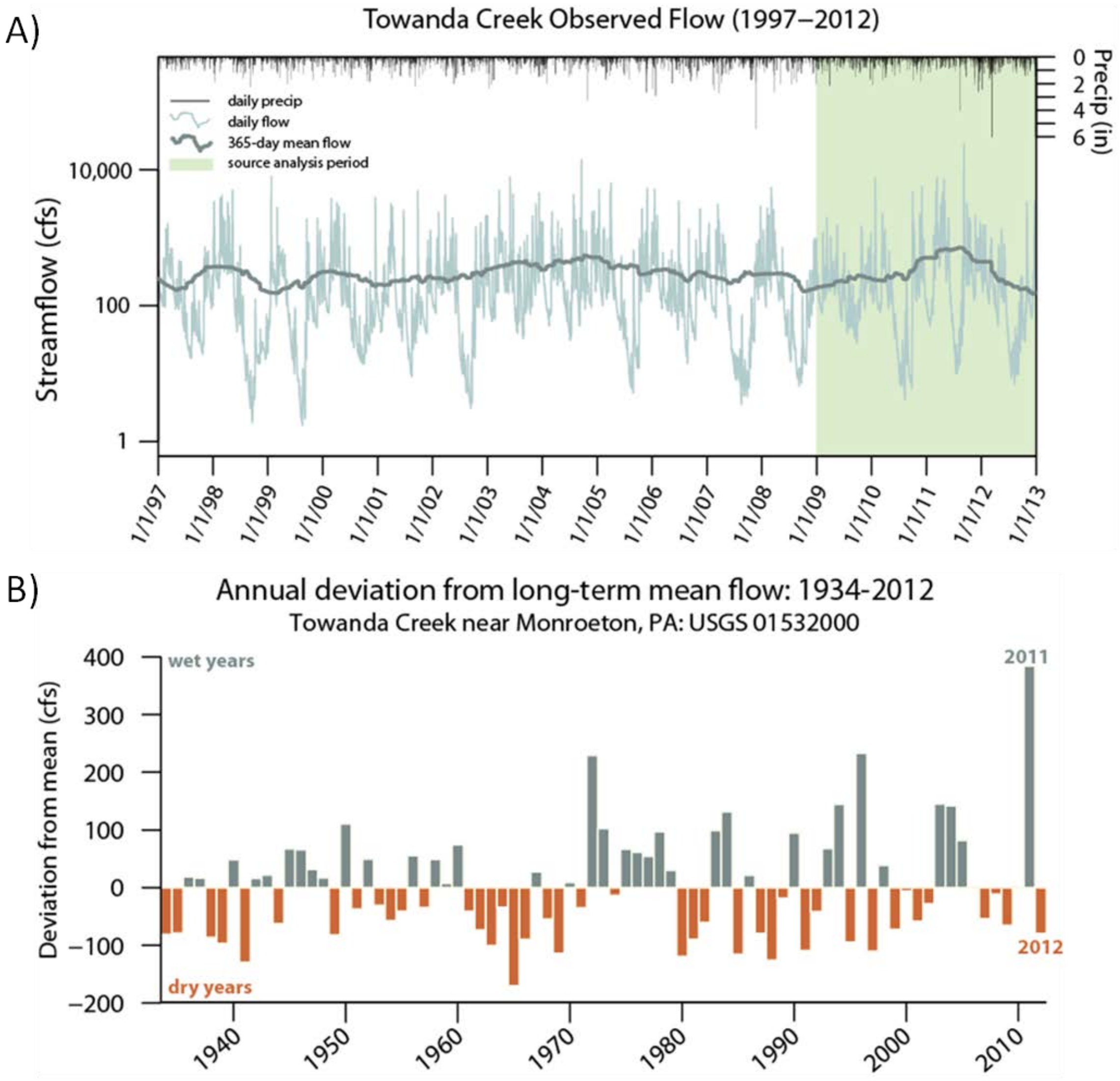


**Figure B-5. A) Towanda Creek observed streamflow: 1997-2012. Towanda Creek near Monroeton, USGS 01532000. The hydrograph and hyetograph show hydrologic conditions during the HSPF calibration period. The running 365-day mean streamflow is shown in dark blue on the hydrograph, and the detailed hydraulic fracturing activity period (2009-2012) is highlighted in green. These plots show that conditions were stationary over the calibration period, while including a range of wet and dry flows. B) Annual deviations from long-term conditions. Positive deviations indicate wet years, while negative deviations indicate dry years. Surface water use intensity (SUI) values are highest when flows are lowest.**

**2. Stream Network Definition and Subbasin Delineation.** The NHD high-resolution network was used as a baseline, with field data collection of stream network locations additionally incorporated. The headwaters extent of the perennial stream network was verified through field survey during the low-flow season (late fall) of 2013 after a period of no rain for more than one week. The timing of the field surveys provided an excellent snapshot of perennial flow conditions in the region (Fig. B-7A). Two lines of information were collected at various points, in association with GPS coordinates: (1) presence/absence of flowing water where the perennial stream network had been mapped

(39 points), and (2) the exact location of flow initiation in first-order streams (24 points). This information was then used to fine-tune the accumulation area threshold and stream network in ArcSWAT by iteratively generating stream networks using a range of accumulation area thresholds, until a visual match between observed and generated networks was achieved (Fig. B-7B). The accumulation area that best matched the NHD and observed perennial stream networks was 0.35 mi$^2$ in the Towanda Creek watershed, but resultant subbasin size ranged considerably. While accumulation area provides a baseline for stream network definition, topographic slope is also important in determining stream network locations. As a result, not all subbasins are equal in size. To achieve a consistency of subbasin areas, which helps ensure realistic hydrologic processes are dominating the streamflow modeling, anomalously small and large subbasins were grouped or split accordingly (Gabriel *et al.* 2014). Within the Towanda Creek watershed, all subbasins less than 0.19 mi$^2$ were merged into adjacent subbasins, and subbasins greater than 1.9 mi$^2$ were split to create multiple subbasins, ensuring that all modeled subbasin areas were within an order of magnitude.

**Figure B-6. Towanda Creek study area. Black triangles indicate National Climatic Data Center gages (CN = Canton; TW = Towanda 1 S). The stream network shown is the perennial stream network used in SWAT and HSPF modeling.**

**3. Pour Point Designations.** The aforementioned automated delineation processes resulted in 288 subbasins of Towanda Creek. These subbasins (each of which corresponds to an individual stream segment) were aggregated into watersheds based on a Strahler stream ordering scheme, delineating the entire contiguous area upstream of each subbasin outlet. Of the original 288 subbasins, 168 locations were retained as simulation pour points. Of these, 134 are first-order stream segments, 26 are second-order, and five are third-order pour points; both the North and South Forks of Towanda Creek are fourth-order pour points, and the main Towanda Creek pour point at Monroeton is a fifth-order stream. Simulated pour point drainage areas ranged from 0.35 to 215 mi$^2$ in Towanda Creek.

**4. Sensitivity Analysis.** The most sensitive parameters were retained based on rank of explained variability stopping once 90% of total sensitivity was explained. This resulted in eight calibration parameters for Towanda Creek (Table B-2).

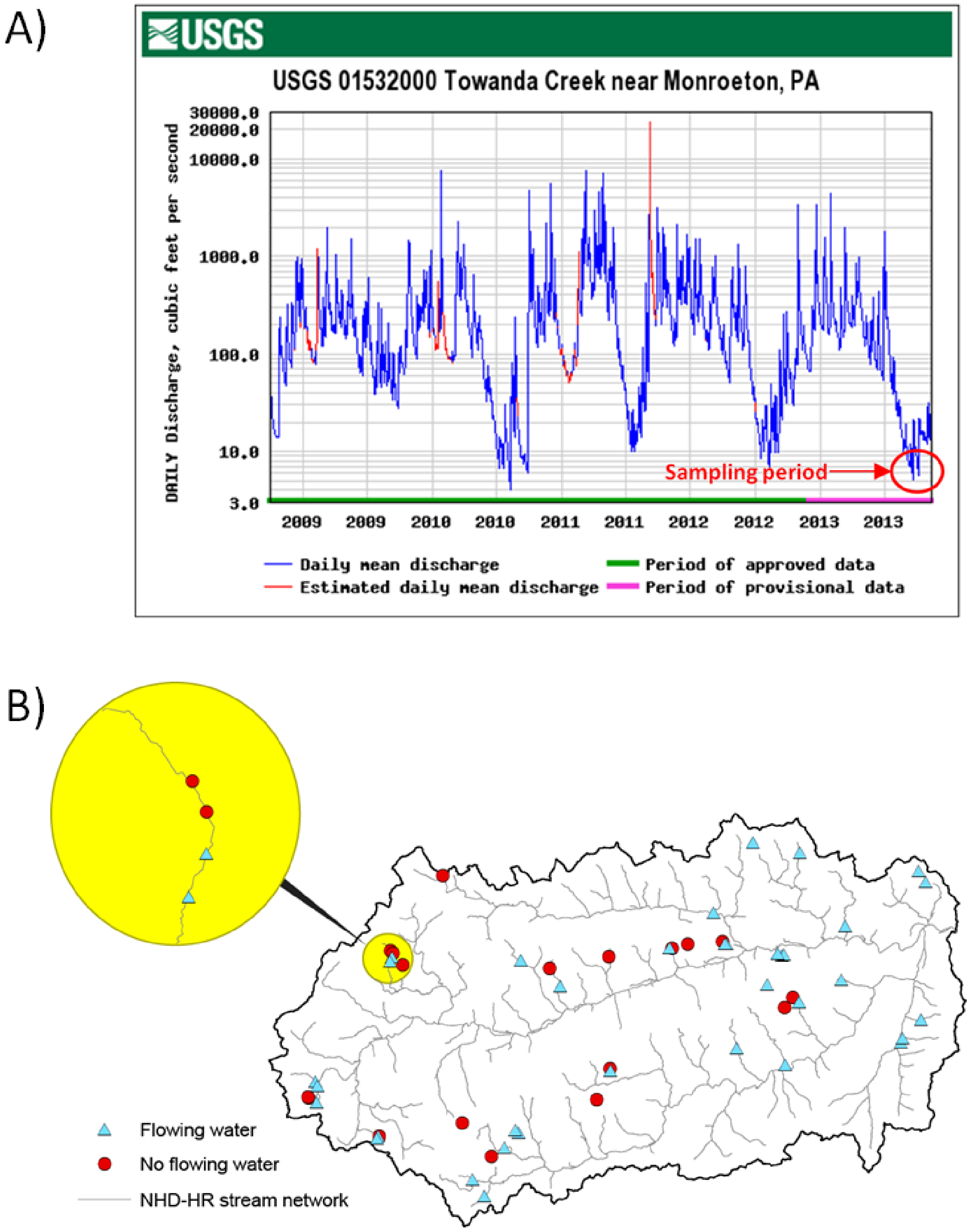


**Figure B-7. Ground-truthing of the perennial stream network by field survey. A) The sampling period was during baseflow-only, seasonal low-flow conditions. B) Sampled locations where flowing water (perennial flow) was observed (blue triangles) or not observed (red circles). The yellow-highlighted inset corresponds to water table elevations used in Appendix C.**

**Table B-2. Sensitive HSPF parameters for Towanda Creek. “Qualified values” refers to simulations with weighted Nash-Sutcliffe (WNS) fit criteria greater than 0.3 and annual water yields within 15% of observed. “Best set” indicates the parameter values associated with the highest WNS score.**

| | | | Qualified values | | | | |
|---|---|---|---|---|---|---|---|
| **Parameter** | **Definition*** | **Initial range** | **Min** | **Max** | **Mean** | **Std** | **Best set** |
| KMELT | Degree day factor | 0 – 10 | 0.003 | 9.997 | 4.9069 | 2.8845 | 0.314 |
| INFILT | Soil infiltration rate | 0.0001 – 2 | 0.0059 | 1.9986 | 0.7874 | 0.5606 | 0.0341 |
| AGWRC | Groundwater recession rate | 0.85 – 0.999 | 0.85 | 0.9989 | 0.9186 | 0.0416 | 0.9282 |
| DEEPFR | Groundwater fraction lost to deep storage | 0 – 1 | 0.0002 | 0.908 | 0.1668 | 0.1239 | 0.0428 |
| BASETP | Fraction of evapotranspiration from baseflow | 0 – 1 | 0.0001 | 0.9989 | 0.4999 | 0.2913 | 0.5041 |
| INTFW | Interflow inflow | 0 – 10 | 0.001 | 9.991 | 4.6989 | 2.8766 | 4.5555 |
| IRC | Interflow recession | 0.0001 – 0.999 | 0.0002 | 0.9989 | 0.4565 | 0.2799 | 0.7732 |
| LZETP | Lower zone evapotranspiration | 0 – 1.5 | 0.0005 | 1.5 | 0.6718 | 0.4329 | 1.0917 |

* Source: EPA Office of Water 2000

**5. Calibration**. HSPF was calibrated by identifying an optimized parameter set that best matched simulated and observed streamflow at the USGS-d Towanda Creek outlet. Overall, calibrations were reasonably successful, with optimized WNS values greater than 0.7. WNS scores will, by definition, be lower than either an optimized raw NS or NSln, because it is simultaneously optimizing two separate functions. The scores achieved in these calibrations exceed common performance thresholds set for raw NS (Narasimhan 2005; Moriasi et al. 2007). All calibration period, validation period, and cross-site validation WNS and R2 scores for Towanda Creek are presented in Table B-3, and optimized parameter values are shown in Table B-2.

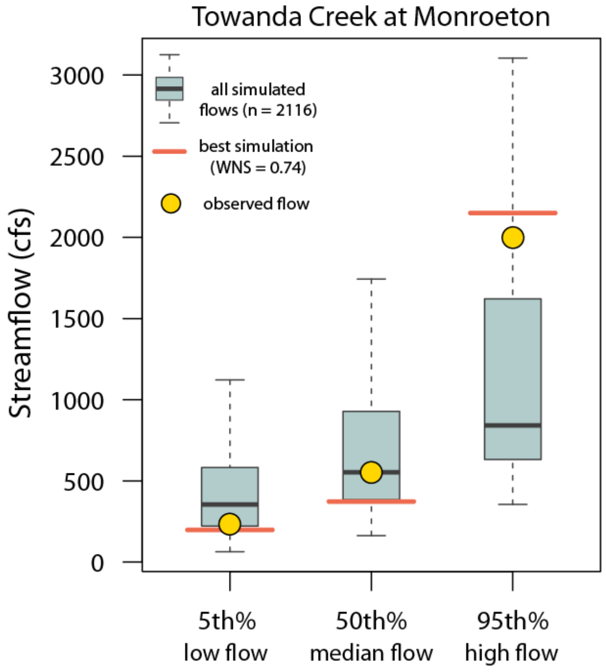


**Figure B-8. HSPF simulation uncertainty across flow magnitudes. Boxplots represent all successful HSPF simulations from the 10,000 run Monte Carlo analyses, with “successful” defined as weighted Nash-Sutcliffe (WNS) fit criterion greater than 0.3 and annual water yield within 15% of observed. The boxes themselves indicate the inner-quartile range, with whiskers extending to the 5th and 95th percentiles of the distributions. Boxes for Towanda Creek are based on 2,116 successful simulations. The three boxes represent three flow magnitudes calculated separately for each simulation. For example, the 5% box shows the distribution of the 5th percentile flow value, across all 2,116 simulations. The orange line and yellow circle indicate the value associated with the optimized parameter set and the observed value, respectively. These figures show that HSPF tended to overestimate low flows and underestimate high flows. However, the optimized parameter sets (the highest single WNS score within 15% of annual water yield) approximated observed flow magnitudes reasonably well.**

**Table B-3. Fit statistics for HSPF calibration, validation, and cross-site comparisons.**

| | | Calibration Period | Validation Period | Cross-site Comparison |
|---|---|---|---|---|
| Towanda Cr. | WNS | 0.74 | 0.57 | 0.86 |
| | $R^2$ | 0.75 | 0.54 | 0.82 |
| White R. | WNS/BE | 0.75 | 0.69* | 0.48*† |
| | $R^2$ | 0.75 | 0.60* | 0.99* |

*Without irrigation adjustment to observed flows

†Benchmark Efficiency (Eq B.7)

**6. Simulation Uncertainty.** Uncertainty was characterized by identifying the range of flows and flow statistics in the subset of simulations that produced daily WNS 0.3 or greater and annual water yields within 15% of observed flows. The boxplots in Fig. B-8 show streamflow magnitudes (at low, median, and high flow) calculated for each main stem Towanda Creek simulation meeting the criteria. The wide range of values for each magnitude indicates large uncertainty across the simulation set. In general, HSPF tended to overestimate low flows and underestimate high flows, but this calibration approach identified an optimized parameter set for each watershed that agrees well with observed flows across a range of magnitudes. The range of simulated flows across a 5th–95th % confidence interval (CI) are shown for a representative range of hydrometeorological conditions (2009–2010) in Fig. B-9.

**7. Streamflow Simulation**. Once calibrated parameter sets were established, streamflow was simulated across all 168 pour points in Towanda Creek. These flows were used as the water availability portion of the SUI calculations, results of which are presented in the main body of this report.

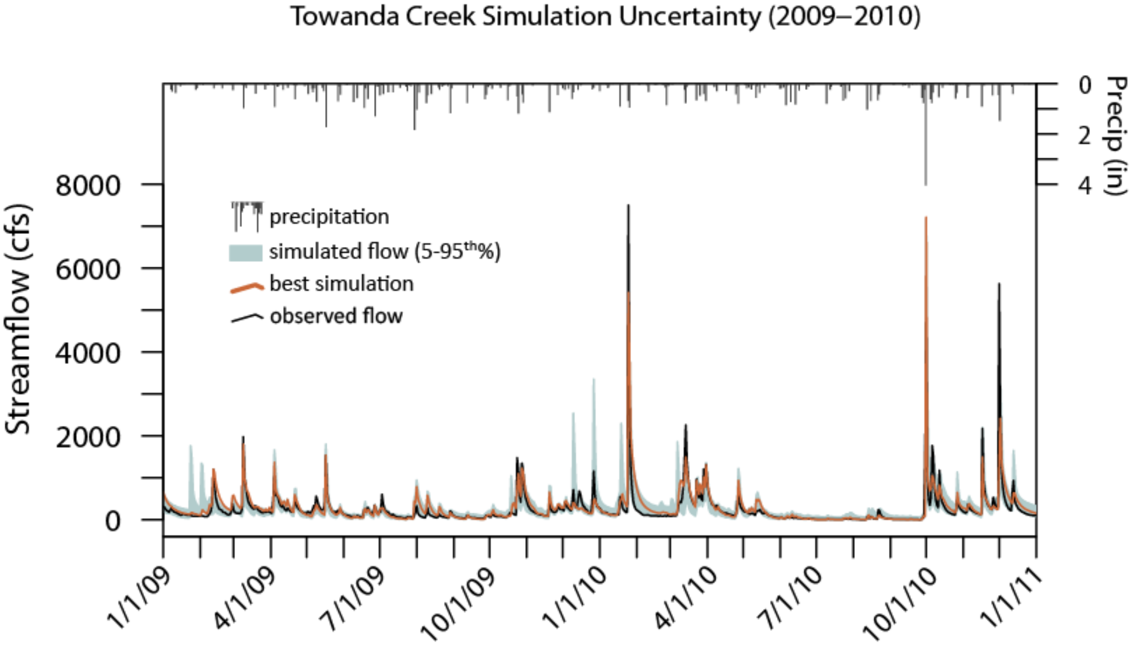


**Figure B-9. Example of HSPF simulation uncertainty: 2009-2010. These hydrographs are subset from our simulation period to illustrate the ranges of “successful” model runs, where successful is defined as weighted Nash-Sutcliffe fit criterion of 0.3 or greater, and annual water yield within ± 15% of observed. The blue band indicates the 5th–95th percentile range across all successful simulations, with the orange and black lines indicating the optimized and observed simulations. Flow was from USGS gage 01532000.**

**Table B-4. Part 1. U.S. Geological Survey streamflow gaging stations used in area-weighted extrapolation**

| USGS Station # | Location | Drainage area (mi$^2$) | Name | Period of Record |
|---|---|---|---|---|
| USGS04233300 | Lat 42°24'11", Long 76°26'07" | 39.0 | Sixmile Creek at Bethel Grove NY | March 1995 to current year |
| USGS01521500 | Lat 42°23'45", Long 77°42'42" | 30.6 | Canisteo River at Arkport NY | January 1937 to current year |
| USGS01529950 | Lat 42°08'47", Long 77°03'28" | 2006.0 | Chemung River at Corning NY | 1941, 1968-69. October 1974 to current year |
| USGS01531000 | Lat 42°00'08", Long 76°38'06" | 2506.0 | Chemung River at Chemung NY | September 1903 to current year |
| USGS01518700 | Lat 41`57'09", Long 77`06'56" | 446.0 | Tioga River at Tioga Junction PA | July 1976 to current year |
| USGS01516350 | Lat 41`47'49", Long 77`04'50" | 153.0 | Tioga River near Mansfield PA | July 1976 to current year |
| USGS01503000 | Lat 42°02'07", Long 75°48'12 | 2232.0 | Susquehanna River at Conklin NY | November 1912 to current year |
| USGS01515000 | Lat 41°59'05", Long 76°30'05" | 4773.0 | Susquehanna River Near Waverly NY | February 1937 to March 1995, April 1995 to September 2000 |
| USGS01531500 | Lat 41`45'55", Long 76`26'28" | 7797.0 | Susquehanna River at Towanda PA | October 1913 to current year |
| USGS01534500 | Lat 4l`30'16", Long 75`32'33" | 108.0 | Lackawanna River at Archbald PA | October 1939 to current year |
| USGS01534300 | Lat 41`40'47", Long 75`28'20" | 38.8 | Lackawanna River near Forest City PA | October 1958 to current year |
| USGS01538000 | Lat 41`03'33", Long 76`05'38" | 43.8 | Wapwallopen Creek near Wapwallopen PA | October 1919 to current year |
| USGS01533400 | Lat 4l`36'26", Long 76`03'02" | 8720.0 | Susquehanna River at Meshoppen, PA | October 1976 to current year |
| USGS01544500 | Lat 41`28'33", Long 77`49'34" | 136.0 | Kettle Creek at Cross Fork PA | October 1940 to current year |
| USGS01550000 | Lat 41`25'06", Long 77`01'59" | 173.0 | Lycoming Creek near Trout Run PA | December 1913 to current year |
| USGS01547950 | Lat 41`06'42", Long 77`42'09" | 152.0 | Beech Creek at Monument PA | October 1968 to current year |
| USGS01544000 | Lat 41`24'06", Long 78`01'28" | 245.0 | First Fork Sinnemahoning Cr near Sinnemahoning PA | October 1953 to current year |
| USGS01447720 | Lat 41`05'05", Long 75`36'21" | 118.0 | Tobyhanna Creek near Blakeslee PA | October 1961 to current year |
| USGS01549500 | Lat 41`28'25", Long 77`13'52" | 37.7 | Blockhouse Creek near English Center PA | October 1940 to current year |
| USGS01553700 | Lat 41`03'42", Long 76`40'50" | 51.3 | Chillisquaque Creek at Washingtonville PA | May 1979 to current year |
| USGS01546500 | Lat 40`53'23", Long 77`47'40" | 87.2 | Spring Creek near Axemann PA | October 1940 to current year |
| USGS01541303 | Lat 41`00'16", Long 78`27'25" | 474.0 | West Branch Susquehanna River at Hyde PA | October 1978 to current year |
| USGS01542500 | Lat 41`07'03", Long 78`06'33" | 1462.0 | WB Susquehanna River at Karthaus PA | October 1995 to present. February 1940 to September 1995 |
| USGS01547200 | Lat 40`56'35", Long 77`47'12" | 265.0 | Bald Eagle Creek bl Spring Creek at Milesburg PA | October 1955 to current year |
| USGS01541500 | Lat 40`58'18", Long 78`24'22" | 371.0 | Clearfield Creek at Dimeling PA | October 1913 to current year |
| USGS01440485 | Lat 41`05'38", Long 75`19'21" | 6.6 | Swiftwater Creek at Swiftwater PA | September 21, 1994 to April 18, 2001 (measurements only); April 2001 to current year |
| USGS01443900 | Lat 40°58'50", Long 75°02'21" | 5.3 | Yards Creek near Blairstown NJ | October 1966 to current year |
| USGS01510000 | Lat 42°32'28", Long 75°54'00" | 147.0 | Otselic River at Cincinnatus NY | June 1938 to September 1964, October 1969 to current year |
| USGS01540500 | Lat 40`57'29", Long 76`37'10" | 11220.0 | Susquehanna River at Danville PA | March 1899 to current year |
| USGS01545500 | Lat 41`l9'28", Long 77`45'03" | 2975.0 | West Branch Susquehanna River at Renovo PA | October 1907 to current year |
| USGS01520000 | Lat 41`59'48", Long 77`08'25" | 298.0 | Cowanesque River near Lawrenceville PA | June 1951 to current year |
| USGS01500000 | Lat 42°20'00", Long 75°14'07" | 103.0 | Ouleout Creek at East Sidney NY | August 1940 to current year |
| USGS01531908 | Lat 41`41'52", Long 76`34'43" | 112.0 | Towanda Creek near Franklindale, PA | July 2010 to current year |
| USGS01555000 | Lat 40`52'00", Long 77`02'55" | 301.0 | Penns Creek at Penns Creek PA | October 1929 to current year |

**Table B-4. (continued). U.S. Geological Survey streamflow gaging stations used in area-weighted extrapolation**

| USGS Station # | Location | Drainage area (mi$^2$) | Name | Period of Record |
|---|---|---|---|---|
| USGS01541200 | Lat 40°57'41", Long 78°31'10" | 367.0 | Wb Susquehanna River Near Curwensville PA | October 1955 to current year |
| USGS01549700 | Lat 41°16'25", Long 77°19'28" | 944.0 | Pine Creek Bl L Pine Creek Near Waterville PA | October 1957 to current year |
| USGS01552500 | Lat 41°21'25", Long 76°32'06" | 23.8 | Muncy Creek Near Sonestown PA | October 1940 to current year |
| USGS01516500 | Lat 41°47'27", Long 77°00'54" | 12.2 | Corey Creek Near Mainesburg PA | May 1954 to current year |
| USGS01525981 | Lat 42°04'20", Long 77°17'56" | 102.0 | Tuscarora Creek Above South Addison NY | Annual maximum only--October 1989 to September 2000; October 2000 to current year |
| USGS01429500 | Lat 41°36'26", Long 75°16'03" | 64.6 | Dyberry Creek Near Honesdale PA | October 1943 to current year |
| USGS01432900 | Lat 41°40'05", Long 74°46'50" | 76.6 | Mongaup River At Mongaup Valley NY | Occasional low-flow and/or miscellaneous discharge measurements, water years 1949, 1957-61, 1965, 1970, 1973-74. October 2002 to current year |
| USGS01551500 | Lat 41°14'10", Long 76°59'49" | 5682.0 | Wb Susquehanna River At Williamsport PA | March 1895 to current year |
| USGS01518862 | Lat 41°55'23", Long 77°31'56" | 90.6 | Cowanesque River At Westfield PA | August 1983 to current year |
| USGS01531325 | Lat 41°45'38", Long 76°40'30" | 93.6 | Sugar Creek At West Burlington PA | July 2010 to current year |
| USGS01532000 | Lat 41°42'25", Long 76°29'06" | 215.0 | Towanda Creek Near Monroeton PA | February 1914 to current year |
| USGS01428750 | Lat 41°40'28", Long 75°22'35" | 40.6 | West Branch Lackawaxen River Near Aldenville PA | Occasional discharge measurements and annual maximums, water years 1975-86. October 1986 to current year. Published as station number 01427950, 1975-88 |
| USGS01542810 | Lat 41°34'44", Long 78°17'34" | 5.2 | Waldy Run Near Emporium PA | Occasional discharge measurements and annual maximum, water years 1963-64. September 1964 to current year |
| USGS01541000 | Lat 40°53'49", Long 78°40'38" | 315.0 | West Branch Susquehanna River At Bower PA | October 1913 to current year |
| USGS01531250 | Lat 41°50'25", Long 76°49'38" | 8.8 | Nb Sugar Creek Trib Near Columbia Cross Roads PA | September 1962 to September 1968; October 1968 to March 1981(partial record); May 13, 2010 to current year |
| USGS01534000 | Lat 41°33'30", Long 75°53'42" | 383.0 | Tunkhannock Creek Near Tunkhannock PA | February 1914 to current year. Prior to October 1965, published as "at Dixon" |
| USGS01572950 | Lat 40°26'20", Long 76°35'55" | 5.5 | Indiantown Run Near Harper Tavern PA | August 2002 to current year |
| USGS01548500 | Lat 41°31'18", Long 77°26'52" | 604.0 | Pine Creek At Cedar Run PA | July 1918 to current year. Prior to October 1918 monthly discharge only, published in WSP 1302 |
| USGS01543500 | Lat 41°19'02", Long 78°06'12" | 685.0 | Sinnemahoning Creek At Sinnemahoning PA | July 1938 to current year. Prior to October 1938 monthly discharge only, published in WSP 1302 |
| USGS01415000 | Lat 42°07'12", Long 74°49'07" | 33.2 | Tremper Kill Near Andes NY | February 1937 to current year. Published as "near Shavertown" 1937-67 |
| USGS01557500 | Lat 40°41'01", Long 78°14'02" | 44.1 | Bald Eagle Creek At Tyrone PA | October 1944 to current year. Prior to October 1967, published as South Bald Eagle Creek at Tyrone |
| USGS0142400103 | Lat 42°10'25", Long 75°16'46" | 20.2 | Trout Creek Near Trout Creek NY | June 1952 to June 1967, annual maximum only--1996, maximum only--November 1996, December 1996 to current year. Prior to November 1996, published as Trout Creek near Rockroyal (01424000). |

## Empirical Streamflow Estimation: Susquehanna River Basin

**Area-Weighted Extrapolation of Regional Data.** SUI was calculated at the locations of permitted O&G water withdrawal sites, none of which is co-located with a USGS gaging station. However, there were an ample number of regional USGS gages elsewhere in the SRB that could be used for empirically-based data extrapolation at known withdrawal sites. Following standard USGS methods (Ries 2007), availability was estimated at 95 permitted sites using an area-weighting factor based on 56 nearby gages of similar size. Und withdrawal sites were subjectively paired with gaged sites based on nearness and similarity of basin area. Regional gages included are presented in Table B-4.

Watershed areas above withdrawal points ranged from 1.8 – 10,547 mi$^2$, corresponding to USGS gaged watershed areas of 5.2 – 11,220 mi$^2$. This area-weighting method was cross-validated using five pairs of USGS gages. In each pair, flow was estimated for one based on observed flow from the other, replicating the method used for each permit site/ pair. These extrapolations were then compared with the actual flow measured at the cross-validation using five pairs of USGS gages. In each pair, flow was estimated for one gage based on observed flow from the other gage, replicating the method used for each permit site/gage pair. These extrapolations were then compared with the actual flow measured at the cross-validation gage. In most cases, results were excellent, with NS and NS$_{\ln}$ values as high as 0.96 and 0.98, respectively (Table B-5). From these results, it can be concluded that the estimated streamflows applied at ungaged sites using this area-weighting method are indeed representative of actual streamflows.

| Pair | Gage ID | Area (mi$^2$) | Distance (mi) | NS | NS$_{\ln}$ |
|---|---|---|---|---|---|
| 1 | USGS 01541500 | 371 | 3 | 0.83 | 0.91 |
| | USGS 01541303 | 474 | | | |
| 2 | USGS 01532000 | 215 | 4 | 0.96 | 0.95 |
| | USGS 01531908 | 112 | | | |
| 3 | USGS 01541000 | 315 | 9 | 0.76 | 0.97 |
| | USGS 01541200 | 367 | | | |
| 4 | USGS 01553700 | 51 | 22 | 0.76 | 0.7 |
| | USGS 01552500 | 24 | | | |
| 5 | USGS 01503000 | 2232 | 36 | 0.96 | 0.98 |
| | USGS 01515000 | 4773 | | | |

**Table B-5. Cross-validation of area-weighting method. Each pair represents two gaged watersheds on which the area-weighting method was tested. Flow for the second member of each pair was estimated by extrapolating values from the first member of the pair, with the NS and NS$_{\ln}$ scores indicating the fit between this estimation and the actual observed flows. "Distance" is the straight-line distance between the two gaging stations.**

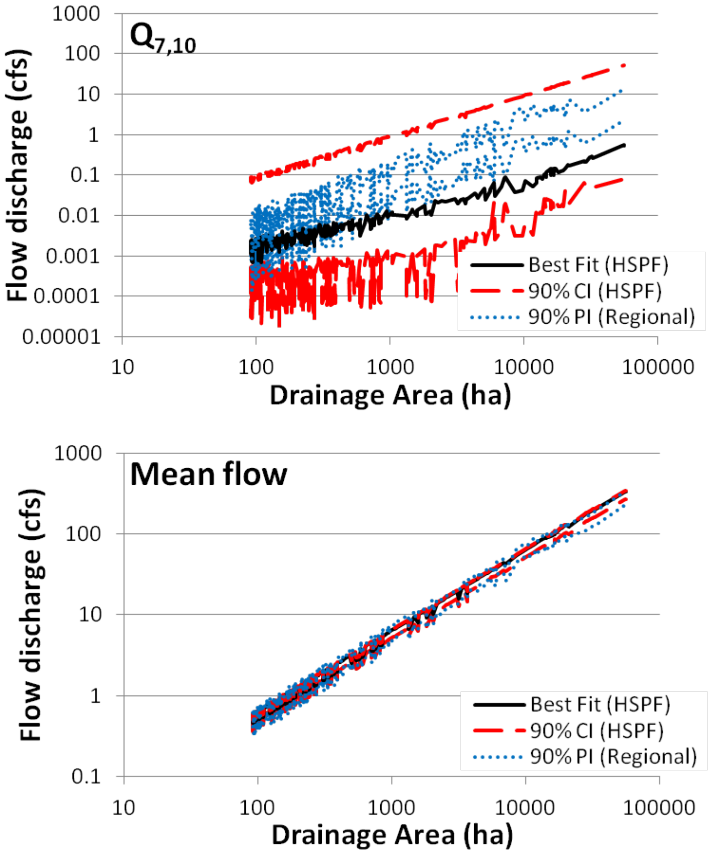


**Figure B-10. Relationship between extreme low flow (Q$_{7,10}$, and mean flow with drainage area, produced by empirical modeling (regional equations) and mechanistic modeling (HSPF) approaches. The 90% confidence interval is shown for both methods. The black line represents the single best HSPF simulation, based on optimized weighted Nash-Sutcliffe fit criterion and annual water balance.**

**Regional Equations.** Multiple regression equations are frequently developed from gaged stream locations to estimate streamflow in und locations, based on watershed geologic, topographic, and land use characteristics. Many managers can more easily access regional equations than estimates derived from deterministic models, given the time, expertise, and computational resources necessary for rigorous calibration and simulation. These equations are not used to generate continuous time series, as is the case with deterministic modeling and area-weighted extrapolation methods, but are instead used to estimate key flow magnitudes, such as extreme low flows and median flows.

Regional equations were previously developed for low and median flows in five regions of Pennsylvania by USGS and the Pennsylvania Department of Environmental Protection (Stuckey 2006). Multivariate predictive equations were developed for various metrics of flow magnitude, linking watershed characteristics to each flow magnitude based on observed data from 293 regional streamflow gages.

Agreement was evaluated between flow statistics derived from these regional equations and the deterministic modeling for ungaged subwatersheds of the Susquehanna River. This served two objectives: 1) to confirm that the deterministic models were reasonably representative of low flow magnitudes, given their importance in this impact assessment, and 2) to determine whether regional regression techniques could be used for such impact assessments, independent of deterministic modeling. Both methods suffer from lack of measured streamflow in very small streams.

Stuckey's (2006) regression analysis showed that the most important watershed characteristics for predicting low and mean flow statistics in this part of the Susquehanna River System are:

- Drainage area (DA, $mi^2$)
- Mean annual precipitation (Ppt, inches)
- Percent watershed area that was glaciated (Gla, %)
- Percent watershed area in forest cover (F, %)
- Mean elevation (El, ft.)
- Percent watershed area in urban land use (U, %)

The importance of drainage area in these equations for determining streamflow is a key theme of the SUI analyses presented throughout this report. From the six low-flow metrics evaluated in Stuckey's (2006) regional regression analysis, two commonly used indices were calculated: mean annual flow ($Q_m$) and the $Q_{7,10}$ for exploration in this analysis. Mean annual flow is simply the mean instantaneous streamflow (in cubic feet per second, cfs) occurring at each analysis point. $Q_{7,10}$ is the lowest seven-day average flow that occurs on average once every 10 years, and is a common benchmark of a very low flow metric in watershed management (Mitchell *et al.* 2013).

The variables in these equations were calculated from readily available data sources. Drainage area (*DA* $mi^2$) and mean elevation (*El*, ft) were determined via digital elevation model (DEM) analysis, forest (*F,* %) and urban (*U,* %) land cover percentages were derived from the National Land Cover Database (NLCD), and mean annual precipitation (*Ppt*, inches) was obtained from regional gages (location of digital data sources is further listed in Appendix A). Percent of watershed glaciation (*Gla*, %) is an important variable for statewide Pennsylvania predictive equations, because the Pleistocene ice margin transects the state.

$$Q_m = 10^{-3.2363} DA^{1.0081} El^{0.1283} Ppt^{1.7949} (1 + 0.01F)^{0.4136} (1 + 0.01U)^{0.4130} \quad \textbf{Equation B-5}$$

$$Q7{,}10 = 10^{-12.22164} DA^{1.27803} Ppt^{5.43165} (1 + 0.01Gla)^{1.83875} (1 + 0.01F)^{4.15769} \quad \textbf{Equation B-6}$$

However, the entirety of the Middle and Upper Susquehanna River Basins were entirely glaciated during the Pleistocene (Engel *et al.* 1996), and a value of 100% was used for the glaciation variable in all cases.

**Comparison of Empirical and Deterministic Methods.** Statistical relationships between drainage area and flow magnitude were established for $Q_m$ and $Q_{7,10}$, using 1) the 2116 HSPF Monte Carlo simulations meeting the pre-established fit criteria, at all 168 pour points (described above in "Deterministic Watershed Modeling"), and 2) the regional regression equations shown previously at each of the permitted sites (Stuckey 2006). Results showed that the statistics estimated within the 90% CI by the regional equations agreed reasonably well with the 90% CI of the HSPF simulations (Fig. B-10). The best-fit HSPF $Q_{7,10}$ estimates agree well with the regional equation-derived estimates, particularly in smaller watersheds, which were the focus of much of this analysis. HSPF tends to estimate lower $Q_{7,10}$ flow than the regional equations, particularly in larger watersheds. Mean flows across a wide range of drainage areas were all very close using these two methods.

## Colorado: Parachute and Roan Creeks

### Study Area Hydrometeorology

Within the Parachute and Roan watersheds (198 and 509 $\text{mi}^2$), surface bedrock is sandstone and shale, with no Quaternary glacial influence. These watersheds show high relief and pronounced dissection, with elevations ranging from 4890 feet ASL at the confluence of Roan Creek and the Colorado River, to 9299 feet ASL along Parachute Creek's eastern divide. Soils are primarily loamy, well-drained aridisols and mollisols forming in colluvium, loess, and rock outcrop, with some poorly-drained entisols occurring in alluvial valleys (Harman and Murray 1985).

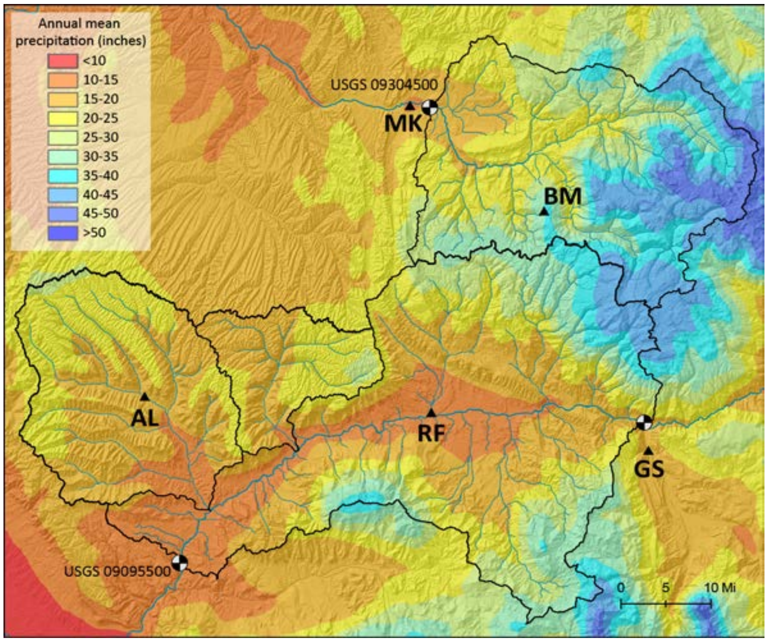


**Figure B-11. Upper Colorado River Basin annual mean precipitation, 1981–2010. National Climatic Data Center gages are shown for reference as black triangles (AL = Altenbern Ranch; BM = Burro Mountain; GS = Glenwood Spgs #2; MK = Meeker; RF = Rifle), but precipitation interpolations shown were derived from PRISM data (PRISM Climate Group 2013).**

Thirty-year annual average precipitation in Altenbern, CO (station ID = USC00050214 located in the Roan Creek watershed; station elevation = 6800 feet ASL) is 17.9 inches (Fig. B-11). The lowest mean monthly precipitation occurs in June (0.98 inches), while the highest occurs in October (2.00 inches). Snowpack typically develops at higher elevations (BLM 2006). Minimum and maximum monthly mean temperatures occur in January (24.4°F) and July (69.7°F), respectively (Arguez *et al.* 2012). Garfield, Mesa, and Rio Blanco Counties are all classified as 'arid steppe' (Bs) (Kottek *et al.* 2006).

The stationarity of hydrological conditions during the study period is demonstrated by the nearby USGS on the Colorado River near Cameo (Fig. B-12A). The second highest annual average flow occurred in 2011 and the third lowest occurred in 2012. Due to significant snowpack development along the Rocky Mountain crest in the eastern part of the UCRB, there is dominant snowpack/snowmelt cycle evident in the mainstem Colorado River. A persistent but thinner snowpack develops on top of the Roan Plateau that forms the headwaters the Parachute and Roan watersheds.

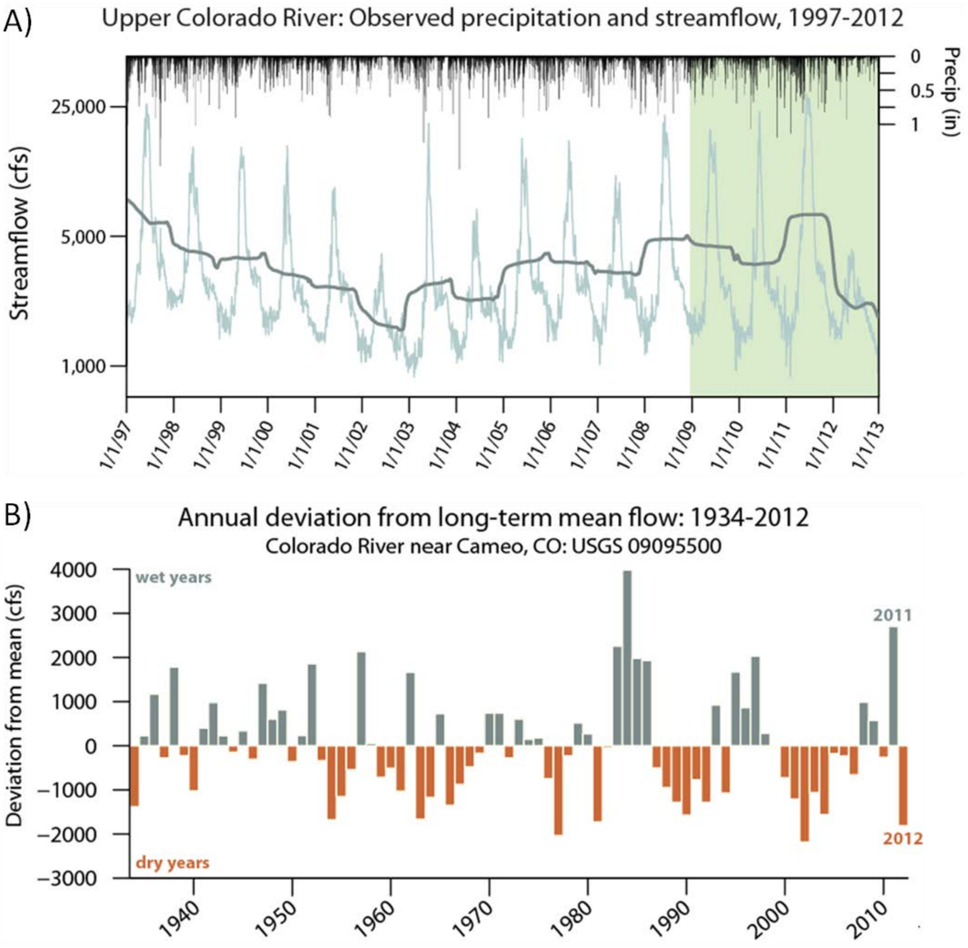


**Figure B-12. A) Upper Colorado River observed streamflow: 1997–2012. Colorado River near Cameo, USGS 09095500 (7,986 mi$^2$). The hydrograph and hyetographs show hydrologic conditions during our calibration period. The running 365-day mean streamflow is shown in dark blue on each hydrograph, and our "hydraulic fracturing activity period" (2009–2012) is highlighted in green. These plots show that conditions were stationary over the calibration period, while including a range of wet and dry flows. B) Annual deviations from long-term hydrological conditions. Positive deviations indicate wet years, while negative deviations indicate dry years. The length of the bar corresponds to the magnitude of the difference. Surface water use intensity (SUI) values are highest when flows are lowest. This figure shows that while 2012 was a statistically dry year, the high SUI values observed are likely to recur with regularity, as similarly dry years have occurred repeatedly throughout the long-term record.**

## Deterministic Watershed Modeling: Upper White River, Parachute Creek, and Roan Creek

There are no long-term gaging records available for Parachute and Roan Creeks but there was episodic gaging of Parachute Creek by the USGS for a total of 23 years within a 60-year period from 1921 to 1982, with records available monthly. Observed streamflow records were insufficient for calibrating the hydrologic model but could be used for evaluating the simulated streamflow. While there are several gages on the main stem UCR in the vicinity of Parachute and Roan Creeks, they were not considered appropriate for calibration. The large size of the UCRB at this point, and its flow dependency on remote alpine regions with far greater precipitation as well as flow regulation structures made them not ideal for calibrating HSPF in the tributaries. Other smaller watershed USGS sites were available but the measurement period was too short to be useful. The USGS gage on the White River at Meeker, CO (09304500) (760 mi$^2$) was deemed the better choice for calibration among the few available gages in this area that had a sufficiently long record of flow (Figure B-13). The calibration gage is 30 miles from the study area and White River tributaries border the study watersheds. The contributing watershed area is similar to Roan and Parachute Creeks. Geomorphology and climate in the lower White River is reasonably similar to the study area, although the White River heads in the mountainous alpine climate. Calibrated streamflow was cross-validated using gages on the mainstem UCR and to the observed flow in Parachute Creek.

There were additional challenges for creating the streamflow record. The hydrologic system of the UCRB is intensively managed, and there are hundreds of diversion structures used for water withdrawal for municipal, industrial, and agricultural purposes. Importantly, streamflow at gaged sites is affected by diversion of significant volumes of flow for irrigation during the period April to November. The project required a "natural" streamflow record with the effects of irrigation diversions removed for calculation of SUI. Flows were adjusted for irrigation after calibration at the White River gage. Finally, the streamflow was checked against the observed discontinuous flow record from Parachute Creek as an additional validation step. The details of calibration and flow adjustment steps are presented in the following sections

Preliminary calibration and simulations were again performed with both HSPF and SWAT, with HSPF chosen for detailed analyses based on shorter runtimes and greater simulation accuracy.

**1. Setup of Model Inputs.** Standard model inputs of land cover and topography were obtained for the area covered by the upper White River watershed and the portion of the UCR between Glenwood Springs and Cameo (Fig. B-13). Calibration was performed on the White River, which had three available meteorology stations, and one USGS streamflow gaging station located near Meeker, CO (USGS 09304500, elevation 6,300 feet ASL, 760 mi$^2$).

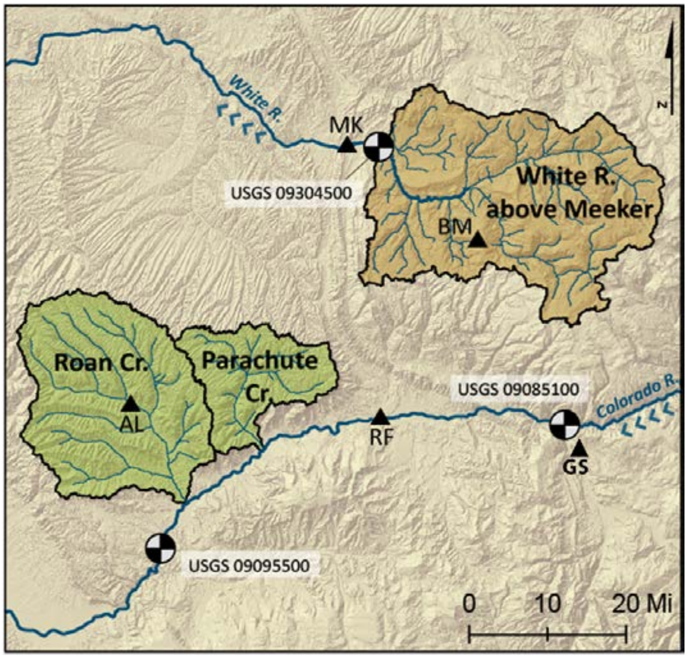


**Figure B-13. White and Colorado Rivers, Colorado. NCDC gages are shown as black triangles (AL = Altenbern Ranch; BM = Burro Mountain; GS = Glenwood Spgs #2; MK = Meeker; RF = Rifle). HSPF calibration was performed on the White River above Meeker and cross-site valid validation was performed between the two USGS gages shown on the UCR. Our focus study areas are the Parachute and Roan Creek watersheds within the UCRB.**

**2. Stream Network Definition and Subbasin Delineation.** The NHD high-resolution network was used as a baseline, incorporating field observations and perennial flow data from CODWR. Winter road conditions prevented detailed field mapping of the stream network, but six observations of presence versus absence of flowing water were collected at locations where mapped perennial stream networks disagreed. All available information was then used to fine-tune the accumulation area threshold and stream network in ArcSWAT. Networks were iteratively generated using a range of accumulation area thresholds, until a visual match between observed and generated networks was achieved. The accumulation area that best matched the NHD and observed perennial stream networks was 3.9 mi$^2$ in the White River watershed, but again, resultant subbasin size ranged considerably. To achieve a consistency of subbasin areas, anomalously small and large subbasins were grouped or split accordingly (Gabriel *et al.* 2014). These delineation processes were originally performed on the upper White River for model calibration, and were replicated for the UCR between Glenwood Springs and Cameo, including Parachute and Roan Creeks.

**3. Pour Point Designations.** Model calibration in the upper White River and cross-validation in the UCRB were based solely on simulated and observed flows at the gaged watershed outlets, meaning no additional pour point designation steps were required. However, it was desirable to establish a wide range of watershed areas for SUI calculation in the focus study areas of Parachute and Roan Creeks, similar to what was achieved in Towanda Creek. The original delineation resulted in 80 subbasins of the Parachute and Roan watersheds, which were aggregated to sequentially larger-order watersheds. Subbasins were then eliminated following the criteria detailed previously (see "Description of Modeling Steps"), with 48 simulation pour points retained. Of these 48, there were 35 first-order pour points, nine second-order, three third-order (including the outlet of Parachute Creek), and one fourth-order pour point at the outlet of Roan Creek. Simulated pour point drainage areas ranged from 4.4 to 509 mi$^2$ in this study area.

**Table B-6. Sensitive HSPF parameters: White River. "Qualified values" are all parameter values associated with simulations meeting the threshold criteria of weighted Nash-Sutcliffe (WNS) fit criterion of 0.3 or greater and annual water yield within 15% of observed. "Best set" indicates the parameter values associated with the highest WNS score.**

| | | | Qualified values | | | | |
|---|---|---|---|---|---|---|---|
| **Parameter** | **Definition*** | **Initial range** | **Min** | **Max** | **Mean** | **Std** | **Best set** |
| KMELT | Degree day factor | 0 – 10 | 0.010 | 0.212 | 0.050 | 0.034 | 0.035 |
| KVARY | Nonlinear groundwater recession rate | 0 - 5 | 0.015 | 0.981 | 0.377 | 0.274 | 0.194 |
| AGWRC | Linear groundwater recession rate | 0.85 – 0.999 | 0.951 | 0.999 | 0.989 | 0.009 | 0.987 |
| DEEPFR | Groundwater fraction lost to deep storage | 0 – 1 | 0.294 | 0.501 | 0.405 | 0.055 | 0.412 |
| BASETP | Fraction of evapotranspiration from baseflow | 0 – 1 | 0.0003 | 0.197 | 0.077 | 0.054 | 0.075 |
| CEPSC | Canopy interception | 0 - 1 | 0.0001 | 0.199 | 0.080 | 0.060 | 0.009 |

* Source: EPA Office of Water 2000

**4. Sensitivity Analysis.** The most sensitive parameters by rank of variability explained were retained for HSPF calibration. Only three parameters explained 90% of sensitivity, which is less than the minimum of six established for this methodology. Thus, the six most sensitive parameters were retained, together accounting for 95% of total streamflow sensitivity (Table B-6).

**5. Calibration.** There are no long-term gaging records available for Parachute or Roan Creek. The UCR has two gages in the river in this area. However, these gages were not ideal for calibrating HSPF for Parachute or Roan for the following reasons: the large size of the UCRB at this location, its flow dependency on remote alpine regions with far greater precipitation, and flow regulation structures. Thus, calibration was performed on the White River watershed above Meeker and applied to neighboring Parachute and Roan Creeks (Fig. B-13), following a cross-site validation step. This White River gage is located about 20 miles from Parachute Creek, and is in a much smaller watershed, but it too originates in the alpine headwaters in the Rocky Mountains. The best available cross-validation option near the Parachute and Roan watersheds was the Colorado River at Cameo, which drains a very large watershed and requires a great deal of input data and computation time. Thus, flow was simulated between the Cameo gage and the next upstream gage, which is the Colorado River near Glenwood Springs (Fig. B-13). Because the added flow volume between these two gages was a small proportion of the total river flow, use of the WNS score was inappropriate. Instead, an alternative metric for this cross-site validation was used, the benchmark efficiency criterion (BE). BE is analogous to NS, but the user specifies the benchmark model, which is the overall mean in NS (Schaefli and Gupta 2007). For this application, the mean difference between the two gaging stations was used as the benchmark model.

$$q_b(t) = q_{in}(t) + \frac{\sum_{t=1}^{N}[q_{obs}(t) - q_{in}(t)]}{N}$$

**Equation B-7**

where, $q_{in}(t)$ is observed inflow from upstream gaging station at time $t$.

**6. Simulation Uncertainty Estimation.** Following calibration, simulation uncertainty was characterized by identifying the range of flows and flow statistics in the subset of simulations that produced daily WNS $\geq 0.3$ and annual water yields within 15% of observed flows. The boxplots in Fig. B-14 show streamflow magnitudes (at low, median, and high flow) calculated for each White River simulation meeting the criteria. The wide range of values for each magnitude indicates large uncertainty across the simulation set. In general, HSPF tended to overestimate low flows and underestimate high flows, but calibration identified an optimized parameter set for each watershed that agrees well with observed flows across a range of magnitudes. The range of simulated flows across a $5^{th}$-$95^{th}$% confidence interval are shown for a representative range of conditions (2009-2010) in Fig. B-15.

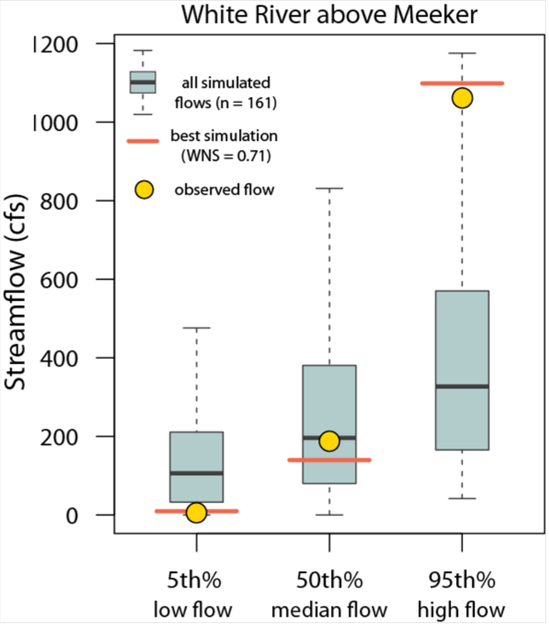


**Figure B-14. HSPF simulation uncertainty across flow magnitudes. These boxplots represent all "successful" HSPF simulations from our 10,000 run Monte Carlo analyses, with successful defined as weighted Nash-Sutcliffe (WNS) fit criterion of 0.3 or greater, and annual water yield within 15% of observed. The boxes themselves indicate the inner-quartile range, with whiskers extending to $5^{th}$–$95^{th}$ percentiles of the distributions, based on 134 successful simulations.**

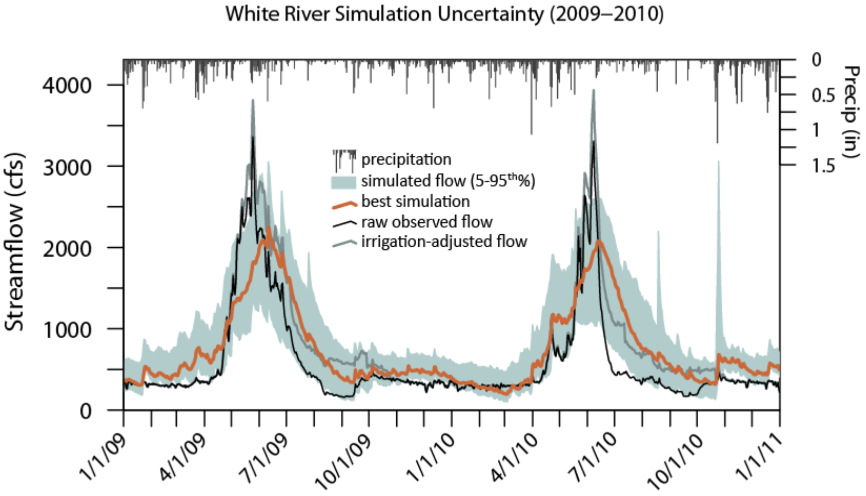


**Figure B-15. Example of HSPF simulation uncertainty: 2009-2010. These hydrographs are subset from the simulation period to illustrate the ranges of 'successful' model runs, where successful is defined as weighted Nash-Sutcliffe fit criterion of 0.3 or greater and annual water yield within ± 15% of observed. The blue band indicates the $5^{th}$-$95^{th}$ percentile range across all successful simulations, with the orange and black lines indicating the optimized and observed simulations. As seen in Figure B-14, despite model uncertainty, calibration identified optimized parameter ranges that were able to replicate observed streamflow reasonably well.**

These calibration results tend to support the use of the Monte Carlo parameter selection method, at the parameter set that achieved the overall best match to observed flow (the red line matches the yellow circle in Fig. B-15) was found outside the central tendency of the parameters (e.g. the 5th percentile low flow and 95th percentile high flow bars). It is evident from this figure that uncertainty was far greater in the Colorado simulations than in Towanda Creek. This greater uncertainty is likely due to the combined challenges of modeling in this mountainous setting, with its snowpack/snowmelt cycles, sharp transitions between steep hillslopes and alluvial valleys, and highly variable precipitation associated with steep elevation gradients.

Streamflow in Parachute and Roan Creeks was simulated with the weather data from Altenburn Ranch The streamflow record generated by the model calibrated to the White River gage at Meeker was considered the best representation of the daily fluctuations of flow to local weather. However, streamflow at the Meeker gage, like most in the region, is heavily affected by irrigation. The SUI analysis required an “irrigation-free” record, thus the simulated flow was manually adjusted to remove the effects of diversions on streamflow, as described in the next step.

**7. Finalized Simulated Natural Flows.** Water is diverted from rivers through ditches that inefficiently convey water for irrigation. Water leaks from the ditches and drains back into the floodplain returning water to the streams. Some irrigation water is consumed by crops and lost to the system. The combined crop and structure loss (termed “structure inefficiency”) has been quantified by Leonard Rice Engineers (2009) for water supply planning in the StateMod modeling system (CODWR 2014e). Just 31% of diverted water is delivered while 82% of applied irrigation water is consumed by crops (Lin and Garcia 2012), varying monthly. The streamflow record was adjusted by adding the appropriate volume of water that was diverted but returned to the stream system back into the streamflow record.

Two HSPF models with unique parameter sets were produced (each calibrated on flow data from the White River at Meeker, as described above) to serve as lower and upper flow bounds. The lower bound model was the original flow record at the gage, while the upper bound model added the diversion volume back into the observed streamflow series. The two records were compared on a daily basis and the difference was found to vary from day to day due to the nonlinearity of some model processes.

The difference between the records was multiplied by the structural inefficiency factors that varied monthly to adjust the daily streamflow:

**Equation B-8**

$$Flow_A = 0.31*(Flow_U - Flow_L) + Flow_L$$

where $Flow_U$ is the record with diversion added and $Flow_L$ is the actual hydrologic record.

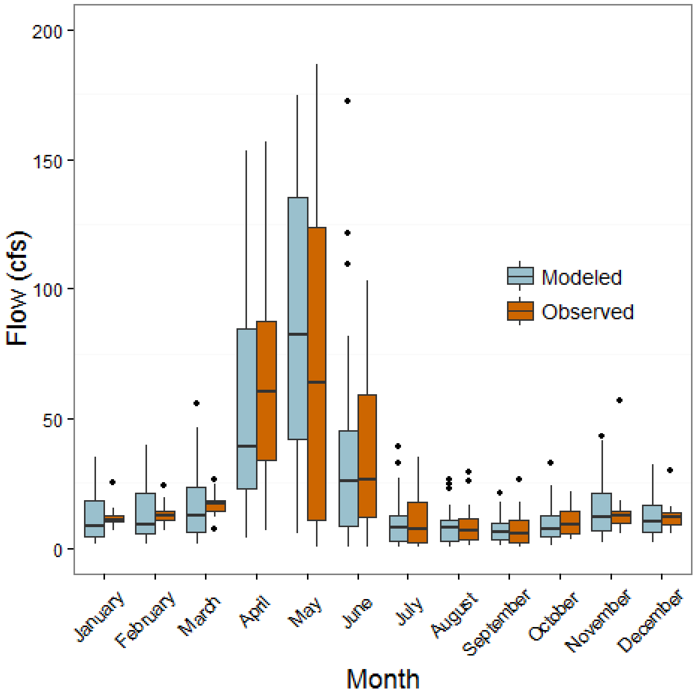
This adjusted record was considered to be the “natural” flow with appropriate daily fluctuations based on the White River record.

**Comparison to Historic Observations.** Once a single adjusted flow series had been created, the average monthly flows of this series (spanning the period 1987-2012) were compared to observed monthly flows in Parachute Creek during three historic periods (1921-1927, 1948-1954, and 1974-1982). Some differences in monthly averages would be expected due to different time frames represented in the data. Nevertheless, monthly averages were reasonably close during the summer months but were in error during the winter and spring months (Table B-7).

Flows were significantly underestimated during the spring snowmelt months and overestimated during the winter months from January to March. This pattern suggests winter precipitation was applied as rainfall rather than stored in a snowpack delivered later during the spring. The weather data was collected 3,000 feet lower and annual rainfall is 3 inches less than in the headwaters (BLM 2006). There was no representative data from the plateau available that would improve snow representation. Rather than trying to adjust weather data, the flow record itself was adjusted. The Parachute Creek streamflow was constrained to match the observed flow. A monthly adjustment factor was computed by comparing observed to predicted (Table B-7) and applied to each daily value. This increased flow during the spring months, lowered flow from January to March, and left the remaining months unchanged. The resulting streamflow record was closer to observed, as indicated in the boxplot of modeled and observed datasets in Figure B-16.

**Table B-7. Correspondence between average monthly simulated (1987-2012) and observed (1921-1927, 1948-1954, 1974-1982) flows in Parachute Creek. Units are cubic feet per second (cfs).**

| Month | Modeled | Observed | Ratio |
|---|---|---|---|
| January | 17.4 | 11.8 | 0.68 |
| February | 20.6 | 13.3 | 0.65 |
| March | 22.1 | 17.3 | 0.78 |
| April | 24.4 | 62.7 | 2.57 |
| May | 20.4 | 171.1 | 8.37 |
| June | 15.1 | 38.9 | 2.58 |
| July | 10.3 | 10.1 | 0.98 |
| August | 8.8 | 8.7 | 0.99 |
| September | 9.2 | 7.4 | 0.80 |
| October | 11.2 | 10.3 | 0.92 |
| November | 12.2 | 14.8 | 1.22 |
| December | 13.6 | 12.3 | 0.90 |



In conclusion, the simulated Parachute Creek streamflow record was a much manipulated data set. The daily streamflow matched the daily fluctuations observed at weather stations, represented "natural" flows without the influence of irrigation diversions, and was constrained to match the range of flow observed in Parachute Creek, but outside the calibration period of the streamflow simulation. As such, there is lower confidence in the streamflow record used for SUI and scenario assessment in the UCRB. Nevertheless, the streamflow record represents the general volume of flow in the stream and may be somewhat high given the adjustment factors.

**Figure B-16. Boxplots of average monthly flows for the adjusted model results (blue) and observed flows in Parachute Creek over three historic periods (orange).**

## Empirical Streamflow Estimation: Parachute and Roan Creeks

In addition to modeled pour points, SUI was also calculated at diversion structures on Parachute and Roan Creeks known to be used as withdrawal points by the O&G industry (Fig. B-17). Again, none of these locations was directly gaged, and area-weighting was used to estimate flow at each structure for SUI calculation. While USGS regional gages were used for this extrapolation process in Pennsylvania, where there is a large number of gaging stations across a wide range of watershed sizes, few gages exist in UCRB. Instead, the area-adjusted simulated flows from the closest HSPF sub-basin outlet was applied to each diversion structure in the study area. Given the small differences in drainage area, it can be assumed that these interpolated and extrapolated estimates are of similar to accuracy to the directly simulated HSPF pour points.

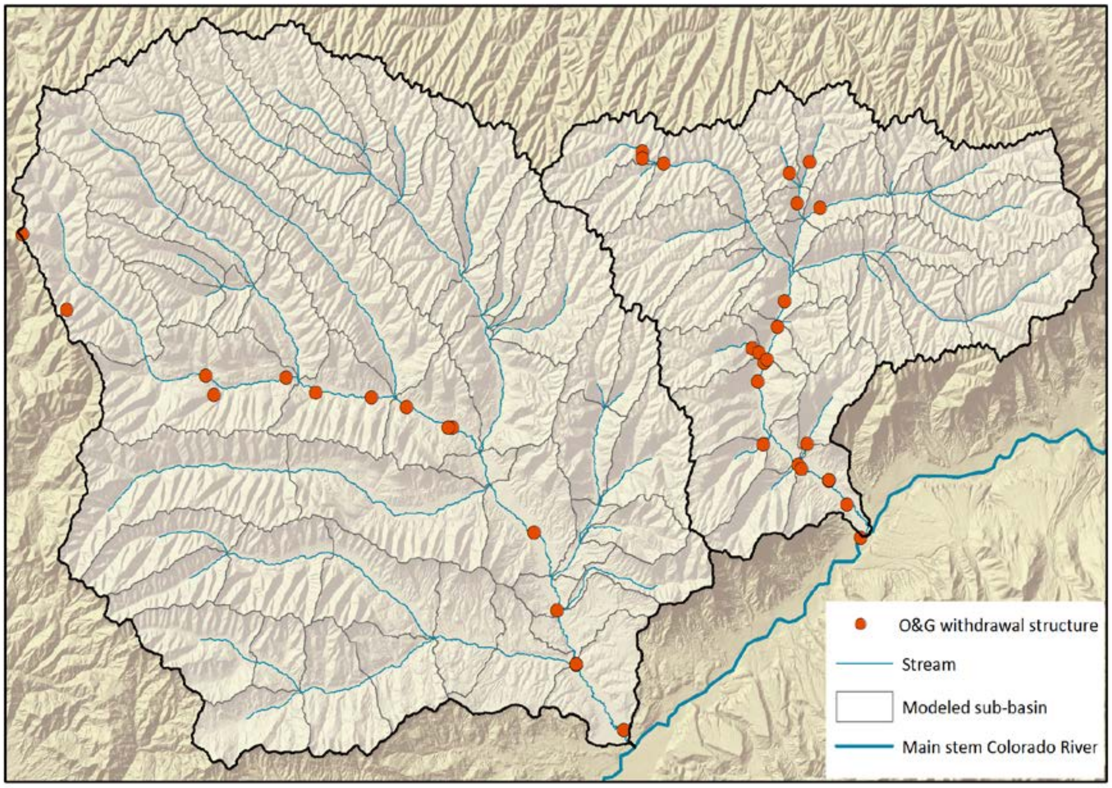


**Figure B-17. O&G owned diversion structures in Parachute and Roan Creeks. Most are used for irrigation and not HF.**

# References

Abbaspour, K. C. 2009. SWAT-CUP2: SWAT calibration and uncertainty programs—a user manual. Eawag, Swiss Federal Institute of Aquatic Science and Technology, Department of Systems Analysis, Integrated Assessment and Modelling, Dübendorf, Switzerland. 95pp.

Ahmad, Z., M. Hafeez, and I. Ahmad. 2012. Hydrology of mountainous areas in the upper Indus Basin, northern Pakistan with the perspective of climate change. Environmental Monitoring and Assessment 184(9): 5255-5274.

Andréassian, V., C. Perrin, L. Berthet, N. Le Moine, J. Lerat, C. Loumagne, L. Oudin, T. Mathevet, M. -H. Ramos, and A. Valéry. 2009. Crash tests for a standardized evaluation of hydrological models. Hydrology and Earth System Sciences 13(10): 1757-1764.

Arguez, A., I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. R. Heim Jr., and T. W. Owen. 2012. NOAA's 1981–2010 U.S. climate normals: An overview. Bulletin of the American Meteorological Society 93(11): 1687-1697.

Atkins, J. T., Jr., J. B. Wiley, and K. S. Paybins. 2005. Calibration parameters used to simulate streamflow from application of the Hydrologic Simulation Program—FORTRAN Model (HSPF) to mountainous basins containing coal mines in West Virginia. USGS Scientific Investigations Report 2005-5099. 79 pp.

Beven, K. 2006. A manifesto for the equifinality thesis. Journal of Hydrology 320(1-2): 18-36.

Bicknell, B.R, J.C. Imhoff , J.L Kittle, A.S. Donigian, and R.C. Johanson (1997) Hydrological Simulation Program--Fortran: User's manual for version 11. (U.S. Environmental Protection Agency, Athens, GA), p 755.

Booker, D. J. and R. A. Woods. 2014. Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. Journal of Hydrology 508: 227-

Buchanan, C., H. L. N. Moltz, H. C. Haywood, J. B. Palmer, and A. N. Griggs. 2013. A test of the Ecological Limits of Hydrologic Alteration (ELOHA) method for determining environmental flows in the Potomac River basin, U.S.A. Freshwater Biology 58(12): 2632-2647.

Engel, S. A., T. W. Gardner, and E. J. Ciolkosz. 1996. Quaternary soil chronosequences on terraces of the Susquehanna River, Pennsylvania. Geomorphology 17(4): 273-294.

Faramarzi, M., K. C. Abbaspour, S. A. Vaghefi, M. R. Farzaneh, A. J. B. Zehnder, R. Srinivasan, and H. Yang. 2013. Modeling impacts of climate change on freshwater availability in Africa. Journal of Hydrology 480: 85-101.

FEMA (Federal Emergency Management Agency). 2013. Hydrologic models meeting the minimum requirement of National Flood Insurance Program: Current nationally accepted hydrologic models. Available at: http://www.fema.gov/national-flood-insurance-program-flood-hazard-mapping/hydrologic-models-meeting-minimum-requirement

Gabriel, M., C. Knightes, E. Cooter, and R. Dennis. 2014. The impacts of different meteorology data sets on nitrogen fate and transport in the SWAT watershed model. Environmental Modeling and Assessment 19(4): 301-314.

Golden, H. E., C. R. Lane, D. M. Amatya, K. W. Bandilla, H. R. Kiperwas, C. D. Knightes, and H. Ssegane. 2014. Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods. Environmental Modelling and Software 53: 190-206.

Grubb, R. G. 1986. Soil survey of Bradford and Sullivan Counties, Pennsylvania. U.S. Department of Agriculture, Soil Conservation Service. 135 pp.

Harman, J. B., and D. J. Murray. 1985. Soil survey of Rifle area, Colorado: Parts of Garfield and Mesa Counties. U.S. Department of Agriculture, Soil Conservation Service. 161 pp.

Hawkins, R. H., T. J. Ward, D. E. Woodward, and J. A. Van Mullem. 2009. Curve number hydrology: State of the practice. American Society of Civil Engineers, Reston, VA. 116 pp.

He, Z., Z. Wang, C. J. Suen, and X. Ma. 2013. Hydrologic sensitivity of the Upper San Joaquin River Watershed in California to climate change scenarios. Hydrology Research 44(4): 723-736.

Johnson, M. S., W. F. Coon, V. K. Mehta, T. S. Steenhuis, E. S. Brooks, and J. Boll. 2003. Application of two hydrologic models with different runoff mechanisms to a hillslope dominated watershed in the northeastern US: a comparison of HSPF and SMR. Journal of Hydrology 284(1): 57-76.

Kim, Y. and E.-S. Chung. 2014. An index-based robust decision making framework for watershed management in a changing climate. Science of the Total Environment 473: 88-102.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel. 2006. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15(3): 259-263.

Krause, P., D. P. Boyle, and F. Bäse. 2005. Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences 5: 89-97.

Lin, Y., and L. A. Garcia. 2012. Assessing the impact of irrigation return flow on river salinity for Colorado's Arkansas River Valley. Journal of Irrigation and Drainage Engineering 138: 406-415.

Matott, L. S., J. E. Babendreier, and S. T. Purucker. 2009. Evaluating uncertainty in integrated environmental models: A review of concepts and tools. Water Resources Research 45(6).

Mitchell, A. L., M. Small, and E. A. Casman. 2013. Surface water withdrawals for Marcellus Shale gas development: Performance of alternative regulatory approaches in the Upper Ohio River Basin. Environmental Science and Technology 47(22): 12669-12678.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 50(3): 885-900.

Morway, E. D., T. K. Gates, and R. G. Niswonger. 2013. Appraising options to reduce shallow groundwater tables and enhance flow conditions over regional scales in an irrigated alluvial aquifer system. Journal of Hydrology 495: 216-237.

Narasimhan, B., R. Srinivasan, J. G. Arnold, and M. Di Luzio. 2005. Estimation of long-term soil moisture using a distributed parameter hydrologic model and verification using remotely sensed data. Transactions of the ASAE 48(3): 1101-1113.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, J. R. Williams. 2011. Soil and Water Assessment Tool: Theoretical Documentation, Version 2009. Texas A&M University System, College Station, TX.

NOAA Coastal Services Center. 2014. Historical Hurricane Tracks. Available at: http://www.coast.noaa.gov/hurricanes/#

NRCS (Natural Resources Conservation Service). 2006. U.S. general soil map (STATSGO2). U.S. Department of Agriculture, NRCS National Cartography and Geospatial Center.

Philip, J. R. 1957. The theory of infiltration: 1. The infiltration equation and its solution. Soil Science 83(5): 345-358.

Price, K., K. Kim, T. Hong, M. C. Gabriel, S. T. Purucker, C. D. Knightes, and K. Sullivan. (in preparation). A comparison of SWAT and HSPF parameter sensitivity and streamflow simulation accuracy: Two case studies from active hydraulic fracturing regions.

Price, K., S. T. Purucker, S. R. Kraemer, and J. E. Babendreier. 2012. Tradeoffs among watershed model calibration targets for parameter estimation. Water Resources Research 48(10).

Price, K., S. T. Purucker, S. R. Kraemer, J. E. Babendreier, and C. D. Knightes. 2014. Comparison of radar and gauge precipitation data in watershed models across varying spatial and temporal scales. Hydrological Processes 28(9): 3505-3520.

PRISM Climate Group. 2013. 30-year normal precipitation normal: annual; period: 1981-2010. Oregon State University.

Ries, K. G., III. 2007. The National Streamflow Statistics Program: A computer program for estimating streamflow statistics for ungaged sites. USGS Techniques and Methods 4-A6. Reston, VA. 37 pp.

Schaefli, B. and H. V. Gupta. 2007. Do Nash values have value? Hydrological Processes 21(15): 2075-2080.

Stuckey, M. H. 2006. Low-flow, base-flow, and mean-flow regression equations for Pennsylvania streams. USGS Scientific Investigations Report 2006-5130. 84 pp.

SWAT. 2014. ArcSWAT. Available at: http://swat.tamu.edu/software/arcswat/

U.S. EPA (Environmental Protection Agency). 2000. BASINS technical note 6: Estimating hydrology and hydraulic parameters for HSPF. EPA-823-R00-012. U.S. EPA Office of Water. 32 pp.

U.S. EPA (Environmental Protection Agency). 2011. Automated Geospatial Watershed Assessment: AGWA 2.0 product release. Available at: http://www.epa.gov/esd/land-sci/agwa/arcgis/prod-release.htm

U.S. EPA (Environmental Protection Agency). 2013. BASINS (Better Assessment Science Integrating point and Non-point Sources). Available at: http://water.epa.gov/scitech/datait/models/basins/index.cfm

USGS (U.S. Geological Survey). 2012. The StreamStats program. Available at: http://water.usgs.gov/osw/streamstats/

Watermark Numerical Computing. 2005. PEST model-independent parameter estimation: User manual. 5th edition

# Appendix C. Groundwater Methods

## Contents

## Overview

Groundwater methods used in analyses of the potential impact of large-volume water acquisition by the oil and gas (O&G) industry on drinking water aquifers are described below. O&G uses these large volumes of water in hydraulic fracturing of tight/shale gas. EPA recognized that the investigations should assess the potential for impact at the individual site  of extraction,  or the pumping wellfield. Also, the investigations needed to account for cumulative impacts at the appropriate "groundwatershed" scale. Evaluations of impacts included investigations into the effects of groundwater pumping on streamflow depletion, lowering of piezometric heads, and lowering of the water table. Groundwater computer models were used to test and demonstrate hypotheses regarding potential for impact associated with pumping wells screened in the hidden subsurface. The use of computer models allowed statements beyond basic water balance and empirical observations.

The study areas for this project included the aquifers associated with: (1) the Susquehanna River watershed that overlies the Marcellus shale of Pennsylvania, focusing on the Towanda Creek watershed in Bradford County, Pennsylvania; and (2) the Upper Colorado River watershed that overlies the tight gas units of the Piceance structural basin, focusing on the Parachute Creek watershed in Garfield County, Colorado. Both Bradford County and Garfield County have been among the top producers of natural gas from unconventional reservoirs in the United States.

The supporting methods used in this project included: (1) baseflow separation, to estimate average annual groundwater recharge at the catchment scale; (2) regional groundwater flow modeling, to estimate spatially averaged hydraulic conductivity and generate water table contour maps of aquifers; and (3) local-scale groundwater flow modeling for mapping drawdown of the water table and the source water zone, as well as streamflow capture associated with pumping wellfields. Estimates of baseflow and groundwater recharge informed the groundwater modeling; the calibration and solutions from the regional groundwater modeling informed the local-scale modeling. A step-wise and progressive modeling approach, as described in the next section, was applied at each of the study areas.

## Step-Wise and Progressive Groundwater Modeling Approach

The groundwater impact investigation used a step-wise and progressive modeling approach incorporating hand calculations, empirical and spreadsheet analyses, and mechanistic groundwater simulation modeling. This investigation dealt with shallow and unconfined aquifers, and involved water balance and flow issues only. The analytic element method (Strack and Haitjema 1981a, 1981b; Strack 1989) and the GFLOW model (Haitjema 1995) were selected for characterization of averaged steady-state conditions. The finite difference model MODFLOW (Harbaugh 2005) was used to represent transient flow solutions.

A practical advantage of the analytic element method is operational efficiency. While groundwater models implementing numerical solutions (e.g., finite differences and finite elements) deal with grids or meshes, the geohydrologist building an analytic element model works with hydrologic features. For example, representation of streams by strings of straight line elements and lakes by polygons is an intuitive task. The standard analytic elements, including elements representing wells, rivers, lakes, inhomogeneities, and recharge, are shown in Fig. C-1. For initial modeling runs, a limited set of surface water features may be introduced. Later, when insight into the groundwater flow regime increases, more data may be added to refine the model.

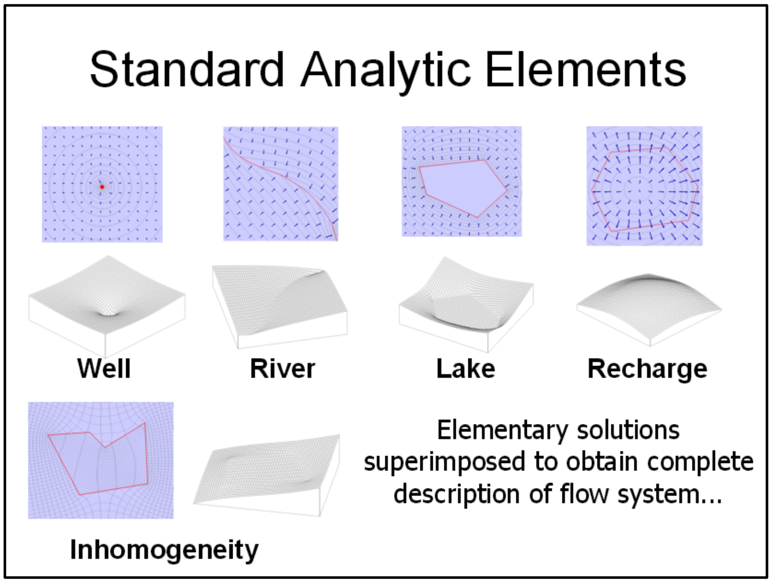


**Figure C-1. The suite of standard analytic elements available for superposition in the model domain to create a site specific model. The influence of the element on the hydraulic head contours and gridded surface and the velocity vectors is shown (Source: Craig 2014).**

The stepwise and progressive groundwater modeling approach is not new. The ensuing discussion draws from Henk Haitjema's description (http://www.haitjema.com). Ward and others applied what they called a telescopic mesh refinement modeling approach (TMR) to the Chem-Dyne hazardous waste site in southwestern Ohio (Ward *et al.* 1987). However, Ward *et al.* had to use three different computer models for the three different scales at which they were modeling. Conditions on the grid boundary of the local scale were obtained from the regional-scale modeling results, while, similarly, the conditions on the grid boundary of the site scale were obtained from the local-scale modeling results. In contrast, the analytic element method allows these different scales to be treated within the same model by locally refining the input data, thus avoiding transfer of conditions along artificial boundaries from one model into the other.

The analytic element modeling approach allows progression from simple to more complex representations in order to test understanding. A suite of simple models with few measurable parameters is preferred over a multi-parameter model that may better fit the data (Kelson *et al.* 2002). Simple models are used within a deterministic approach in this investigation; a stochastic approach would require more field data than were available.

While especially suitable for groundwater flow modeling at different scales, analytic element modeling does have some limitations. For instance, both transient flow and three-dimensional flow are only partially available. While an analytic element model can represent macro-scale heterogeneities (such as the difference in hydraulic conductivity associated with alluvium and hard-rock aquifers) in a piece-wise manner, the models do not currently represent gradually varying aquifer properties. The representation of multi-layer aquifer flow is an advanced technique.

Simple hand calculations can help guide the complementary use of steady-state and transient groundwater models (Haitjema 2006). When needed in our investigation, the finite difference numerical model MODFLOW was extracted from the regional analytic model GFLOW to facilitate a local-scale transient representation of the groundwater system. This hybrid approach is well documented (Dunning *et al.* 2004; Feinstein *et al.* 2003). As explained in the next section, the complexity of the modeling used in this project was tested to demonstrate whether it was appropriate for the uses intended.

## Appropriateness of GFLOW™ and GMS™-MODFLOW for Project Use

Both field cases for this investigation involved shallow, unconsolidated valley-fill aquifers containing perennial groundwater-supplied creeks surrounded by tighter rock units with topographic relief. The GFLOW and MODFLOW models were evaluated and deemed appropriate for representing steady and transient flow to pumping wells in these single-layer hydrogeologic systems. Model performance was demonstrated using pump test data at a private groundwater supply in Wyoming County, Pennsylvania, which is also a permitted private supplier of groundwater to the O&G industry.

### GFLOW

The GFLOW computer program (v.2.1.2; July 8, 2007) was used in this project to solve for regional and steady groundwater flow in single-layer aquifers (Haitjema 1995). GFLOW is well documented and accepted within the groundwater modeling community (Hunt 2006; Yager and Neville 2002), particularly when applied to shallow groundwater flow systems involving groundwater/surface water interactions (Johnson and Mifflin 2006; Juckem 2009) and for recharge estimation (Dripps et al. 2006). The mathematical foundations of the model include equations that express the physics of steady advective groundwater flow within a continuum; continuity of flow and Darcy's law (water flows down the hydraulic potential gradient) are satisfied at the mathematical elementary volume. GFLOW solves the regional steady-state groundwater flow equations using the analytic element method (Haitjema 1995; Strack 1989) based on the principle of superposition of elements—line-sink elements represent streams, point-sink elements represent wells, line-doublet polygon elements represent discontinuities of aquifer properties (such as hydraulic conductivity, base elevation, and no-flow boundaries), and area elements represent aquifer recharge. The influences of these elements on the regional flow field are shown in Fig. C-1**.** GFLOW includes standard example run files to test proper model installation.

In practice, the basic steps for building a GFLOW groundwater flow model are to:

1. Collect data for model building and testing, including U.S. Geological Survey (USGS) stream gage data for baseflow characterization and static water levels in wells; USGS digital elevation maps (DEM) and digital raster graphic (DRG) topographic maps; and USGS digital line graph (DLG) maps of hydrography.
2. Build the model base map for hydrography and geology. Assign labels of topographic elevation (with respect to the mean sea level datum) along stream reaches.
3. Create the elements using line-sink strings to represent streams, point elements for wells, and area element polygons for various aquifer properties (recharge, hydraulic conductivity, aquifer base).
4. Run the GFLOW model and conduct manual or automated calibration, minimizing residuals (model simulated water table elevations compared to observed elevations; model line-sink network cumulative baseflow to field observed baseflow at the watershed outlet).
5. Refine the local scale, adding wellfields and conducting drawdown analyses and source water zone mapping.

The areas of interest for GFLOW models in this project ranged in scale from full groundwatershed aligned with the surface watershed down to an individual groundwater depot (e.g., pumping wellfield). Theoretically, analytic element solutions are spatially infinite, and good modeling practice typically represents both a far field, with coarse representation of elements and geohydrologic features, and a near field at higher resolution.

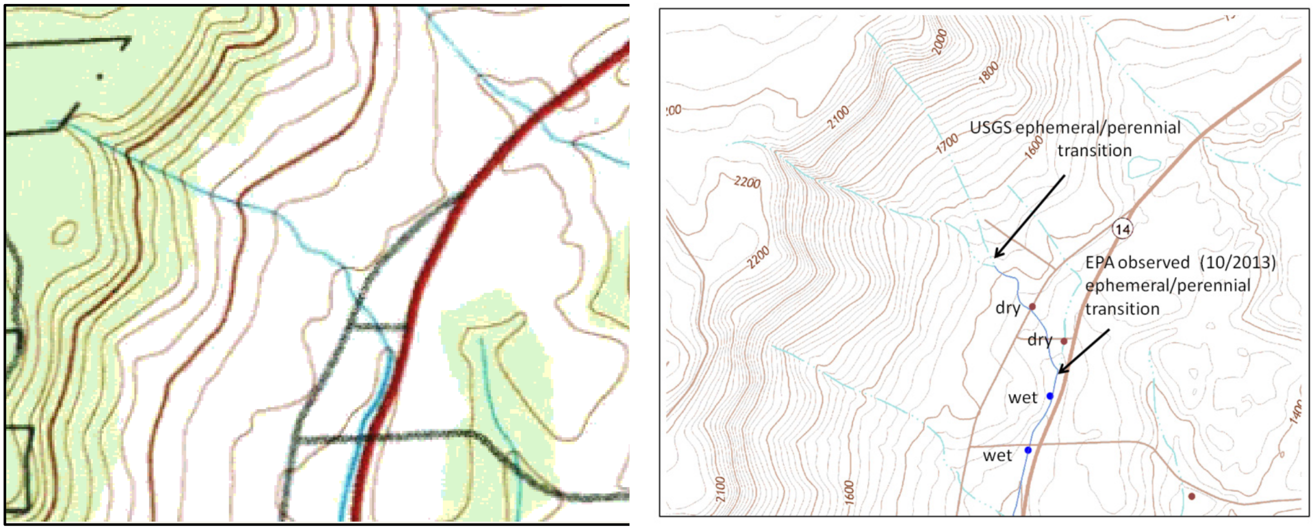
To create a bounded flow solution in GFLOW assigned to a topographically defined surface watershed, a closed string of no-flow line elements was placed on the perimeter of the surface watershed. Even though the static no-flow boundary is an artificial one (not actually occurring in the natural system), the setup is justified in geohydrologic systems where the shape of the shallow water table tends to follow the shape of the surface topography, permitting the assumption that groundwater fluxes in and out of this boundary are insignificant. Also, the base of the single-layer aquifers are assumed to be horizontal and to constitute a no-flow boundary—indeed, it was evident that deep leakage in both case studies was minimal. GFLOW can represent flow in the aquifer as either unconfined or confined, or both. The present models represent shallow, unconfined aquifers. The bounded solution setup simplifies the calibration of a water balance associated with a surface watershed.

Shallow groundwater flow systems are intimately linked with surface drainage. The perennial stream network is understood to be flowing year round. In contrast, the ephemeral stream network is dry most of the year, only flows during intense rainfall events, and contributes to rapid surface runoff. The intermittent stream network is understood to be supported by shallow drainage of the unsaturated soil horizon. For a stream to be flowing when it has not rained for many days, the source of the river water is subsurface groundwater drainage, also called baseflow. The distinction on the landscape of perennial, intermittent, and ephemeral flow is dynamic and dependent on antecedent soil moisture conditions.

Field evidence of a snapshot of the topographically defined drainage network, including ephemeral, intermittent, and perennial channels, appears on USGS topographic maps (the dashed lines are assigned to intermittent channels, the solid blue lines to perennial channels). For the maps in our study area, and based on field reconnaissance, the “blue lines” were confirmed to give a reasonable first estimate of the perennial stream network. The perennial stream network was used as a calibration target in the GFLOW model. Granted, the transition point on the landscape will move up and down the stream segment depending on groundwater recharge and the movement up and down of the shallow aquifer water table, the USGS blue line is hypothesized to be an effective representation of average drainage conditions.

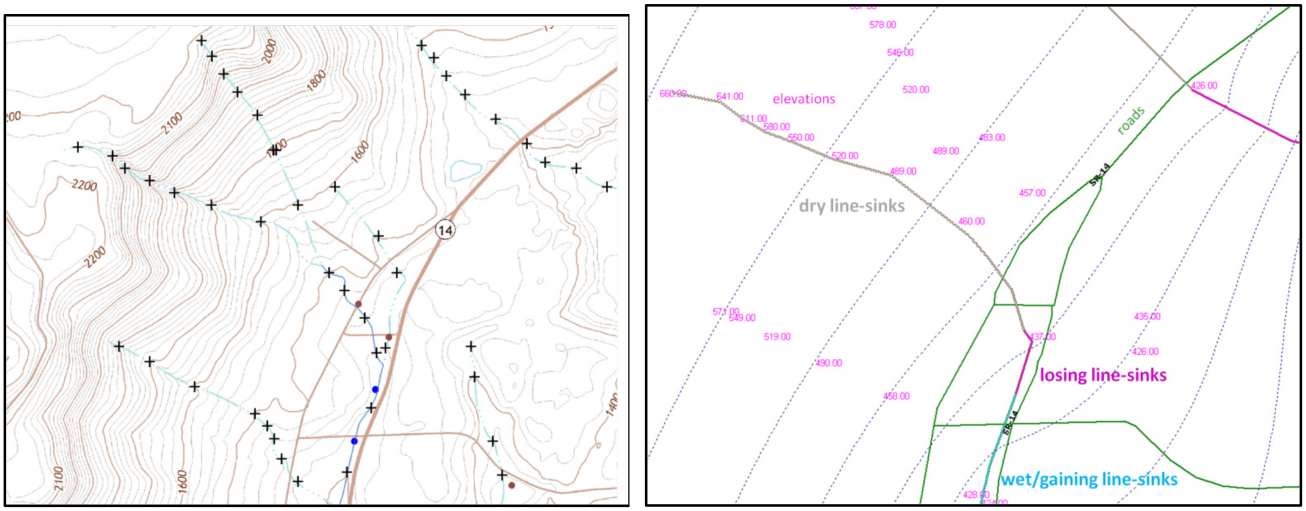
The perennial stream network defines an internal boundary condition for GFLOW, and the network of line-sinks integrates and routes drainage from recharge to baseflow discharge at the groundwatershed outlet (Mitchell-Bruker and Haitjema 1996). The nominated stream locations from USGS topographic maps or digital elevation models (DEM) were translated into GFLOW line-sink representations of streams. Head at a location on the landscape is understood to be the elevation at which water saturates an open pipe piezometer driven into the aquifer. The strength (or inflow/outflow per unit length) of the line-sink is determined in the analytic element solution by maintaining a specified head in the center of the line-sink element. A combination of methods was used to estimate the land surface elevation at select locations on the GFLOW base map (Fig. C-2A–C-2D): (1) labeling elevations where elevation contour lines from the USGS map crossed the stream channel; and/or (2) labeling elevations at selected points on the landscape using a 30m resolution DEM. The GIS software ArcView 3.3 with the Spatial Analyst plug-in and an Avenue Script (sppntzVal.ave) were used to select the specific points along the drainage network where elevations were labeled. The GFLOW line-sinks were then manually superimposed on the base map, ensuring that vertices at the end of line-sink strings corresponded with points of known head/elevation from the USGS sources (see Fig. C-2D). The head at the center of each of the line-sink strings is calculated through linear interpolation.

The GFLOW conjunctive groundwater–surface water solution integrates the baseflow in the network of tributary streams represented by line-sinks to the watershed outlet, and through numerical iteration results in a flow solution that defines an active line-sink network. Headwater line-sinks that appeared above the water table in the model were allowed to dry up (Fig. C-2D). The GFLOW recharge parameter was adjusted and associated with the areal element (inhomogeneity) and the baseflow was summed in the activated line-sink network to match the inferred baseflow observed at the USGS stream gage at the watershed outlet. The USGS computer program PART and chemical methods were used for baseflow separation. PART uses streamflow partitioning to estimate daily groundwater discharges under the streamflow record (Rutledge 1998). The method designates groundwater discharge to be equal to streamflow on days that fit a requirement of antecedent recession, linearly interpolates groundwater discharge for other days, and is applied to a long period of record to obtain an estimate of the mean rate of groundwater discharge. If one assumes there is no deep groundwater leakage and no subsurface flux of groundwater across the watershed boundary, the average groundwater recharge rate for the time period can be translated as the volume of baseflow distributed over the watershed area.



A) USGS 1:100K Topo Map

B) USGS 1:24K Topo Map



C) Extraction of elevations along stream channels

D) GFLOW line-elements

**Figure C-2. Example of steps to parameterize the GFLOW line-elements. A) The USGS 1:100K topographic maps suggest the active stream channels. B) The USGS 1:24K topographic maps show stream channels as ephemeral (dashed blue lines) and perennial (solid blue lines), and were confirmed by EPA field reconnaissance as wet or dry. (See Appendix B, "Surface Water Hydrology," Fig. B-7B). C) The labeling of points on the base map for extraction of the elevation either manually from the contour line or digitally using a background DEM. D) Assignment of topographic elevations to the vertices of the line-elements resulting in the conjunctive groundwater–surface water solution resulting in line elements contributing to baseflow (wet, colored as aqua) and not contributing to baseflow (dry, colored as gray).**

Another output of the GFLOW regional groundwater model is a continuous surface representing piezometric head, or groundwater flow potential, for the unconfined aquifer. This surface of heads is the same as the water table surface for unconfined aquifers. The water table solution depends on the aquifer recharge rate and the aquifer transmissivity (or hydraulic conductivity times aquifer thickness). Assuming a constant transmissivity, the higher the recharge rate, the higher the model-predicted elevation of the water table. Conversely, assuming a higher recharge rate, the higher the aquifer transmissivity, the lower the water table will be. Once the recharge rate is known after conducting baseflow separation as described above, the model can be calibrated to "fit" the observed water table elevations at points by varying the aquifer transmissivity, and monitoring the model-predicted water table at monitoring wells where the water table elevation is measured. Additionally, comparing model predictions of the geographic transitions between perennial/intermittent streams may provide additional opportunities to compare model predictions to field observations.

In summary, the two calibration targets, baseflow at the watershed outlet and observed elevations of the water table in unconfined aquifers, allow for the parameterization of the average recharge and transmissivity of the regional steady-state aquifer flow system equations in the GFLOW model.

For the shallow aquifers of Pennsylvania and Colorado, it is recognized that the groundwater systems are dynamic and responsive to changes in recharge and evapotranspiration, surface water boundary conditions, and water pumping. A visual inspection of the observed water table at the USGS Bradford County Observation Well shows that there is seasonal periodicity to the water table response, and in the long term, the range of water table change is approximately 10 feet above and below a mean (Fig. C-7). A long-term record of a well screened in the alluvium of the Colorado River was not available, but it is expected that the aquifer responds quickly and periodically about a mean. In this project, GFLOW is used to represent annual (or longer-term) averaging. The model can represent the long-term average mean, or, equally interesting, the long-term average low flow condition of the system. The veracity of the averaging assumptions is tested in the next sections.

### GMS-MODFLOW

The USGS MODFLOW model was used to represent transient groundwater responses to pumping wells. The MODFLOW-2005 (Harbaugh 2005) open source groundwater solver is included in the Groundwater Modeling System (GMS) version 10.0 (Aquaveo 2014). MODFLOW is the most widely applied groundwater modeling flow model in the United States. It has undergone 30 years of development and quality testing by USGS. GMS includes standard MODFLOW example run files to confirm proper model installation. In addition to facilitating a standard cell-based interface to the MODFLOW finite difference grid, GMS includes a geohydrological conceptual design environment much like GFLOW. Therefore, the data preparation and regional solution that were previously described for GFLOW were used.

### Testing Model Parameters with Pumping Test Data

To test the appropriateness of conceptual assumptions of single-layer aquifers and averaged steady flow, a data-rich field site was selected for model testing. The publicly available pump test data were acquired for the private groundwater supply wellfield (SID 3711/3712) in Wyoming County, Pennsylvania from the Susquehanna River Basin Commission (SRBC). The data had been submitted in support of the permitting of three pumping wells (Casselberry and Associates 2009, 2010, 2014). The request was approved to sell freshwater and effluent to the O&G industry. The private water supply wells are on the Bowman Creek floodplain, which delineates the valley-fill glacial outwash deposits bounded by bedrock uplands having high topographic relief (Fig. C-3). The bedrock is composed of very fine-grained sandstone, siltstone, mudstone, and shale belonging to the Catskill formation. The essentially horizontal outwash aquifer is approximately 40–60 feet thick (Fig. C-4).

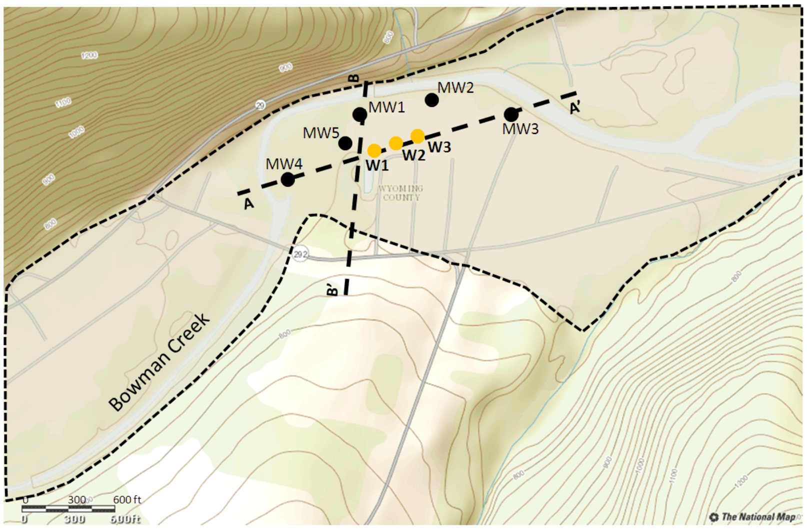


**Figure C-3. The setup for the 600-gallon-per-minute pump test of December 21–24, 2009, at the Wyoming County, Pennsylvania, private water supply wellfield — three pumped wells (W1, W2, W3) and five monitoring wells. The outwash deposits of Bowman Creek are bounded by bedrock uplands of high topographic relief (approximate limits shown as a tight dashed line) (after Casselberry and Associates 2009, with permission).**

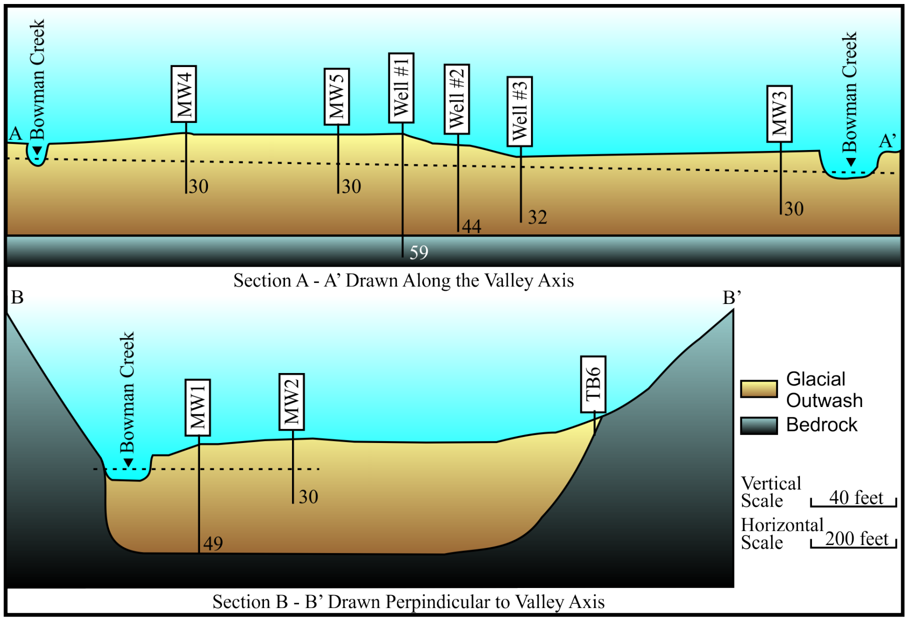


**Figure C-4. Geologic cross-sections through Bowman Creek Valley at the private water supply location (after Casselberry and Associates 2009, with permission).**

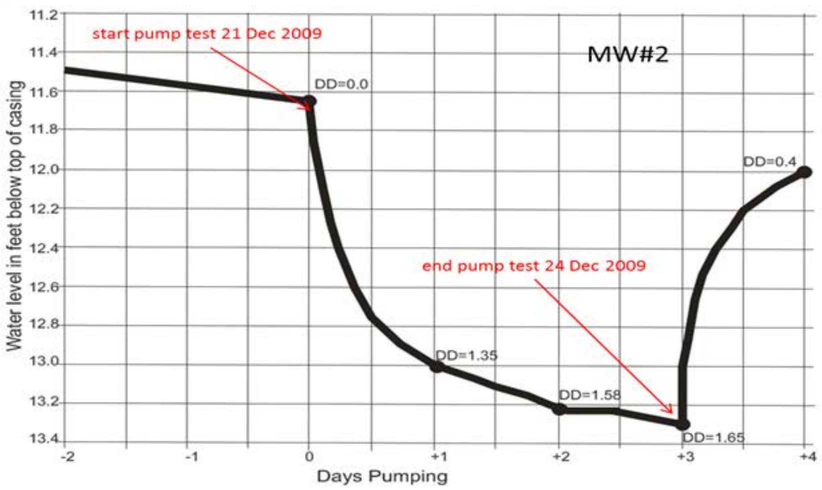


**Figure C-5. Typical monitoring well response to the pumping test, including static water level in the well prior to initiation, initial rapid response to maximum drawdown (DD in ft), with equally quick recovery. Data from Casselberry and Associates (2010), with permission.**

A 72-hour pumping test was initiated by Casselberry and Associates on December 21, 2009, at 11 a.m.; the pumping concluded on December 24 at 11 a.m. The 20 horsepower pump is at Well #1 and a suction line connects to Well #2 and Well #3. Interestingly, Well #3 experiences the greatest water level drawdowns (Casselberry and Associates 2010). There were five monitoring wells, as shown in Fig. C-3. The typical water level response to the pumping test is shown for monitoring well #2 in Fig. C-5, with the pre-pumping static water level rapidly responding to the 600 gallons per minute (gpm) pumping to a maximum drawdown, and followed by an equally rapid recovery once the pumping stops. Based on water level response at monitoring well #1, a transmissivity was estimated to be 264,000 gpd/ft, and storativity (specific yield) was estimated at 0.025 (Casselberry and Associates 2010).

The data were used to do a quick back-of-the-envelope calculation to characterize the transient response of the aquifer. Townley (1995) introduced a dimensionless response time of an aquifer to transient recharge:

$$\tau = \frac{SL^2}{TP}$$

where $S$ (-) is the aquifer storativity, $L$ (ft) is the average distance between the stream and a water divide or effective no-flow boundary associated with the rock outcrop, $T$ (ft$^2$/d) is the aquifer transmissivity, and $P$ (d) is the period of the recharge forcing. If $\tau < 1$, then transient groundwater flow can be approximated with successive steady-state solutions (Haitjema 2006). The estimate for dimensionless response time for the wellfield is much less than one ($\tau$ is <<1) given $S = 0.025$, $T = 35{,}291.66$ ft$^2$/d, the width of the outwash valley is approximately 1,200–3,300 feet, and recharge annual forcing is 365 days. Therefore, the steady-state model is expected to approximate the average pre-pumping and the average maximum pumping conditions.

This is further demonstrated with the GFLOW and MODFLOW models.

The regional-scale GFLOW model was parameterized for the wellfield in the steps described above. The perennial stream network that surrounded the wellfield was represented by constant head line-sinks. The head assigned to the center of each line-sink was estimated from elevations provided by USGS topographic maps. The boundary of the outwash aquifer was inferred from USGS topographic maps, and the GFLOW inhomogeneity element was associated with enhanced transmissivity and recharge. The value of the enhanced recharge was provided by baseflow separation using the USGS PART computer program and the USGS annual discharge recorded at the Tunkhannock Creek USGS stream gage (01534000) near Tunkhannock, Pennsylvania. The observed static and pumping water levels at the wells were used to parameterize the hydraulic conductivity of the outwash aquifer.

The USGS PART-modeled average baseflow and watershed recharge for the period 2009 and 2013 was 11.19 in/yr (0.0025519051 ft/d). The recharge was assigned to the inhomogeneity element representing the valley (Fig. C-6).

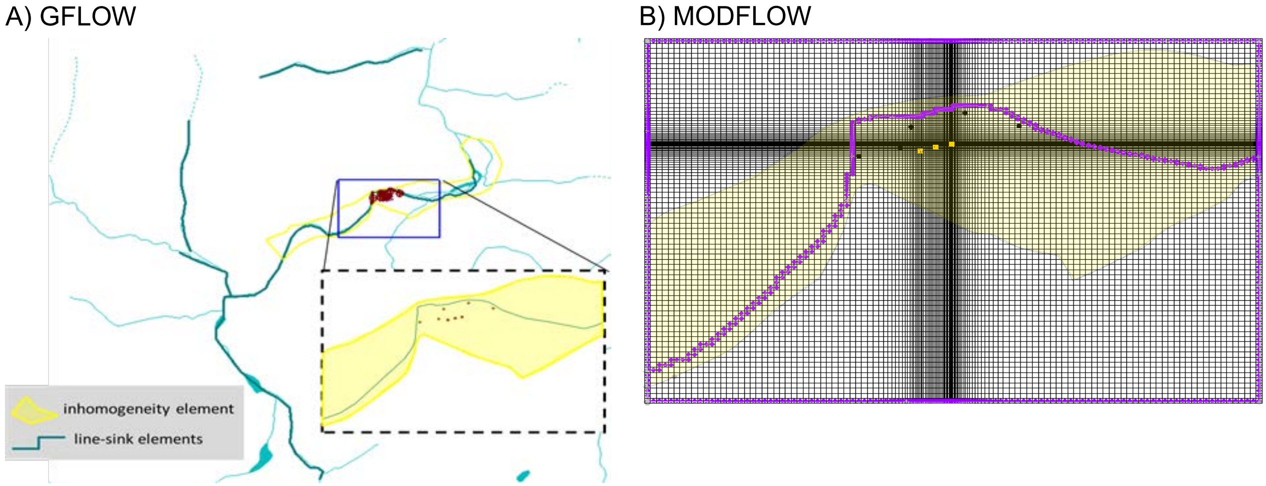
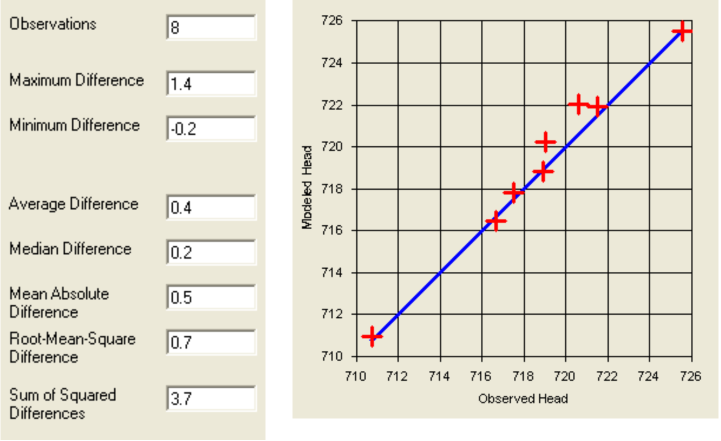


**Figure C-6. Layout of numerical features of the two groundwater flow models for the Wyoming County, Pennsylvania, private water supply case study. A) GFLOW analytic elements. The inhomogeneity element controls the recharge and the hydraulic conductivity of the valley-fill outwash. The line-sink elements represent the perennial creeks. The background map has USGS 1:100,000 scale hydrography. The nearfield includes local detail and the wellfield. B) GMS-MODFLOW has 15,198 cells, showing grid refinement associated with the pumping wells. The purple cells are head specified. The heads of cells associated with Bowman Creek were informed by the U.S. Geological Survey 7.5-minute topographic maps. The heads on the model (grid) boundary were supplied by the GFLOW model. The cells in the yellow region are associated with the properties of the outwash aquifer.**

**Table C-1. GFLOW calibration for steady-state model of Wyoming County private water supply pumping test of December 2009. Drawdown is relative to the no-pumping solution. Observed heads were measured at the three pumping wells and the five monitoring wells.**

| Well | Observed Drawdown (ft) | GFLOW Well Discharge ($ft^3/d$) |
|---|---|---|
| W1 | 3.40 | 14,774 |
| W2 | 5.08 | 23,777 |
| W3 | 9.96 | 77,010 |

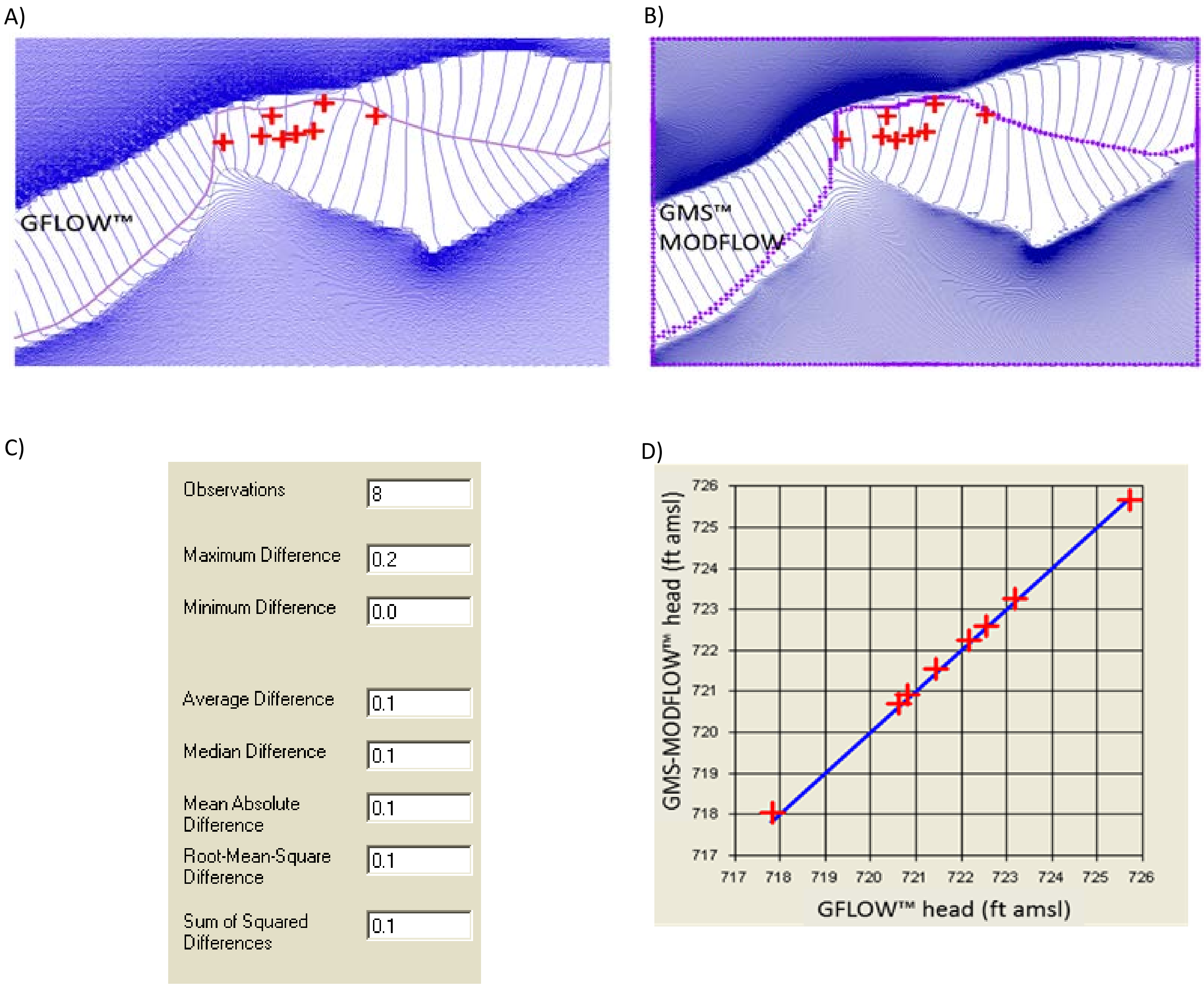

Observations: 8
Maximum Difference: 1.4
Minimum Difference: -0.2
Average Difference: 0.4
Median Difference: 0.2
Mean Absolute Difference: 0.5
Root-Mean-Square Difference: 0.7
Sum of Squared Differences: 3.7

For the steady-state GFLOW model calibration, the observed drawdown associated with the December 2009 pumping test was enforced, and a uniform assigned hydraulic conductivity of 248 ft/d to the valley inhomogeneity element resulted in the 600 gpm (115,500 $ft^3/d$) of pumping to be distributed to the three wells, with acceptable model error, as shown in Table C-1. The hydraulic conductivity of the bedrock was assigned a value of 0.4 ft/d, consistent with the Towanda Creek GFLOW model (described below) and effectively minimizing the impact of the surrounding tight rock formations on the valley aquifer flow system.

The GFLOW steady-state model was transferred to GMS MODFLOW for pre-pumping (Fig. C-7) and pump test (Fig. C-8) scenarios. The GFLOW heads on the boundary were extracted to the GMS MODFLOW boundary. These artificial boundary conditions are far enough away from the pumping center to have no impact on local solution.

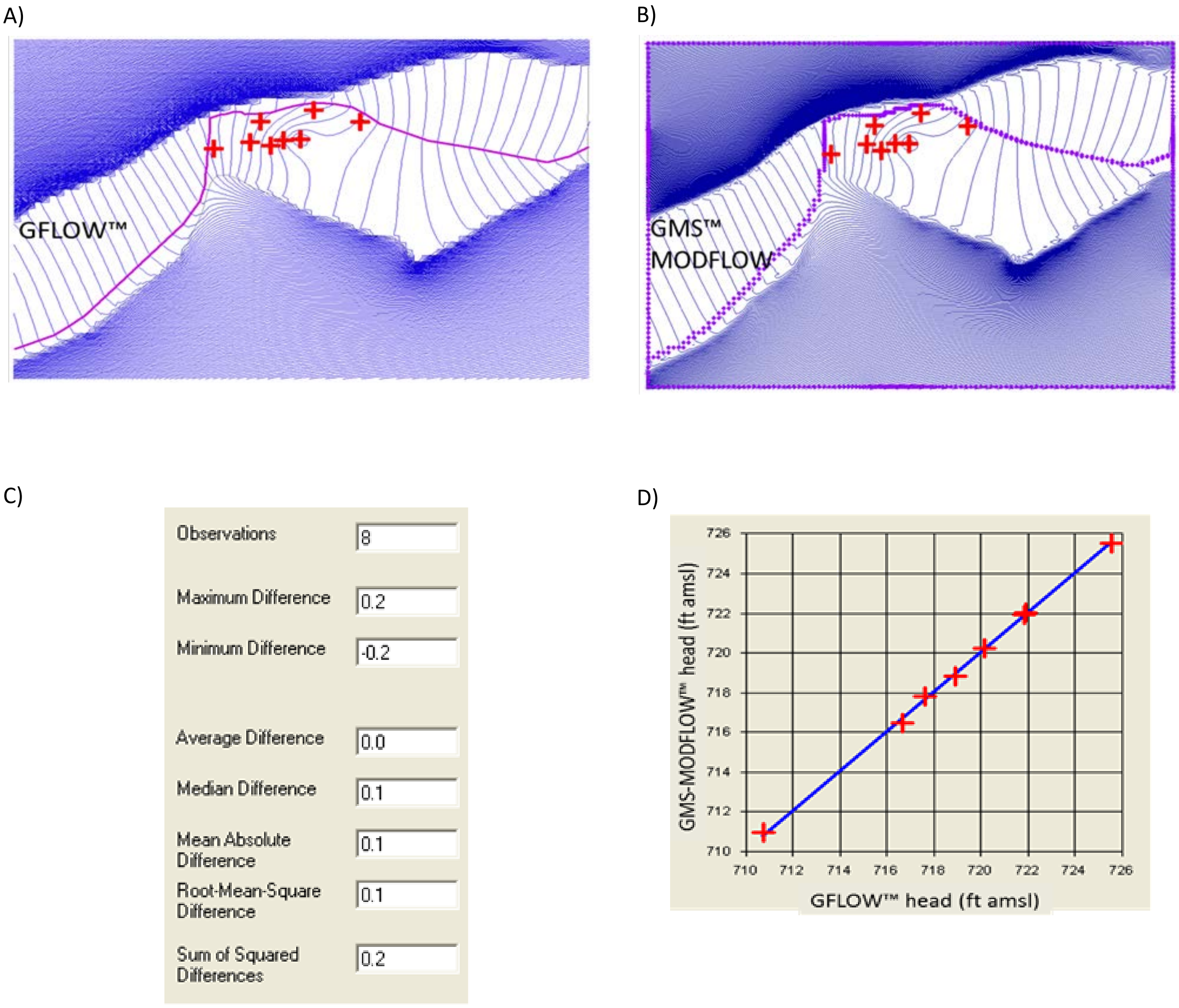
GMS MODFLOW was run in full transient mode, and model predictions of drawdown at the five monitoring wells were compared to the observed drawdown during the 72-hour, 600 gpm pumping test. This is different from the previous comparison, where the MODFLOW-predicted heads were compared to the GFLOW-predicted heads at the monitoring points. In this comparison the MODFLOW-predicted drawdowns are compared to the drawdowns observed during the 2009 pumping test. See Fig. C-9. The initial condition was set to the steady-state pre-pumping condition. The shape of the drawdown curve, which is controlled by the specific yield, is effectively represented in the MODFLOW model. The magnitude of the drawdown is controlled by the hydraulic conductivity represented in MODFLOW, and the model error ranges from 0.1 feet at MW#4 to 1.2 feet at MW#2 and 1.4 feet at MW#5. The typical valley-fill outwash unconsolidated deposits are expected to be stratified and heterogeneous. While the monitoring wells have 30 feet of total depth, they are only screened in the last 10 feet. Both GFLOW and MODFLOW assume a homogeneous single-layer aquifer without resistance to vertical flow (the so-called Dupuit-Forchheimer assumption) and are not expected to represent actual measured heads in a given interval of outwash. Since the observed drawdowns at depths of 30–40 feet appear somewhat larger than the average drawdowns represented by the model, it is reasonable to expect that the drawdowns higher up in the aquifer are then lower than predicted by the model.

Thus, the model slightly overestimates the water table decline due to pumping. The transient MODFLOW model accurately predicted the rapid drawdown during pumping, and rapid recovery once the pumps were turned off. The MODFLOW demonstration supported the use of the steady-state GFLOW model going forward to meet the project's conceptual demonstration and objectives.



| | |
|---|---|
| Observations | 8 |
| Maximum Difference | 0.2 |
| Minimum Difference | 0.0 |
| Average Difference | 0.1 |
| Median Difference | 0.1 |
| Mean Absolute Difference | 0.1 |
| Root-Mean-Square Difference | 0.1 |
| Sum of Squared Differences | 0.1 |

**Figure C-7. Pre-pumping steady-state solutions for A) GFLOW and B) MODFLOW. The constant heads on the boundary of the GFLOW model were extracted to the boundary of the MODFLOW model. The difference in the simulated heads at the well points is insignificant.**



| | |
|---|---|
| Observations | 8 |
| Maximum Difference | 0.2 |
| Minimum Difference | -0.2 |
| Average Difference | 0.0 |
| Median Difference | 0.1 |
| Mean Absolute Difference | 0.1 |
| Root-Mean-Square Difference | 0.1 |
| Sum of Squared Differences | 0.2 |

**Figure. C-8. End of pumping steady-state solutions for A) GFLOW and B) MODFLOW. The difference in the simulated heads at the well points is insignificant.**

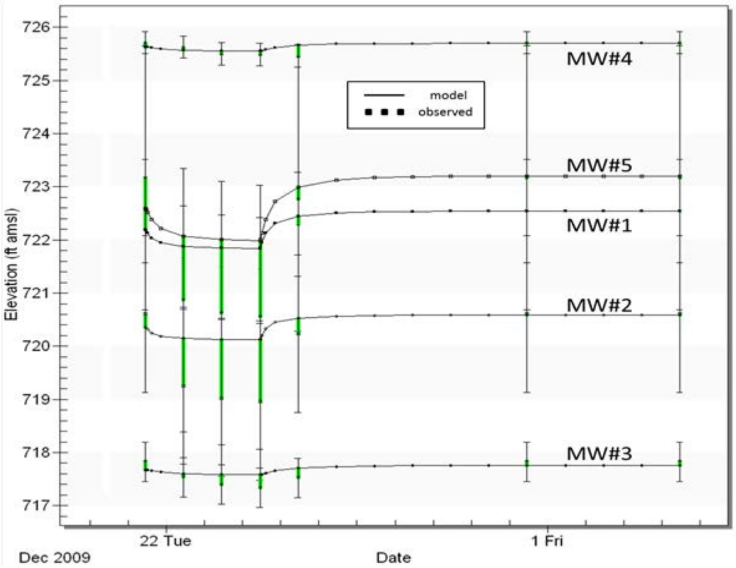


**Figure C-9. Comparison between MODFLOW drawdown and observed drawdown at the Wyoming County private water supply monitoring wells during the December 21, 2009, 72-hour pump test. The differences between the modeled drawdown and the mean drawdown are highlighted in green. The vertical whisker lines span the 95% confidence interval. (Data source: Casselberry and Associates 2010.)**

## Field Application: Towanda Creek Watershed, Bradford County, Pennsylvania

The Towanda Creek watershed (215.6 mi$^2$) of southeastern Bradford County, Pennsylvania, is the focus of our groundwater availability investigation. Bradford County is in the heart of the Marcellus Shale O&G activity, and the Towanda Creek watershed has been a hot spot of O&G drilling since 2009. The watershed was used for the previously described assessment of surface water impact. The watershed contains a public groundwater system that has registered sales to O&G. The watershed outlet is associated with the USGS gage at Monroeton (01532000) (Fig. C-10).

The aquifers in the study area are associated with the sedimentary rocks of the Pennsylvanian, Mississipian, and Devonian periods, and the unconsolidated sediments associated with the retreat of the glaciers (Fig. C-10). The rocks include sandstones, siltstones, and claystones, and the fracturing and bedding provide secondary porosity and permeability supporting freshwater aquifers (Fig. C-11). The unconsolidated deposits include alluvium, valley-fill, and till, associated with the topographic lows and streams.

The Towanda Creek groundwatershed model was built following the step-wise and progressive approach. An inspection of the shallow geology and topography of the area informed a two-zone conceptual model (Fig. C-12). At the full Towanda Creek groundwatershed scale, GFLOW represents the rock aquifers associated with the Pottsville formation and the Chemung formation using inhomogeneity polygon

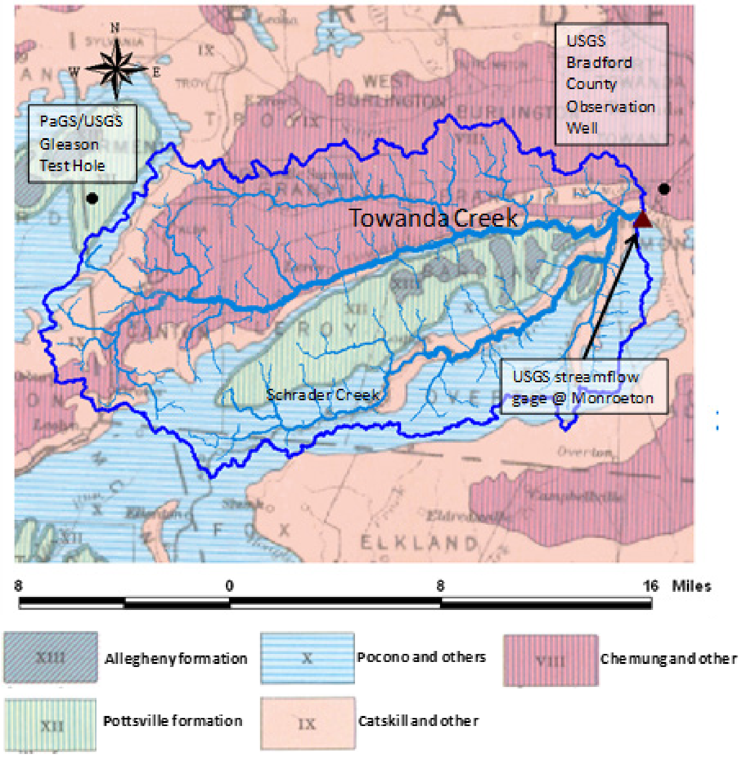


**Figure C-10. The Towanda Creek watershed. The surficial geology is based on Lohman (1939). Also shown are the U.S. Geological Survey (USGS) stream gage at Monroeton, the USGS Bradford County observation well, and the Pennsylvania Geological Survey/USGS Gleason test hole.**

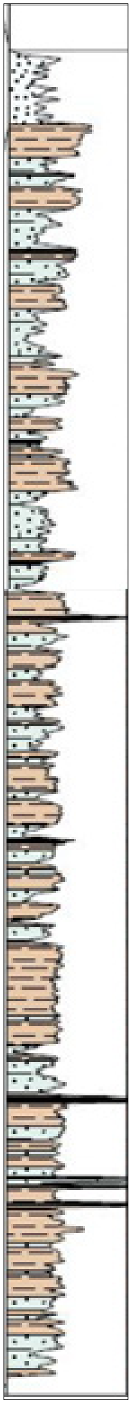
| Depth | Age | Form. | Thickness and Depth (bgs) | Geologic Description | Gamma<br>50 CPS 300<br>Litho gamma |
|---|---|---|---|---|---|
| 0 | Pennsylvanian | Pottsville | 96 feet thick<br>2 to 98 feet bgs | Pale-orange to yellowish gray, fine to medium grained sandstone, cross-bedded with iron staining along bedding planes and iron pitting. Few interbedded claystone layers, claystone rip-up clasts within sandstones and minor mica. Several thin clay layers, 0.25 to 0.50 feet thick, pale-olive to pale-yellowish orange were noted. |  |
| 100<br>200<br>300<br>400<br>500<br>600 | Devonian/Mississippian | Huntley Mountain | 584 feet thick<br>98 to 682 feet bgs | Buff to greenish-gray, very fine to medium-grained, poorly sorted sandstone: thin, planar to cross-bedded micaceous, iron staining along bedding planes, blackish brown speckles, rip-up clasts. Grayish olive-green and greenish-gray siltstones and claystones are finely laminated, plant material and carbonaceous layers common with average thicknesses of 0.5 inches and can have pyrite claystones, siltstones, and minor very fine-grained sandstones as thick as 50 feet contain burrows, root casts, and clay slickensides. | |
| 700<br>800<br>900<br>1000<br>1100<br>1200<br>1300<br>1400<br>1500<br>1600 | Upper Devonian | Catskill | 982 feet thick<br>682 to 1664 feet bgs | Grayish-red, gray, or mottled red and gray, interbedded, micaceous siltstones, claystones, and sandstones. Upper portion is overall sandier and characterized by fining upward sequences grading from intra-formational conglomerate with clay rip-up clasts to claystones. Sandstones are commonly calcareous with low-angle cross-beds, and ripple marks. Silstones and micaceous, planar bedded, finely laminated, commonly bioturbated with burrows and root casts. Claystones have calcareous white nodules, slickensides, root casts. Carbonaceous layers of large-bladed plant fossils are found in the siltstones and claystones. Fossil fish scales, bones, and plates are common in the red units. | |

**Figure C-11. Description of the stratigraphy/lithology of the Gleason Test Hole. The natural gamma log is shown. Depth is feet below ground surface. After Risser *et al.* (2013).**

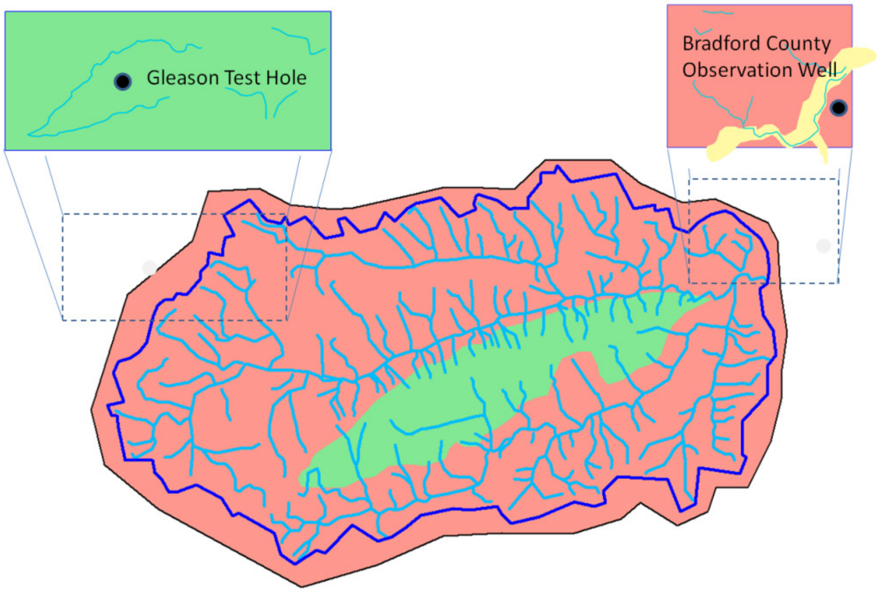


**Figure C-12. The GFLOW modeling strategy for the Towanda Creek watershed. Separate submodels were constructed about the Gleason Test Hole representative of the Pottsville formation (green areas) and the Bradford County Observation Well representative of the Chemung formation (red areas). The effective hydraulic properties of the submodels were transferred to the full groundwatershed-scale model.**

elements. The equivalent hydraulic conductivity of the two zones was estimated from two separate calibrations: a calibration associated with the Gleason Test Hole for the Pottsville zone and a calibration associated with the Bradford County Observation well for the Chemung zone. The full Towanda Creek groundwatershed model was assembled using no flow elements associated with the topographically defined catchment, and line-sink elements representing the perennial stream network. The average annual recharge was supplied by an inhomogeneity element and parameterized based on baseflow separation. The Towanda Creek GFLOW model facilitated the characterization of available groundwater storage at the catchment scale. The Towanda Creek groundwatershed model provided the basis for the local scale GFLOW model that includes the public water supply well. The following sections detail the approach and methods, starting with generation of the baseflow calibration target.

## PART Baseflow Separation at USGS at Monroeton

Baseflow separation was used to extract the groundwater component of the daily streamflow hydrograph recorded at the USGS stream gage at Monroeton, which defines the outlet of the watershed. The USGS computer program PART uses streamflow partitioning to estimate a daily record of groundwater discharge under the streamflow record (Rutledge 1998). The method designates groundwater discharge to be equal to streamflow on days that fit a requirement of antecedent recession, linearly interpolates groundwater discharge for other days, and is applied to a long period of record to obtain an estimate of the mean rate of groundwater discharge. If no deep groundwater leakage is assumed and no subsurface flux of groundwater along the watershed boundary is assumed, the average groundwater recharge rate for the time period can be translated as the volume of baseflow distributed over the watershed area. PART has the advantage of being automated and uses standard USGS daily flow records.

The entire flow record of the USGS gage at Towanda Creek was evaluated using PART baseflow separation (Fig. C-13). The average baseflow leaving the catchment for 1915–2013 is 155.6 cfs (380,687 $m^3$/d), equivalent to an average annual recharge of 9.8 in/yr (0.000682 m/d).

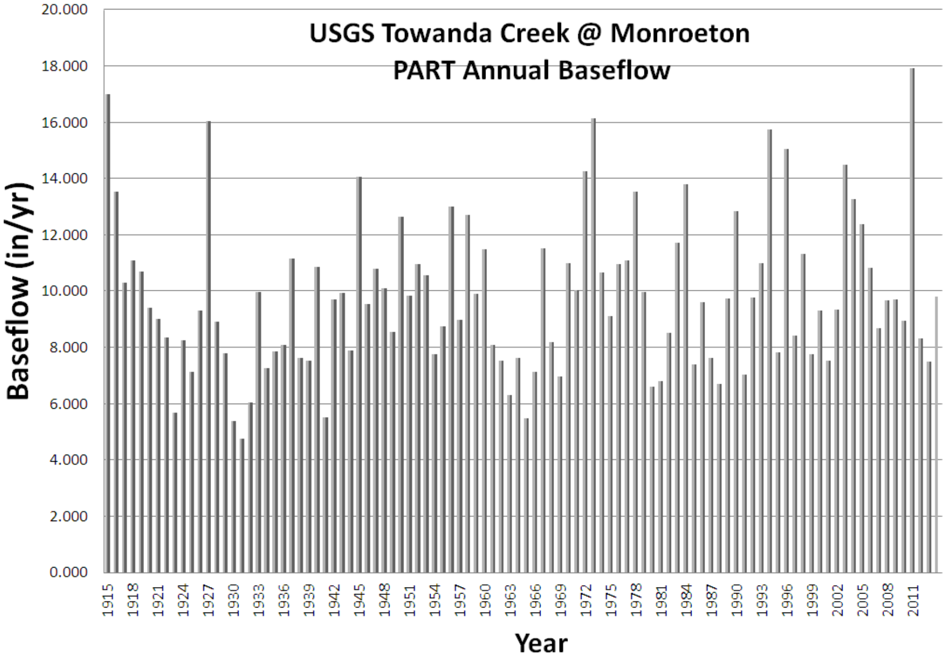


**Figure C-13. Annual PART baseflow at the U.S. Geological Survey gage at Monroeton. Baseflow is expressed as volume of flow divided by contributing watershed area.**

The observed fluctuations of the water table at the nearby USGS Bradford County Observation Well suggest an annual and cyclic frequency (Fig. C-14). The annual time period was assumed for characterization of central tendency of recharge (e.g., the annual average). In fact, 2011 appears to be the wettest year on record, with PART-computed annual average recharge of 17.91 in/yr. The calculated recharge rates for a variety of time periods of interest to the project are summarized in Table C-2.

**Table C-2. PART baseflow separation at the U.S. Geological Survey gage at Monroeton and equivalent recharge at the catchment scale.**

| Time Period | Baseflow (cfs) | Recharge (in/yr) |
|---|---|---|
| 1915–2013 | 155.63 | 9.806 |
| 2000–2011 | 174.66 | 11.00 |
| 2009–2013 | 166.26 | 10.475 |
| 2011 | 284.26 | 17.91 |
| 2013 | 119.10 | 7.504 |

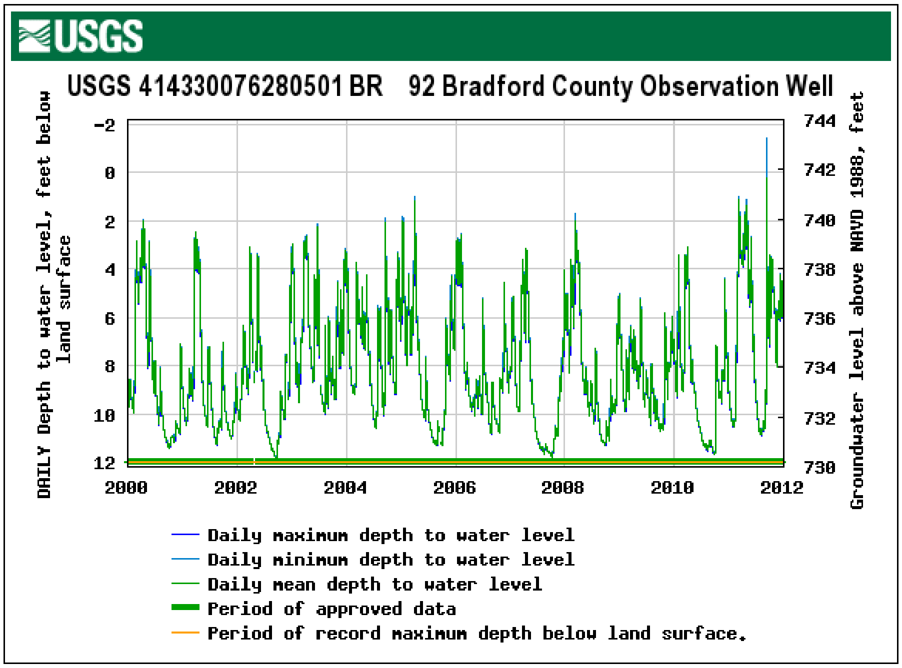
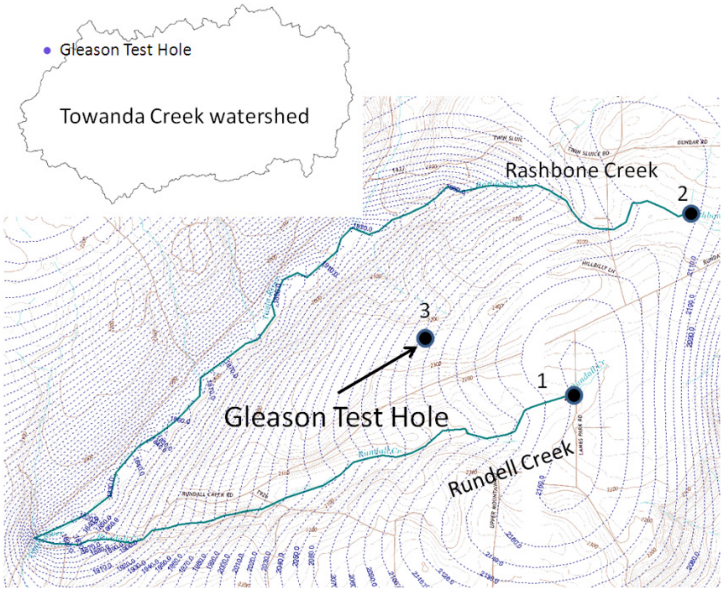


**Figure C-14. Water level hydrograph for the U.S. Geological Survey Bradford County observation well (433007680501) for 2000 to 2012. (Source: http://waterdata.usgs.gov.)**

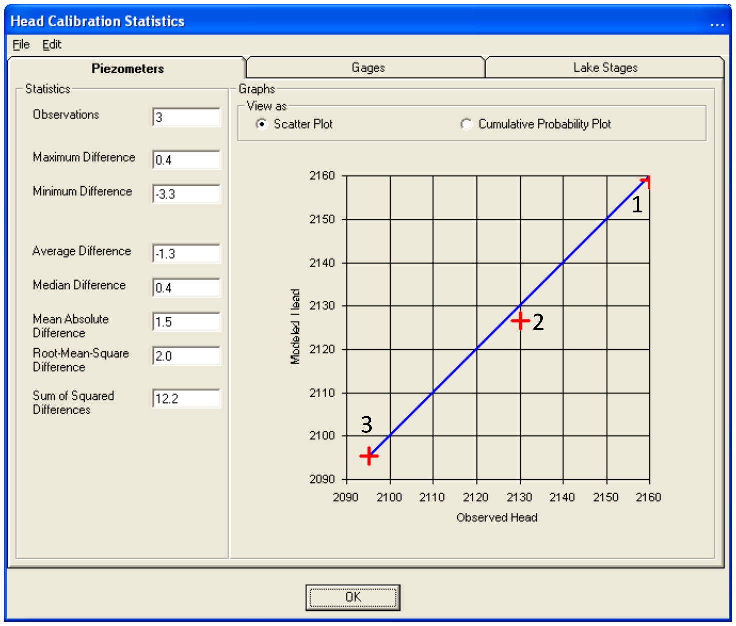
The GFLOW layout of elements and solution for the hydraulic head contours are shown in Fig. C-15A. This is the near field used in the calibration. The surrounding line-elements in the far field associated with perennial streams are not shown. Areal recharge was set to 11 in/yr (0.002511 ft/d) based on the PART baseflow separation for the 2000–2011 period. Drainage to perennial flow in creeks was included with line-sink strings to the north and south of the Gleason test hole. Three points of observed or inferred water table elevation were used to calibrate the GFLOW model and to characterize the hydraulic conductivity of the shallow bedrock aquifer. Note that this assumes perfect communication between the shallow aquifer and the active creeks—there is no representation in the model of a clay layer in the creek beds providing resistance to flow. Field survey revealed mostly rocky stream beds. The elevation of the stream is equal to the elevation of the water table at the creek channel location. The elevation of the water table at Points 1 and 2 was inferred based on evidence of a transition from intermittent to perennial flow, as designated in the USGS Gleason and Canton 7.5 minute quad maps (dashed blue line to solid blue line representation of the creeks). Point 3 is associated with the water table observed at the Gleason Test Hole.

During calibration, the hydraulic conductivity of the rock aquifer was varied to minimize residuals (the differences between model-predicted heads and observed heads at the three points). "Head" is another name for piezometric head, or groundwater flow potential, and includes both elevation and pressure components. If a hollow stand pipe is driven into a shallow aquifer, or piezometer, the elevation to which the water rises in the pipe is a measure of head. And groundwater always flows from higher head to lower head, or down the hydraulic head gradient. For the unconfined aquifer, the elevation of the water table is a measure of head, and direction of groundwater flow can be inferred from a map of the water table surface. Given a constant recharge rate, which for this model was assumed to equal 11 in/yr (0.002511 ft/d), a lowering of the hydraulic conductivity of the rock aquifer would result in a rise in the regional water table. Likewise, raising the hydraulic conductivity of the aquifer would cause a lowering of the water table. The goal of the calibration was to match the water table of the model at the three observation points. The result of the calibration process minimized the measures of difference (Fig. C-15B), and resulted in a rock hydraulic conductivity of k = 0.086 ft/d (0.0262 m/d). Knowing a saturated thickness of 2,095 feet amsl at the Gleason Test Hole, aquifer transmissivity (hydraulic conductivity times aquifer thickness) of 180.2 $ft^2/d$ (16.74 $m^2/d$) was associated with the mapped areas of the outcrop of the Pottsville geologic formation (Figs. C-10, C-12). This rock transmissivity was used in the GFLOW model of the Towanda Creek watershed, as described below.

A)



B)



Statistics

Observations: 3

Maximum Difference: 0.4

Minimum Difference: -3.3

Average Difference: -1.3

Median Difference: 0.4

Mean Absolute Difference: 1.5

Root-Mean-Square Difference: 2.0

Sum of Squared Differences: 12.2

View as: ● Scatter Plot ○ Cumulative Probability Plot

**Figure C-15. A) GFLOW model for the Gleason Test Hole, showing the layout of elements and contours of solution for hydraulic heads. B) GFLOW calibration statistics at points 1, 2, and 3. Heads are in feet above mean sea level.**

## GFLOW Calibration at the USGS Bradford County Observation Well

A GFLOW groundwater flow model was constructed in association with the USGS Bradford County Observation Well (Fig. C-12). The purpose of this model was to assist in the characterization of the permeability of the rock aquifers of this area. The observations of the water table at the Bradford County Observation Well provided a valuable calibration target for the groundwater flow model. Once developed, this local-scale model informed the full Towanda Creek groundwatershed flow model.

The USGS Bradford County Observation Well was drilled to 117 feet below land surface and completed in the Lock Haven rock formation, which underlies the Catskill formation and is associated with the Chemung and other formations (Fig. C-10). The maximum fluctuation of the water table is approximately 10 feet, and there is an annual cycle of low water tables in the late summer and high water tables in early spring (Fig. C-14).

The GFLOW groundwater model represents the long-term average geohydrologic state of the aquifer system. Four points of observed or inferred water table elevation were used to calibrate the model in the geographic area surrounding the USGS Bradford County Observation Well (Fig. C-16A). The USGS Bradford County observation well, shown as Point 4, provided an average static water table elevation of 8.261 feet below ground surface from 2000 to 2011 (Table C-3). The land surface elevation at the USGS well is 741.6 feet amsl. Therefore, the average water table elevation for 2000–2011 at the USGS observation well is 733.3 feet amsl (223.5 m). The heads (or water table elevation) at Points 1, 2, and 3 were assigned to the points of transition from intermittent to perennial flow in creeks in the area, as inferred from the Monroeton and Ulster USGS 7.5-minute quad maps (dashed blue lines transitioning to solid blue lines) (Fig. C-16B).

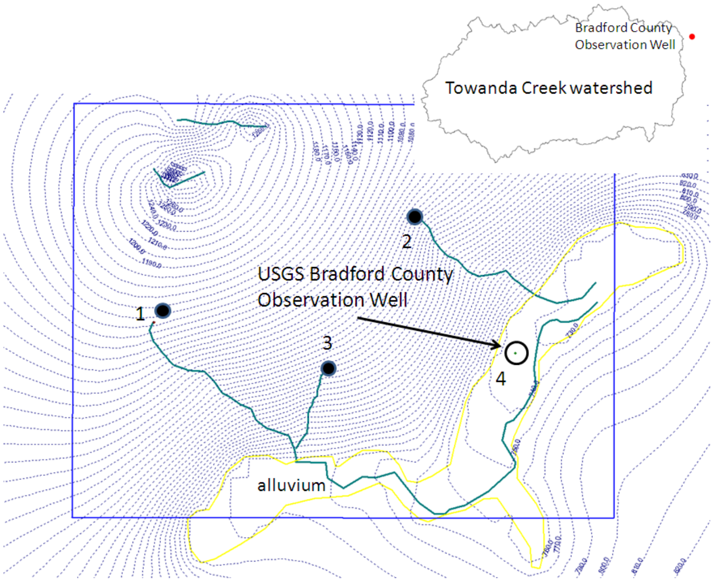
**Table C-3. Static water table elevations in the U.S. Geological Survey Bradford County Observation Well (2000-2009).**

| Year | Static water elevation (ft below ground surface) | Head (ft above mean sea level) |
|---|---|---|
| 2000 | 8.294 | 733.3 |
| 2001 | 9.088 | 732.5 |
| 2004 | 7.093 | 734.5 |
| 2006 | 8.080 | 733.5 |
| 2007 | 8.769 | 732.8 |
| 2009 | 8.755 | 732.8 |
| 2010 | 8.785 | 732.8 |
| 2011 | 7.220 | 734.4 |
| Average | 8.261 | 733.3 |

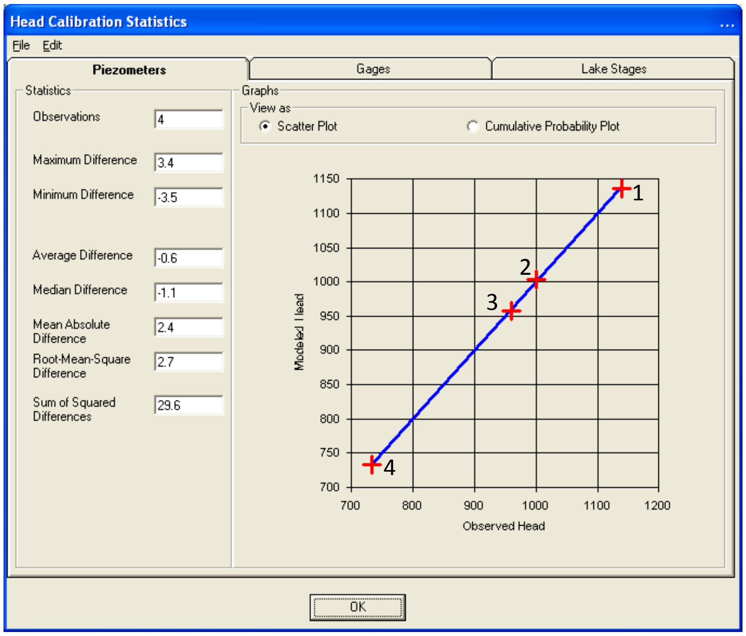
The GFLOW model represented two major geology zones: the glacial valley fill (alluvium) and the surrounding rock aquifers. The model has line-sinks for streams, area elements for recharge (2000–2011, 11 in/yr or 0.002511 ft/d), and inhomogeneity elements to represent the jump in hydraulic conductivity between the alluvium from the surrounding bedrock. The base of the aquifer was set at sea level. During calibration, the hydraulic conductivity was varied to minimize residuals between model-predicted heads and observed heads. The solution was insensitive to the hydraulic conductivity of the alluvium which was set to 100 ft/d, typical of sand and gravel. The best fit parameterization that resulted in the lowest measures of difference (Fig. C- 16B) has hydraulic conductivity of the rock at k = 0.38 ft/d (0.116 m/d). This rock and hydraulic conductivity was associated with the mapped outcrop of the Chemung and other formations (Figs. C-10, C-12), and approximated a transmissivity (hydraulic conductivity times thickness) of 278.7 ft$^2$/d (25.9 m$^2$/d) at the USGS Bradford County Observation well.

The next section presents a full-scale Towanda Creek groundwatershed model based on the GFLOW models for the Gleason Test Hole and the Bradford County Observation Well, and the estimates of the hydraulic conductivity of the two major rock geology zones.

A)



B)


**Head Calibration Statistics**

File Edit

Piezometers | Gages | Lake Stages

Statistics

Observations: 4

Maximum Difference: 3.4

Minimum Difference: -3.5

Average Difference: -0.6

Median Difference: -1.1

Mean Absolute Difference: 2.4

Root-Mean-Square Difference: 2.7

Sum of Squared Differences: 29.6

Graphs

View as

● Scatter Plot ○ Cumulative Probability Plot

**Figure C-16. A) Layout of GFLOW elements and solution showing the contouring of heads. B) GFLOW calibration statistics for the model of the USGS Bradford County well. Heads in ft above mean sea level.**

## GFLOW Model of the Towanda Creek Watershed

The Towanda Creek GFLOW groundwater model includes the complete stream channel network that drains to the watershed outlet at the USGS gage at Monroeton (Fig. C-10). The creeks were represented with line-sinks and an area element was used to represent recharge over the catchment; no-flow elements were used to represent an artificial boundary condition, effectively aligning the groundwatershed with the surface watershed.

A two-zone geologic model (two rock types) was tested for its ability to capture the essence of the groundwater system. At this scale, it the alluvium was assumed to be unimportant to the water balance. The hydraulic conductivity from the Gleason Test Hole GFLOW model was mapped to the Pottsville affiliated formations, and the hydraulic conductivity of the USGS Bradford County observation well GFLOW model was mapped to the Chemung affiliated formations, both from previously described calibrations (Fig. C-12).

The conjunctive groundwater-surface solution using GFLOW is achieved through iteration, and the solution integrates the cumulative baseflow in the line-sink network for comparison to the discharge observed at the USGS gage at Monroeton (the outlet of the Towanda Creek watershed). The GFLOW model removes from the solution the headwater stream channels that are above the water table, and thus do not receive any groundwater, that is, GFLOW allows the non-contributing creeks to go dry. The Towanda Creek GFLOW solution is shown in Fig. C-17, based on the areal recharge of 11 in/yr. The two zones of hydraulic conductivity are the Pottsville zone inhomogeneity element (green zone) and the Chemung zone areas outside of the Pottsville zone (red zone). Also shown are the continuous water table surface, represented by the contours of hydraulic head, and the cumulative baseflow, as represented by the thickness of the line-sinks representing the creeks. The dried-up creeks are grayed out.

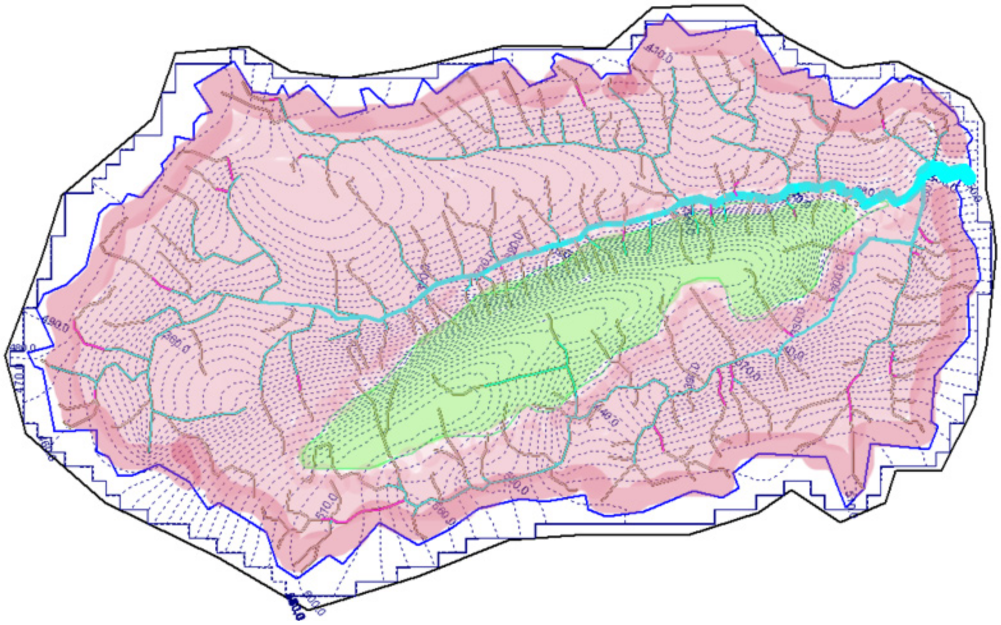


**Figure C-17. GFLOW model of Towanda Creek aquifer system, showing hydraulic head contours and cumulative baseflow in the line-sink network. GFLOW represents two zones of hydraulic conductivity.**

To this point, a Towanda Creek groundwatershed model has been presented based on annual average areal recharge and two zones of rock transmissivity, resulting in an output of a smooth and continuous water table surface that honors the elevations of the perennial stream network. The surface can be used for estimating the aquifer thickness and estimating available groundwater in storage.

## GFLOW Model of a Towanda Creek Watershed Municipal Wellfield

A local-scale groundwater model was built centered on a municipal wellfield (PA2080003) within the Towanda Creek watershed to demonstrate the potential impact of water withdrawals. The municipal wellfield sells surplus groundwater to the O&G industry. The stratified-drift unconfined aquifers in the valleys and the post-glacial alluvium associated with the streams in the area are the most important sources of shallow and available groundwater (Fig. C-18).

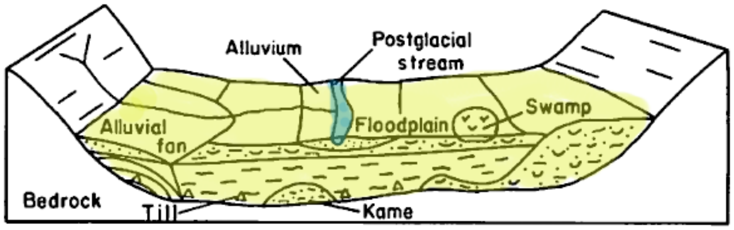


**Figure C-18. The principal aquifer of the municipal wellfield is associated with the post-glacial valley-fill deposits of Towanda Creek. (Image source: Williams *et al.* 1998.)**

The hydrogeologic system in the area was represented in GFLOW as a two-geologic-zone model with transmissivity associated with the bedrock and the valley-fill (Fig. C-19A). The wellfield is within the model near-field with detailed representation of point-sinks (wells), line-sinks (streams), and inhomogeneities (aquifer types with relevant hydraulic conductivity). The model far-field extends the elements in much coarser expression and far enough away from the wellfield so that its influence on the near-field solution is insignificant. The rectangular areal element providing recharge extends into the far-field. The represented line-sinks in the far-field are informed by the previously described Towanda Creek watershed GFLOW model, with its perennial stream network associated with observed baseflows (Fig. C-19B).

The municipal wells were drilled to a depth of 120 feet from the land surface elevation of 1,128 feet amsl, and the pumps are rated at 350 and 305 gpm, or a combined 655 gpm (3,570 $m^3$/d). The two wells are represented as a single pumping center in the GFLOW model. The base of the aquifer beneath the wellfield was set at 307.2 meters amsl.

Three observation points of static water levels close were used to inform the near-field calibration. Calibrating the two-zone GFLOW model involved varying the hydraulic conductivity of the rock and alluvium to minimize the difference between the observed head and the model-predicted heads at the locations of the three observations of static water levels. An additional requirement was that the hydrogeologic system had to support a wellfield drawdown to the base of the aquifer (307.2 m) at the maximum pumping rate of the wells (3,570 $m^3$/d). The hydraulic conductivities of $k_{rock} = 0.113$ m/d and $k_{alluvium} = 6.554$ m/d met the requirements. The solution is shown in Fig. C-20.

The GFLOW groundwater model allowed the mapping of the cone of depression of the water table, the zone contributing recharge at the maximum supported pumping rate, and the local streamflow capture. The discussion of the Marcellus Shale/Susquehanna River Basin in Chapter 4 of this report includes analysis of groundwater use intensity.

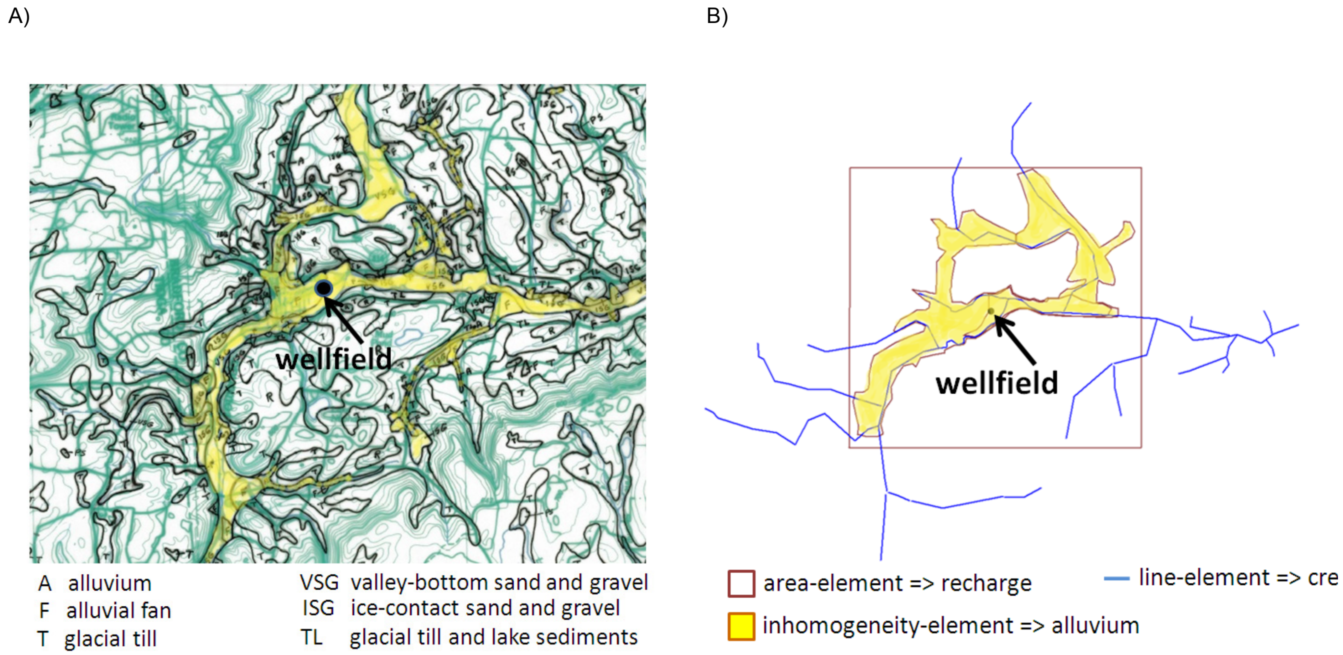


**Figure C-19. A) The distribution of alluvium based on the surficial geology map of Sevon and Braun (1997). B) Layout of analytic elements in the GFLOW model of the municipal wellfield.**

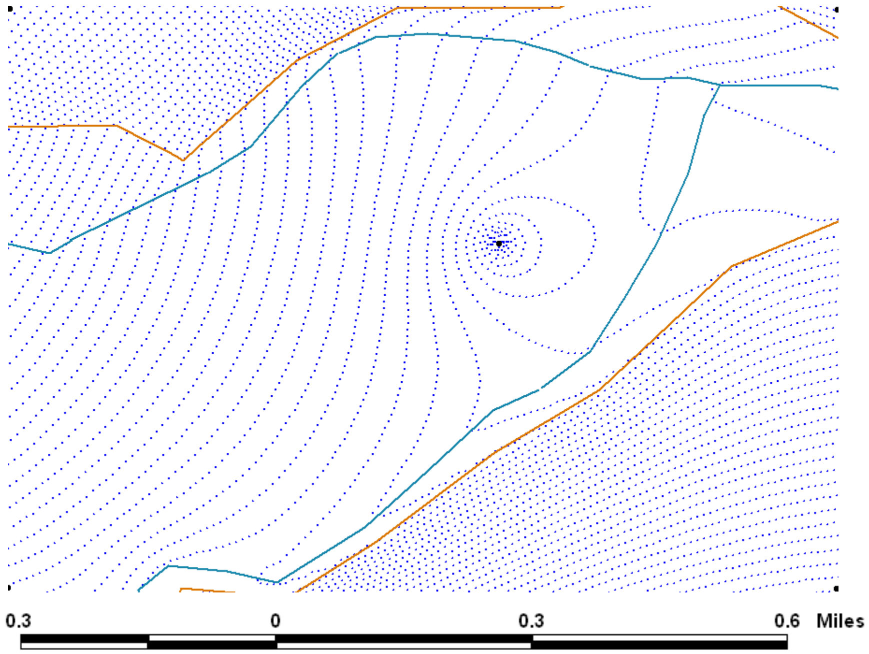


**Figure C-20. GFLOW solution showing hydraulic head or water table contours for the Towanda Creek watershed municipal wellfield for the maximum supported pumping rate.**

# Field Application: Colorado River Watershed Between Glenwood Springs and Cameo, Colorado

The project study area for groundwater impact included the watershed of the Colorado River in Garfield County between the USGS stream gage below Glenwood Springs and the USGS stream gage near Cameo (drainage area 1,975 mi$^2$) (Fig. C-21). Of particular interest was the confluence of the Parachute Creeks, which is the location of an oil & gas structure, a significant r groundwater wellfield that is sourcing the O&G industry. The investigation included the use of chemical baseflow separation to estimate the areal recharge rate, the use of the recharge rate to build a GFLOW Colorado River/Garfield County groundwatershed model to estimate the regional rock transmissivity, and the use of both the recharge and the rock transmissivity to build a near-field GFLOW model of the Parachute Creek confluence. The Parachute Creek confluence GFLOW model was used to model and map the localized cone of depression and streamflow capture associated with the O&G wellfield.

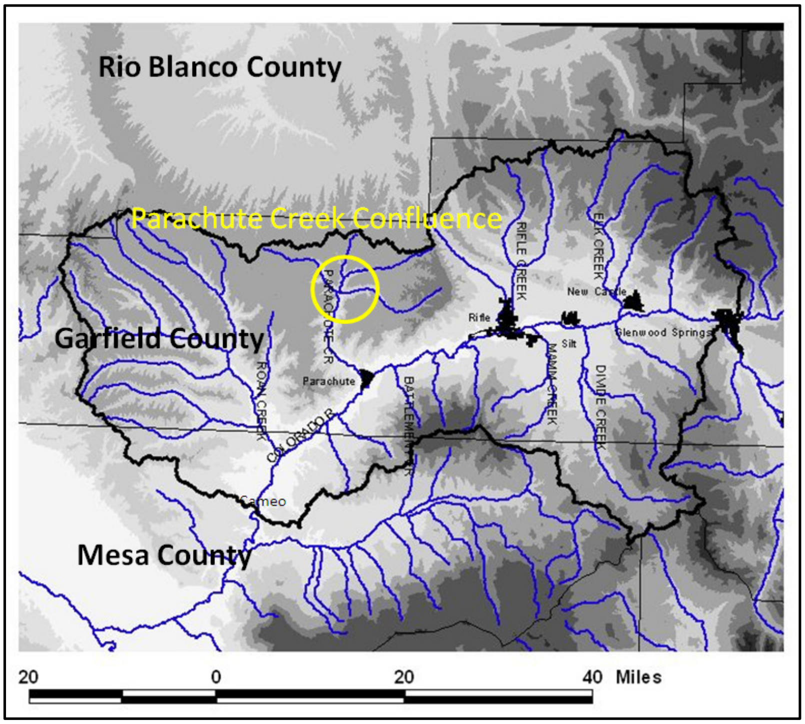


**Figure C-21. The Colorado River watershed between Glenwood Springs and Cameo, and the Parachute Creek confluence, location of a major water supply wellfield supplying oil and gas.**

## Baseflow Separation USGS Gage at Cameo

The graphic method for baseflow separation using USGS PART did not prove effective for this snowmelt-dominated watershed. There were sufficient data for Miller *et al.* (2014) to perform a chemical baseflow separation method using stream water conductance measurements to distinguish runoff from baseflow in the Upper Colorado River Basin. The analysis was associated with the Colorado River watershed draining to the USGS gage at Cameo (7,986 mi$^2$ drainage area), and mean annual stream discharge for the 2007–2012 period of 4,061 ft$^3$ per second (dfs). The chemical data suggested annual average baseflow of 44% of discharge (1,892 ft$^3$ per second); snowmelt period baseflow 29% of discharge; and low flow period baseflow 72% of discharge. Adjusting for the drainage area between the USGS gage at Glenwood Springs and Cameo, the effective annual average recharge for 2007–2012 was 1.03 in/yr.

## GFLOW Model of the Colorado River Between Glenwood Springs and Cameo

The purpose of the GFLOW Colorado River groundwater flow model was to distribute baseflow spatially to the perennial stream network of the catchment of the Colorado River between Glenwood Springs and Cameo. The model represented the creeks with line-sinks, used an area element to represent recharge over the catchment, and no-flow elements to represent an artificial boundary condition, effectively aligning the groundwatershed with the surface watershed. The heads associated with the line-sinks were informed by USGS topographic maps and DEM. The two-zone (alluvium, rock) model performed better than a single-zone model (rock) based on difference statistics comparing model-predicted water table to average observed water table. The GFLOW solution is shown in Fig. C-22. The average baseflow at the Parachute Creek confluence for 2007–2012 was 485,063 $ft^3/d$ (5.614 cfs).

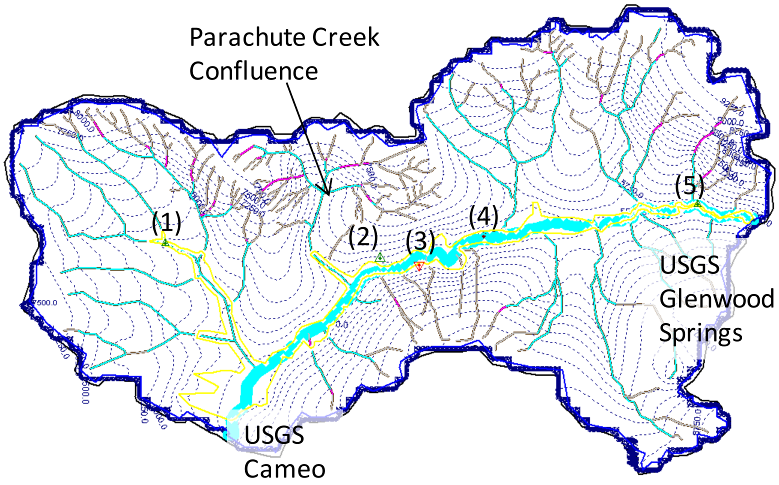
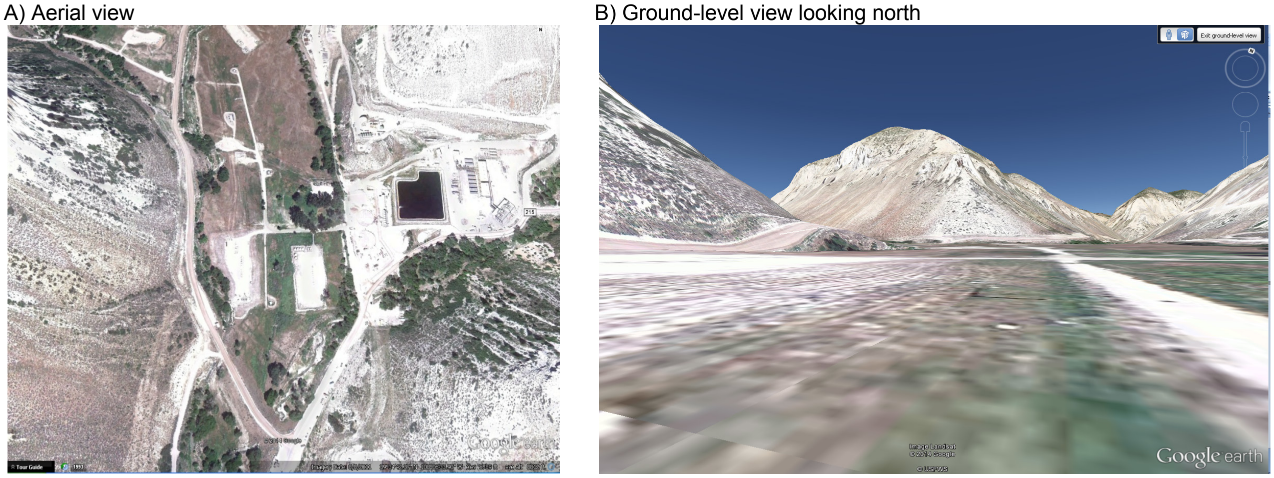


**Figure C-22. GFLOW solution showing contouring of hydraulic heads, and cumulative baseflow in the streams. The five USGS observations wells are represented as triangles, with the orientation and color based on the sign of the residual (difference between model and observed: red triangle with point down means model head too low, green triangle pointing up means model head too high), and the size representative of the total difference between modeled and observed. The average difference was 9.5 feet.**

### GFLOW Model Groundwater Depot at Parachute Confluence

An example of a private groundwater depot or structure to supply fresh water to the O&G industry in the study area is located at the confluence of the west fork, the middle fork, and the east fork of Parachute Creek in Garfield County. The flat alluvial valley is surrounded by the steep slopes of the mountains (Figs. C-23A, C-23B).


A) Aerial view

B) Ground-level view looking north

**Figure C-23. Aerial and ground-level views of the confluence of the Parachute Creeks (© 2014 Google Earth, Street View Image Landsat © USFWS).**

The O&G Water Well No. 1 (structure 395298) in the Parachute Creek confluence area provided source groundwater to industry from 2007 to 2010, and the O&G Well No. 1A (structure 395301) provided source groundwater to industry from 2011 to 2012. The depth of both wells is 57 feet and the elevation of the land surface at the wellfield is 5,790 feet amsl.

The hydrogeological conceptual model for the Parachute Creek area shows that the fractured rock of the mountain areas provides focused discharge to the alluvium of the creek valleys (Fig. C-24).

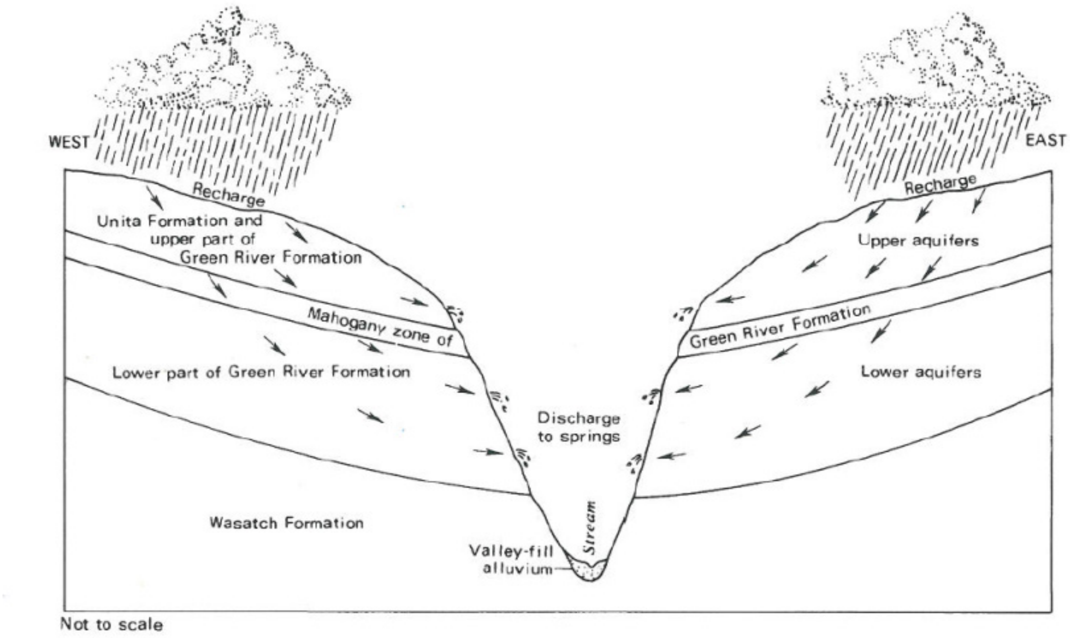


**Figure C-24. Generalized geologic cross-section of Parachute Creek. (Source: Adams *et al.* 1986.)**

The GFLOW model of the Parachute Creek confluence includes line-sink representation of the perennial creeks, an area element to provide the recharge, and line-elements to differentiate the mountain rocks from the creek valley alluvium. The wellfield is represented by a single point-sink pumping center (Fig C-25). The transmissivities from the regional model, with horizontal base of the aquifer set at sea level (0 ft amsl) and regional model hydraulic conductivities of the mountain and alluvium, were translated to the local model hydraulic conductivities, assuming a horizontal base 5,730 feet amsl and static (no pumping) water levels at the wellfield and the saturated thickness of the aquifer (59.8 ft).

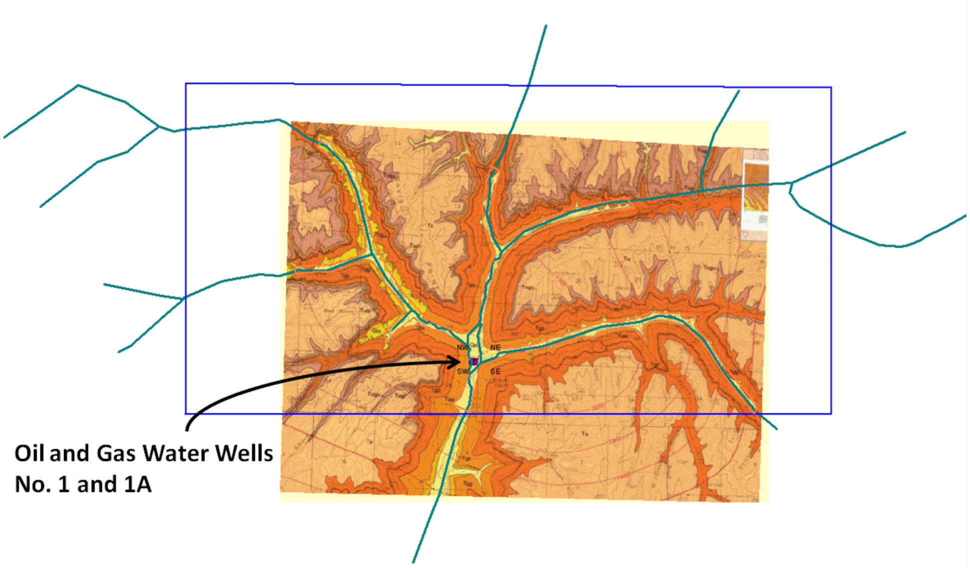


**Figure C-25. GFLOW model of the Parachute confluence. The shallow bedrock geology comes from Hail *et al.* (1989), showing valley-fill alluvium in yellow, and rock formations marlstone, claystone, and mudstone in shades of orange. The GFLOW analytic elements include line-sinks for creeks and inhomogeneities for areal recharge and alluvium.**

The O&G wellfield rated pumping is 45,430 ft$^3$/d. A model with a rock hydraulic conductivity of 1.1115 ft/d and alluvium 22.2 ft/d supported the maximum pumping rate, with drawdown reaching the base of the aquifer (5,730 ft) at the wellfield location. The contouring of hydraulic head for the GFLOW solution associated with the maximum rated pumping is shown in Fig. C-26.

The Parachute confluence GFLOW groundwater model allows mapping of the cone of depression of the water table at the maximum supported pumping rate at the O&G structure, knowing the pre-pumping water table and the pumping influenced water table. The Parachute confluence GFLOW also allows modeling and mapping of the zone contributing water to the pumping wellfield, including capture of baseflow in the nearby creeks. The analysis of groundwater use intensity is included in the discussion of the Piceance structural basin/Upper Colorado River Basin in Chapter 5 of this report.

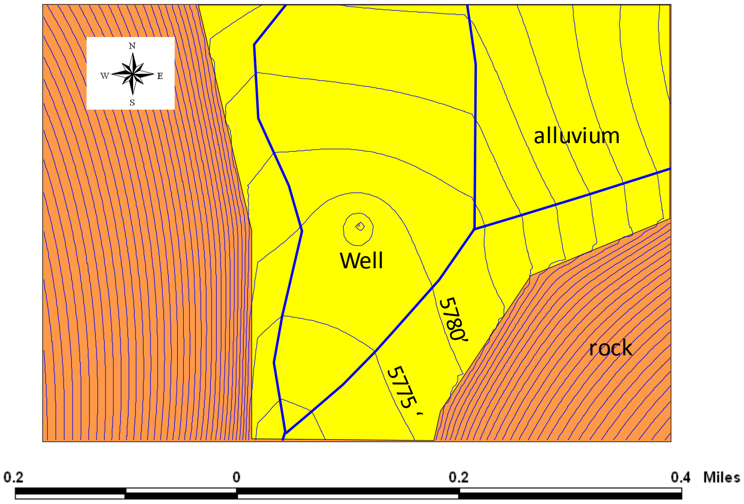


**Figure C-26. GFLOW model solution of the Parachute Creek confluence supporting the maximum rated pumping.**

## References

Adams, D. B., K. E. Goddard, R. O. Patt, and K. C. Galyean. 1986. Hydrologic data from Roan Creek and Parachute Creek basins, Northwestern Colorado. USGS Open-File Report 83-859.

Aquaveo. 2014. MODFLOW modeling with GMS. Available at: http://www.aquaveo.com/software/gms-modflow

Casselberry & Associates. 2009. Sugar Hollow Trout Park & Hatchery long-term aquifer testing plan, Wyoming County, Monroe Township, Pennsylvania. Report submitted to the Susquehanna River Basin Commission.

Casselberry & Associates. 2010. Sugar Hollow Trout Park &0 Hatchery water-supply well evaluation, Eaton Township, Wyoming County, Pennsylvania: December 2009 aquifer testing results, sustained yield assessment and evaluation of the potential impacts of pumping on surface-water features and groundwater supplies. Report submitted to the Susquehanna River Basin Commission.

Casselberry & Associates. 2014. Sugar Hollow Trout Park and Hatchery, October 2013 aquifer testing results, Eaton Township, Wyoming County, Pennsylvania. Report submitted to the Susquehanna River Basin Commission.

Craig, J. 2014. University of Waterloo lecture notes for course E661: Analytical methods in mathematical geology. Available at: http://www.civil.uwaterloo.ca/jrcraig/pdf/EARTH661_AEMLecture.pdf

Dripps, W. R., R. J. Hunt, and M. P. Anderson. 2006. Estimating recharge rates with analytic element models and parameter estimation. Ground Water 44(1): 47-55.

Dunning, C. P., D. T. Feinstein, R. J. Hunt, and J. T. Krohelski. 2004. Simulation of ground-water flow, surface-water flow, and a deep sewer tunnel system in the Menomonee Valley, Milwaukee, Wisconsin. USGS Scientific Investigations Report 2004-5031. 48 pp.

Feinstein, D., C. Dunning, R. J. Hunt, and J. Krohelski. 2003. Stepwise use of GFLOW and MODFLOW to determine relative importance of shallow and deep receptors. Ground Water 41(2): 190-199.

Hail, W. J., Jr., R. B. O'Sullivan, and M. C. Smith. 1989. Geologic map of the Roan Plateau Area, Northwestern CO. USGS Miscellaneous Investigations Series Map 1-1797-C. Available at: http://ngmdb.usgs.gov/Prodesc/proddesc_9919.htm

Haitjema, H. M. 1995. Analytic element modeling of groundwater flow. Academic Press, Inc., San Diego, CA. 394 pp.

Haitjema, H. 2006. The role of hand calculations in ground water flow modeling. Groundwater 44(6): 786-791.

Harbaugh, A. W. 2005. MODFLOW-2005. The U.S. Geological Survey modular ground-water model —the Ground-Water Flow Process. USGS Techniques and Methods 6-A16.

Hunt, R. J. 2006. Ground water modeling applications using the analytic element method. Ground Water 44(1): 5-15.

Johnson, C., and M. Mifflin. 2006. The AEM and regional carbonate aquifer modeling. Ground Water 44(1): 24-34.

Juckem, P. F. 2009. Simulation of the regional ground-water-flow system and ground-water/surface-water interaction in the Rock River Basin, Wisconsin. USGS Scientific Investigations Report 2009-5094. 38 pp.

Kelson, V. A., R. J. Hunt, and H. M. Haitjema. 2002. Improving a regional model using reduced complexity and parameter estimation. Ground Water 40(2): 132-143.

Lohman, S. W. 1939. Ground water in north-central Pennsylvania. Pennsylvania Geological Survey in cooperation with the U.S. Geological Survey. Water Resources Report 6. Reprinted 1973. Plate 01. Geologic map of north-central Pennsylvania compiled by Geo. W. Stose and O. A. Ljungstedt.

Miller, M. P., D. D. Susong, C. L. Shope, V. M. Heilweil, and B. J. Stolp. 2014. Continuous estimation of baseflow in snowmelt-dominated streams and rivers in the Upper Colorado River Basin: A chemical hydrograph separation approach. Water Resources Research 50(8): 6986-6999.

Mitchell-Bruker, S., and H. M. Haitjema. 1996. Modeling steady-state conjunctive groundwater and surface water flow with analytic elements. Water Resources Research 32(9): 2725-2732.

Risser, D. W., J. H. Williams, K. L. Hand, R.-A. Behr, and A. K. Markowski. 2013. Geohydrologic and water-quality characterization of a fractured-bedrock test hole in an area of Marcellus Shale gas development, Bradford County, Pennsylvania. Pennsylvania Geological Survey. 4th ser. Open-File Report OFMI 13—01.1. 49 pp. 4 appendices.

Rutledge, A. T. 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data—update. USGS Water-Resources Investigations Report 98-4148. 43 pp.

Sevon, W. D., and D. D. Braun. 1997. Surficial geology of the Towanda 30 x 60 minute quadrangle, Pennsylvania. Pennsylvania Geological Survey Open-File Report 97-03.

Strack, O. D. L. 1989. Groundwater Mechanics. Prentice Hall, Englewood Cliffs, NJ. 732 pp.

Strack, O. D. L., and H. M. Haitjema. 1981a. Modeling double aquifer flow using a comprehensive potential and distributed singularities: 1. Solution for homogenous permeability. Water Resources Research 17(5): 1535-1549.

Strack, O. D. L., and H. M. Haitjema. 1981b. Modeling double aquifer flow using a comprehensive potential and distributed singularities: 2. Solution for inhomogeneous permeabilities. Water Resources Research 17(5): 1551-1560.

Townley, L. R. 1995. The response of aquifers to periodic forcing. Advances in Water Resources 18(3): 125-146.

Ward, D. S., D. R. Buss, J. W. Mercer, S. S. Hughes. 1987. Evaluation of a groundwater corrective action at the Chem-Dyne hazardous waste site using a telescopic mesh refinement modeling approach. Water Resources Research 23(4): 603-617.

Williams, J. H., L. E. Taylor, and D. J. Low. 1998. Hydrogeology and ground water quality of the glaciated valleys of Bradford, Tioga, and Potter Counties, Pennsylvania. Pennsylvania Geological Survey. 4th ser. Water Resource Report 68. 89 pp.

Yager, R. M., and C. J. Neville. 2002. GFLOW 2000: An analytic element ground water flow modeling system. Ground Water 40(6): 574-576.

# APPENDIX D. Water Use Estimation Methods

## Contents

## Overview

This research required quantifying water use at individual withdrawal locations in the Susquehanna River Basin (SRB) and Upper Colorado River Basin (UCRB) study areas to determine water use intensity from hydraulic fracturing water acquisition. Water use data were compiled and summarized to develop the factual foundation for understanding patterns and volumes of use. They were then used to apply the water use intensity analytical approach to quantify the water balance effects of observed withdrawals on water bodies. Lastly, scenario analyses were used to fill in gaps related to water bodies, climate conditions, or levels of activity that were not well-represented in observed withdrawals. In these analyses, withdrawal assumptions, developed from observed use, were applied to lengthy hydrologic records. This appendix discusses the data sources used in these analyses, and describes the basis for, and derivation of, water use assumptions for scenario analyses.

## Data Sources

Data relevant to Appendix D were obtained from sources listed in Tables D-1 and D-2. Information primarily involved hydraulic fracturing activities (fluid use for well drilling and fracturing, produced water, numbers of wells drilled, etc.) and water withdrawal volumes. A detailed description of all data sources used throughout the report is given in Appendix A.

**Table D-1. Data sources used for use intensity assessment in the Susquehanna River Basin study area (also listed in Table 4-2 in the main report).**

| Source | Data Type | Location | Query |
|---|---|---|---|
| PADEP (2014) | a. Annual PWS water use report | http://www.pawaterplan.dep.state.pa.us/StateWaterPlan/WaterDataExportTool/WaterExportTool.aspx | Primary Facility Report, by year and county |
| | b. PWS facility information | | Chapter 110 (Act 220) Registration |
| PADEP (2013) | Well drilling reports | http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297 | Wells drilled by county |
| SRBC (2013) | a. Water site water use | http://www.srbc.net/pubinfo/index.htm | Provided by SRBC by written request |
| | b. Miscellaneous reports, policies, maps | http://www.srbc.net/publicinfo/index.htm | Website search |
| | a. Well consumptive Use | http://www.srbc.net/pubinfo/index.htm | Provided by SRBC by written request |
| | c. Docketed permits | http://www.srbc.net/wrp/ | Water Resource Portal/Search for Projects |

**Table D-2. Data sources used for use intensity assessment in the Upper Colorado River Basin study area (also listed in Table 5-2 in the main report).**

| Agency/Organization | Description | Source/query | Data Use |
|---|---|---|---|
| Colorado Division of Water Resources (CODWR 2014) | a. Water rights information | http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx | Priority, decreed use |
| | b. Structure information | http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx | Locations, history, ownership |
| | c. Structure water use | http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx<br>(query structures for diversion reports) | Daily, monthly, annual volumes used |
| | d. StateMod water planning program | http://cdss.state.co.us/Modeling/Pages/SurfaceWaterStateMod.aspx | Scenario analysis of use and structure priority |
| Colorado Oil and Gas Conservation Commission (COGCC 2014) | a. Well starts and completions | http://cogcc.state.co.us<br>Query: staff report | Well counts |
| | b. Produced Water | http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyWaterProdByCounty | Estimates of HF wastewater reuse |
| FracFocus (2014) | Well fluid volumes | http://www.fracfocusdata.org/DisclosureSearch/<br>(query by county, look at individual well reports) | Total well consumption, counts, timing |

## Estimation of Hydraulic Fracturing Water Use

In both study areas, data were obtained for:

- Individual hydraulic fracturing well consumption
- Water withdrawals from sources (streams, ponds, reservoirs, etc.)
- Hydraulic fracturing scenarios: estimating annual hydraulic fracturing activity
- Background water consumption (domestic, agricultural, etc.)

## Susquehanna River/Towanda Creek

The approach for estimating daily hydraulic fracturing demand in modeled subbasins in Towanda Creek was to divide individual hydraulic fracturing well demand by an estimated average number of days used to fracture the well. That daily demand was added to daily background demand, a sum that could then be compared to daily availability (streamflow) to calculate surface water use intensity (SUI) values.

### Individual Hydraulic Fracturing Well Consumption

SRBC provided a database of water used from September 2008 to December 2011 in hydraulic fracturing operations at well pads. This dataset of 944 records was considered a large statistical sample of the entire population of hydraulic fracturing wells in the study area. It contained the following pertinent data fields:

- ABR (a unique ID given to each individual well pad)
- Project sponsor (generally, the name of the pad owner)
- Stimulation start date
- Stimulation end date
- Total fluids injected
- Wastewater injected
- Flowback injected
- Freshwater injected
- Flowback recovered

Data were reviewed and 196 records removed according to the following criteria:

- All data fields identical to another record (duplicate records)
- Zero volume of injected freshwater
- Injected freshwater volume greater than total injected fluid volume

A total of 748 records remained. Their distribution of injected freshwater is shown in Fig. D-1. The mean use was approximately 4 million gallons of freshwater per well. Other statistical information for the sample is shown in Table D-3.

**Table D-3. Information on water usage at hydraulic fracturing wells in the Susquehanna River Basin from 2008 to 2011. (Data source: SRBC 2013a.)**

| Hydraulic Fracturing Well Facts: Susquehanna River Basin | Value |
|---|---|
| Number of wells in sample | 748 |
| Average total injected volume per well (MG) | 4.25 |
| Average total freshwater volume per well (MG) | 3.85 |
| % Freshwater volume per well | 87% |
| % Wastewater | 0.1% |
| % Flowback water injected | 13% |
| % Flowback water returned | 7% |

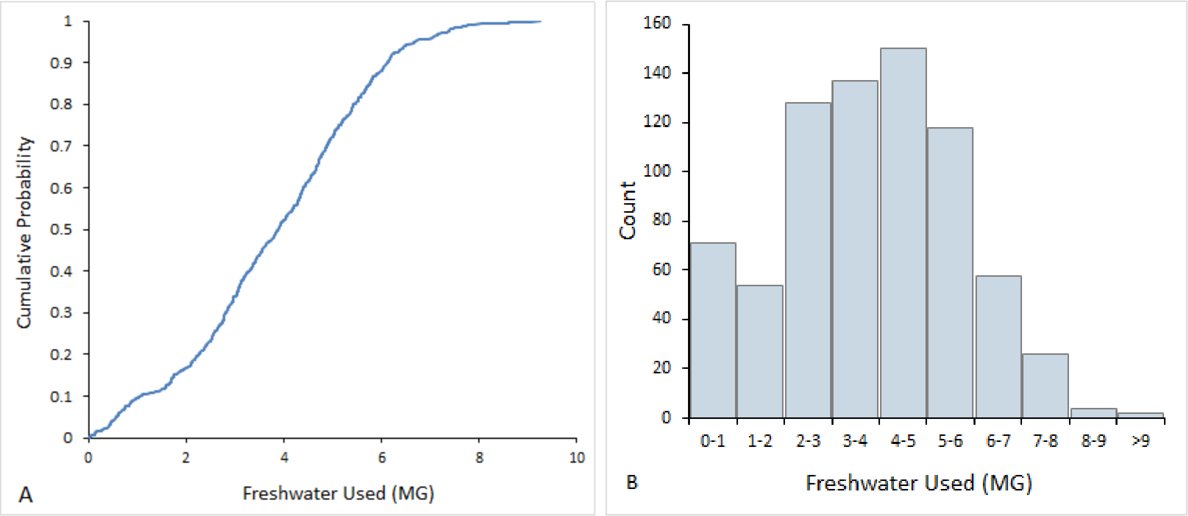


**Figure D-1. The cumulative distribution function (A) and histogram (B) of injected freshwater volumes at 748 hydraulic fracturing wells across the Susquehanna River Basin. (Data source: SRBC 2013a.)**

Since this dataset also provided starting and ending dates of stimulation of each well, the length of the fracturing event was derived by calculating the number of days between them. This period may not accurately represent the duration of stimulation, however, due to work stoppages for reasons such as weekends and holidays, equipment availability, and equipment failure. Additionally, companies sometimes begin stimulation to meet permit requirements, then complete the process later when personnel and equipment are readily available (SRBC staff, personal communication, April 2014). Therefore, events lasting more than 30 days were discarded. The cumulative distribution function (CDF) and histogram of stimulation lengths for the remaining records are shown in Fig. D-2. The mean and median of this distribution were nine and eight days, respectively. Seven days was assumed to be a reasonable estimate for the length of hydraulic fracturing activity at an individual well.

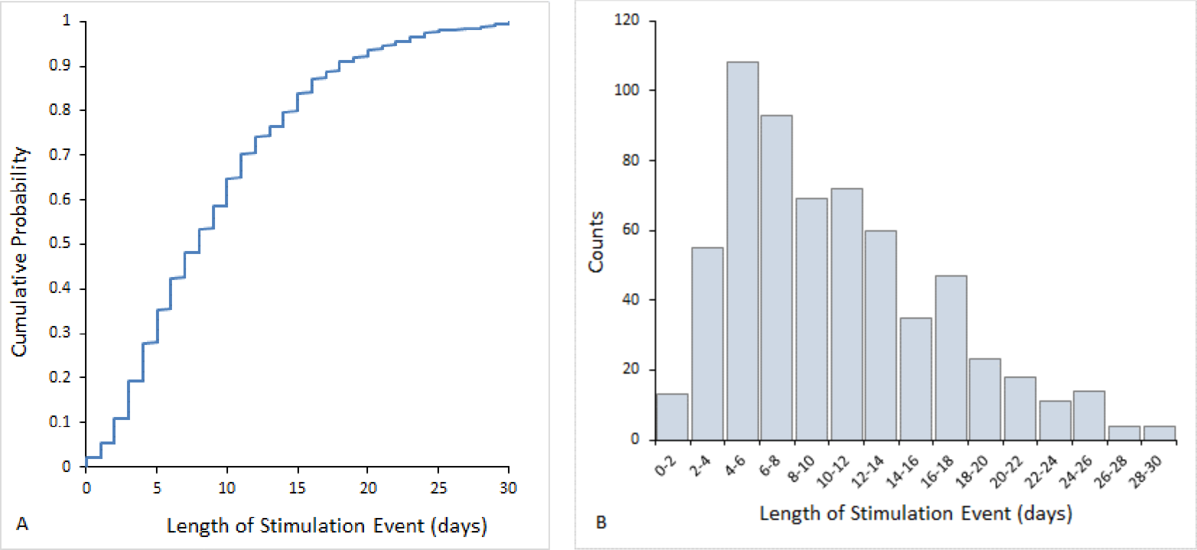


**Figure D-2. The cumulative distribution function (A) and histogram (B) of the length of stimulation events for 748 hydraulic fracturing wells across the Susquehanna River Basin. (Data source: SRBC 2013a.)**

## Water Withdrawals from Permit Sites

SRBC provided a database of water removal from permitted sites across the Susquehanna for 2009–2013. The original database had 35,011 non-zero-volume withdrawal records and the following pertinent data fields:

- Docket # (the number given to an individual withdrawal location)
- Source ID (the number given to a specific entity withdrawing from a certain location)
- Date of withdrawal
- Gallons taken

The data were sorted by source type (stream, pond, reservoir, groundwater well, etc.) and records corresponding to non-stream sites were discarded, leaving 29,907 records of withdrawals for 97 permitted streams. The CDF and histogram of these removal records are shown in Fig. D-3. The median withdrawal was 0.185 MG, and the 95th percentile was 1.0 MG.

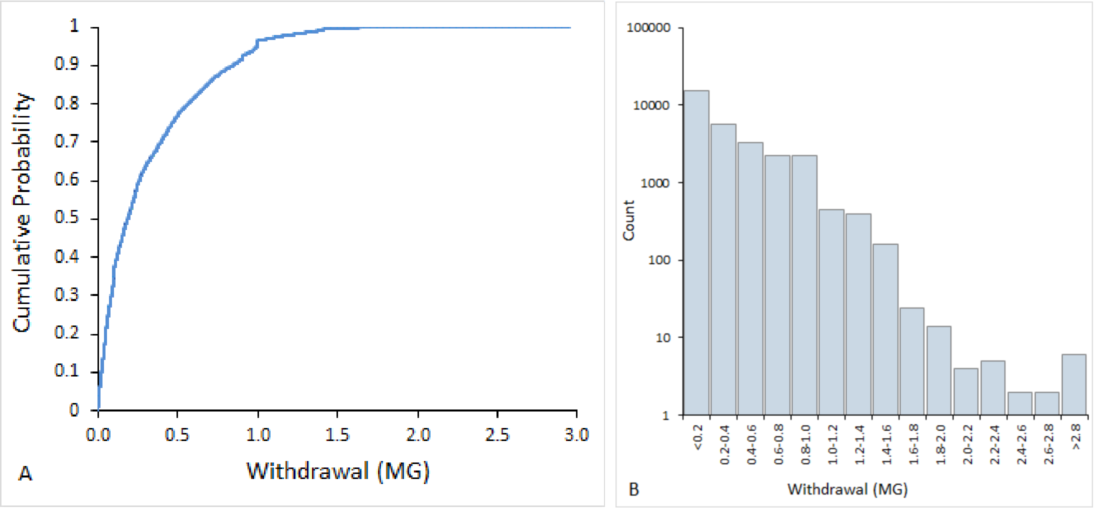


**Figure D-3. The cumulative distribution function (A) and histogram (B) of water volumes removed at permitted sites in the Susquehanna River Basin, 2008–2013. (Data source: SRBC 2013a).**

## Hydraulic Fracturing Scenarios in the Susquehanna River Basin

Hydraulic fracturing scenarios were designed to test all subbasin streamflows during the modeling period (1987–2012) in proportion to their occurrence. Each day, a volume of water representing the sum of hydraulic fracturing and background use was withdrawn. That estimation is discussed in the next section. Three daily hydraulic fracturing demand volumes were investigated. Two reflect current conditions in the SRB: the median (0.185 million gallons per day, or MGD) and mean (0.31 MGD) of the data, presented in Fig. D-3. The third represented a future peak drilling rate in the Towanda Creek basin of 0.57 MGD. That rate was determined using an estimate of 52 hydraulic fracturing wells per year (Fig. D-2) at an average of 4 MG per well. The daily withdrawal volumes in all three scenarios were routinely observed (Fig. D-3B). Scenario analysis assumed that all hydraulic fracturing wells consume water from one source across all 26 years, rather than distributing withdrawals among modeled subbasins.

## Background Consumption

The SRBC is conducting a detailed study to estimate cumulative water use in basins across the Susquehanna watershed. Although it has not yet published a final report on methodology used to derive these estimates, draft documents detailing the study are online at http://www.srbc.net/planning/cwuas.htm. Data used by SRBC are shown in Table D-4. SRBC provided daily water use estimates for the scenario test basin. Residential usage was estimated at 0.11 MGD, livestock at 0.16 MGD, and crop irrigation at 0.215 MGD. These figures were based on county-level data on water use coefficients in residential areas (USGS), population information (U.S. Census Bureau), livestock populations (U.S. Department of Agriculture, or USDA) and per-acre irrigation volumes for various crops (USDA). Estimates took into account the amount of water used in each category that is actually consumed (lost to the system) versus water eventually returned to the stream network.

**Table D-4. Data sources used by the Susquehanna River Basin Commission to estimate non-hydraulic-fracturing water use in Towanda Creek, Pennsylvania.**

| Organization | Description | References | Use |
|---|---|---|---|
| U.S. Geological Survey | Per capita water use coefficients | Shaffer, K.H., and Runkle, D.L. 2007. Consumptive Water-Use Coefficients for the Great Lakes Basin and Climatically Similar Areas: U.S. Geological Survey Scientific Investigations Report 2007–5197. | Residential water use |
| U.S. Census Bureau | Population density by county | United States Department of Commerce, Census Bureau, Geography Division. 2010. 2010 Census Population & Housing Unit Counts—Blocks. TIGER/Line Shapefile. Available at: http://www.census.gov/geo/maps-data/data/tiger-data.html | Residential water use |
| U.S. Department of Agriculture | Livestock population by county | U.S. Department of Agriculture. 2007. Tables 11-17. In: Census of Agriculture. Volume 1, Chapter 2: County data. | Livestock water use |
| | Per-animal water use coefficients | Jarrett, A.R. 2002. Estimation of agricultural animal and irrigated-crop consumptive water use in the Susquehanna River Basin for the years 1970, 2000, and 2025. PSU Department of Agricultural Engineering. | Livestock water use |
| | Crop acreage by county | U.S. Department of Agriculture, National Agriculture Statistics Service. 2010. Cropland data layer. Available at: http://www.nass.usda.gov/research/Cropland/Release/.<br>U.S. Department of Agriculture, National Agriculture Statistics Service. 2007. Tables 10, 26-29, 31, and 33; Appendix B-35. In: Census of Agriculture. Volume 1, Chapter 2: County Data (Maryland, New York, Pennsylvania). | Irrigation water use |
| | Water use per acre by crop type | U.S. Department of Agriculture, National Agriculture Statistics Service. 2008. Table 28: Estimated quantity of water applied and primary method of distribution by selected crops harvested: 2008 and 2003. In: Farm and Ranch Irrigation Surveys. Available at: http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.php. | Irrigation water use |

Daily background use estimates in the three categories were distributed among the modeled subbasins in Towanda Creek using categories of the 2006 National Land Cover Database: agricultural row crops, grass/pasture, and residential/urban (see Appendix A for additional information on data references). The area of a specific cover type within a certain subbasin was compared to the area of that cover type within the entirety of Towanda Creek. This determined the percentage of total daily use volume assigned to that unit. This method produced a unique background use estimate for each subbasin. For example, if a subbasin had 440 acres of grass/pasture and the total grass/pasture area of Towanda Creek was 29,400 acres, that subbasin received 1.5% (440/29,400) of the livestock background water use estimate.

## Upper Colorado River Basin

The approach for estimating daily hydraulic fracturing demand for modeled subbasins in the UCRB was to multiply per-well freshwater usage by number of wells developed annually to arrive at annual hydraulic fracturing demand. Annual demand was then converted to daily demand by assuming that hydraulic fracturing activities occur 365 days a year. Daily demand was added to daily background demand, a sum that could then be compared to daily availability (streamflow) to calculate SUI values.

### Individual Hydraulic Fracturing Well Consumption

Since there is no direct report of how much freshwater is used for hydraulic fracturing wells in databases managed by the state of Colorado, estimates were developed using information provided to federal agencies by hydraulic fracturing operators and data sources listed in Table 5-2. Oil and gas (O&G) companies have reported that freshwater is used only for drilling and its associated activities. According to local operators and agencies, high reuse rates are possible because nearly all hydraulic fracturing fluid injected into directionally drilled tight gas wells in the Williams Fork Formation returns to the surface within a few months after fracturing.

Operators report that drilling of directional wells and related development consume 0.25 MG (0.77 ac-ft) per well. WPX Corporation has begun to drill horizontal wells into the Mancos Shale in recent years, reporting that 1.0 MG (3.2 ac-ft) is needed for these deeper, longer wells (site interview, January 8, 2014).

### Water Withdrawals from Structures

Daily (2008–2013) and total monthly (1950–2013) withdrawal volumes from 21 active diversion structures (Fig. D-4) in Parachute Creek, and 12 in Roan Creek, were obtained from the Colorado Division of Water Resources: http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx. For SUI calculations, daily structure withdrawals in both basins were compared to estimated streamflow at these structures, while historical monthly structure withdrawals were used in a modeling exercise, StateMod, discussed in Section 3.

**Figure D-4. Head gates used to control flows into a diversion (© 2014 Farmers Conservation Alliance, used with permission, http://farmerscreen.org/screen-projects/featured-projects/ ).**

### Hydraulic Fracturing Scenarios

Two sets of two hydraulic fracturing withdrawal scenarios (four in all) were examined for Roan and Parachute watersheds (Table D-5). We define current use as annual mean hydraulic fracturing drilling rates in Garfield County during 2011–2013, and peak use as the highest historic drilling rate, which occurred in 2008 (see main text, Table 5-3). Within both current and peak scenarios, SUI values were computed by assuming all completed wells were directional (0.25 MG fresh water per well) and all new wells were horizontal (1.05 MG fresh water per well). Note: horizontal drilling has just begun in this area; from 2008 to 2013, completed wells were overwhelmingly directional.

**Table D-5. Daily withdrawal rates (in million gallons per day) under the four hydraulic fracturing drilling scenarios.**

| Scenario | Division 5 Drilling Rate (Wells/Year) | Parachute Contribution (Wells/Year) | Parachute Total Water Need (MGY) | Parachute Groundwater Contribution (MGY) | Parachute Surface Water Contribution (MGY) | Parachute Surface Water Withdrawal Rate (MGD) |
|---|---|---|---|---|---|---|
| ***Current Drilling*** | 600 | 300 | | | | |
| Directional | | | 75 | 41 | 34 | 0.093 |
| Horizontal | | | 315 | 41 | 274 | 0.75 |
| ***Peak Drilling*** | 1,700 | 850 | | | | |
| Directional | | | 213 | 41 | 172 | 0.47 |
| Horizontal | | | 893 | 41 | 852 | 2.33 |

**Current Drilling.** From 2011 to 2013, approximately 600 wells were initiated annually in Garfield County (Table 5-3); CODWR water use data suggested that Parachute Creek supplied the water needed for half of them (Fig. 5-18). Structure data indicate that groundwater sources in Parachute supplied 41 MGY of freshwater for hydraulic fracturing use, and it was assumed that this would remain constant across all scenarios. The remaining volume would be supplied by surface waters in Parachute, a magnitude that would depend on the types of wells being developed (Table D-5). The 100% directional well scenario equated to a 0.093 MGD withdrawal rate, assuming withdrawal occurred uniformly for 365 days per year. The 100% horizontal well scenario withdrawal rate equated to 0.75 MGD.

**Peak Drilling.** During peak hydraulic fracturing activity in Garfield County in 2008, almost 1,700 wells were initiated (Table 5-3). Using the same calculations presented in the Current Drilling scenario, the daily withdrawal rate was estimated to be 0.47 MGD under the 100% directional well scenario and 2.33 MGD for the 100% horizontal well scenario.

## Background Consumption

For Parachute and Roan Creeks, background water consumption estimates were derived from 2005 data (Table D-6) on water use in Garfield County (Ivahnenko and Flynn 2010). Only water for domestic (1.2 MGD) and livestock (0.3 MGD) purposes was considered relevant. Though water volumes used for crop irrigation are quite large, the irrigation season coincides with the "call period," which historically runs from mid-April through October. Water use at structures with junior rights may cease if a senior right places a "call" for water. SUI values at withdrawal structures were explicitly calculated for this period, so SUIs for modeled subbasins were only calculated during the "free-river period" (November through mid-April). Municipal water use was excluded because public water supplies in Parachute and Roan are primarily derived from groundwater wells or the Colorado River (see Chapter 5). Industrial use, which includes the hydraulic fracturing industry, was excluded from background use calculations. There are no mining operations in the Parachute and Roan watersheds.

**Table D-6. Daily volumes of water use in Garfield County by category (Data source: Ivahnenko and Flynn 2010).**

| Water Use | Amount (MGD) | Used | Assumption |
|---|---|---|---|
| Domestic | 1.2 | Yes | Relevant |
| Livestock | 0.3 | Yes | Relevant |
| *Irrigation* | *334* | *No* | *Impact directly evaluated using structure data* |
| *Municipal* | *15* | *No* | *Water supply derived primarily from Colorado River* |
| *Industrial* | *0.5* | *No* | *Hydraulic fracturing water use was explicitly estimated* |
| *Mining* | *0.1* | *No* | *Does not occur in the study area* |

County-wide background use was applied to Parachute and Roan Creeks by area. Since these basins constitute 25% of Garfield County, 25% of domestic and livestock water use was included in the SUI analyses. Roan is approximately 510 $mi^2$ and Parachute is 200 $mi^2$, so these areas were used to apportion total background use between the watersheds. Livestock water use was distributed to subbasins using their relative acreage of hay/pasture (from the 2006 National Land Cover Database; see Appendix A for data reference). The same approach was taken in distributing domestic water use to subbasins, but using residential land use relative to acreage instead.

## Colorado Division of Water Resources: StateMod

The Colorado Division of Water Rights has a modeling system called StateMod (http://cdss.state.co.us/software/Pages/StateMod.aspx) to help water planners assess impacts of planned actions on water allocation in the rights system. The user can apply scenarios to determine how much water may actually be acquired from modeled structures, given streamflow. Simulation results are based on

- Location of each withdrawal structure on a stream network
- Priorities of the various water rights held at each structure
- A demand scenario identifying the structure-specific volume of water that may be withdrawn
- A time series of streamflow that represents water availability

StateMod uses this information to route streamflow through the network of structures, removing a portion of flow at each, while maintaining all water rights, limitations, and priorities associated with them. A representation of the StateMod network built for Parachute Creek is shown in Fig. D-5.

This project applied two demand scenarios:

- Per-month median of total monthly withdrawals at each structure since 1950 (MD)
- Per-month total decreed amount of water, summed across all rights at each structure (DD)

These scenarios were calculated from withdrawal records and decreed volumes for primary structures in Parachute Creek obtained from the Colorado Water Conservation Board (http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx). Median and decreed monthly withdrawals for four example structures are shown in Fig. D-6. Note: the DD scenario is the maximum volume that could theoretically be taken under unlimited water availability (i.e., very high streamflow).

StateMod was run under two extreme flow regimes:

- 2011 (second-highest annual streamflow in the Colorado River near Cameo since 1934)
- 2012 (third-lowest annual streamflow in Colorado River near Cameo since 1934)

Four sets of StateMod results were thus produced:

- Median withdrawals in a dry year
- Median withdrawals in a wet year
- Decreed withdrawals in a dry year
- Decreed withdrawals in a wet year

For each set, StateMod's simulated volume of water taken at each structure was compared to volume specified by the demand scenario. *Deficiency* was defined as:

$$\text{Deficiency} = 1 - (\text{Water Taken}/\text{Water Demand}) \qquad \textbf{Equation D-1}$$

If a structure received water equal to the scenario demand, deficiency was 0. If the structure received no water, deficiency was 1. A deficiency map for each scenario is shown in the main text (Fig. 5-25).

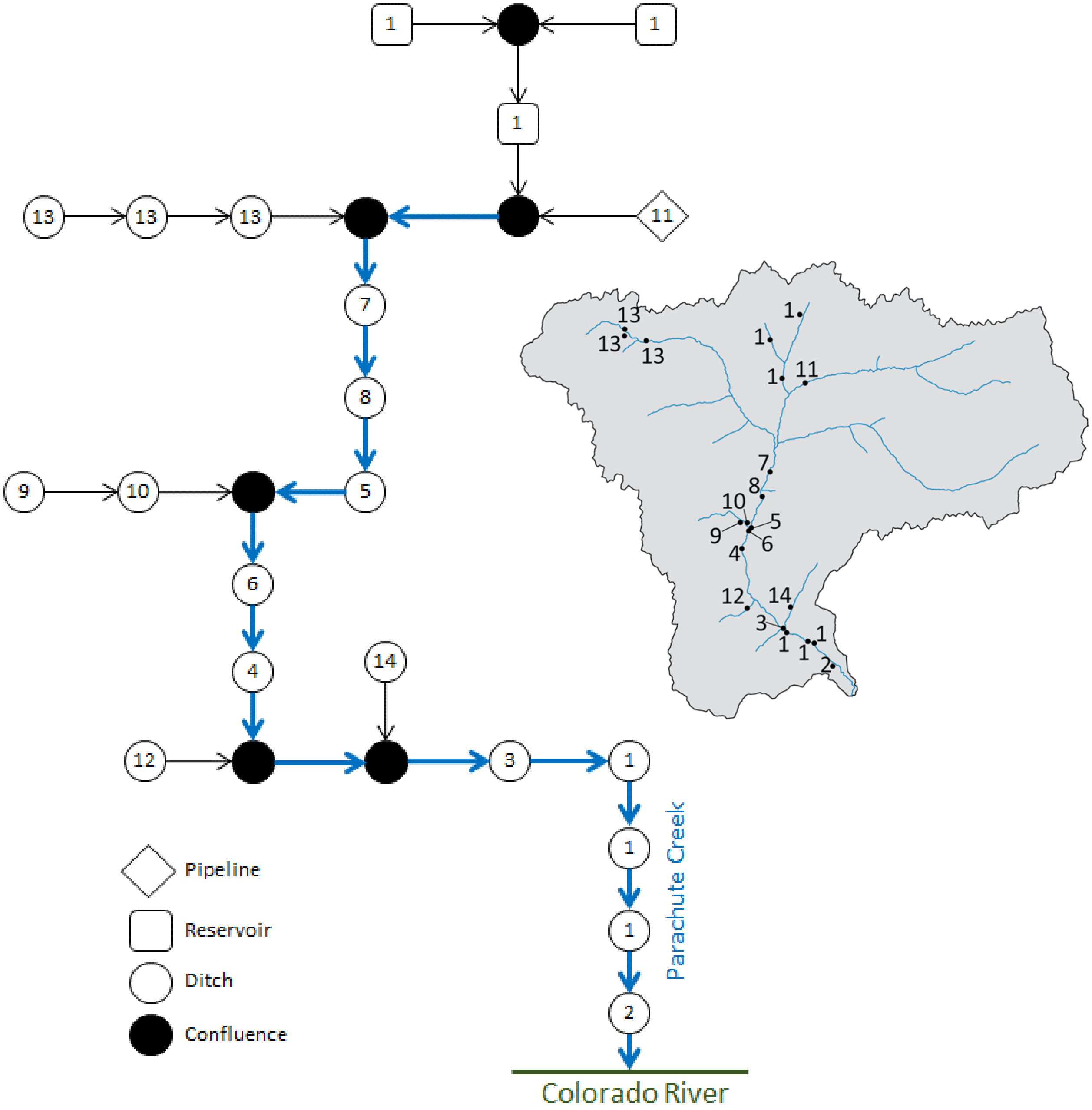


**Figure D-5. Schematic representation of the structures on Parachute Creek simulated in StateMod. Numbers inside the shapes indicate relative priority (1 for highest priority, etc.) of the senior water right at each structure. Inset map depicts location of these structures in the watershed.**

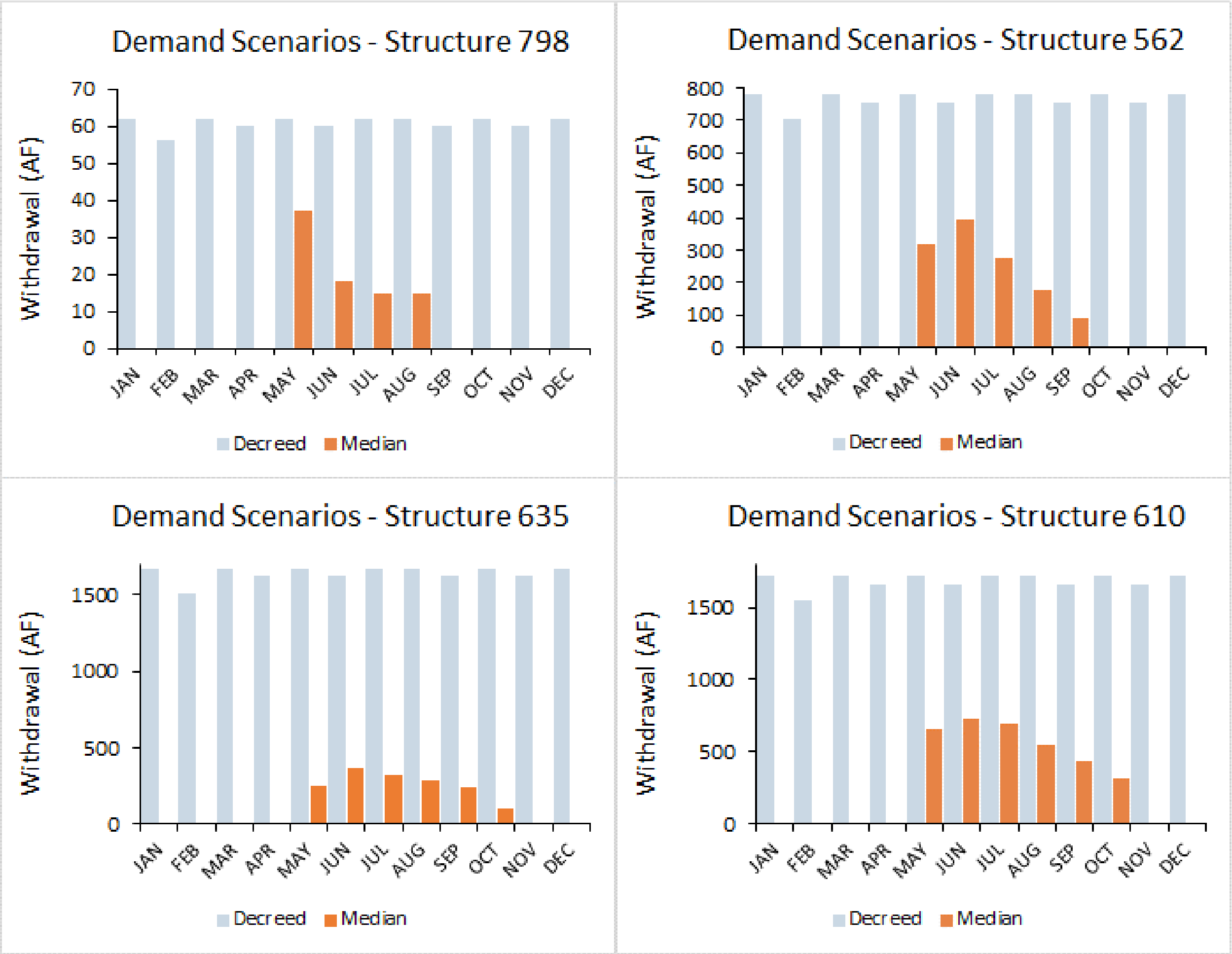


**Figure D-6. Demand scenarios (median and decreed) for example structures in Parachute Creek. Note the different magnitude of y-axes from plot to plot. Information from Colorado Division of Water Resources database on structure withdrawals, 1950–2013.**

Fig. D-7 illustrates scenario results and provides some insight into how the water allocation system locally allocates water during shortages. In the very wet year, the median 60-year irrigation demands (top left in Fig. 5-25) were met at all structures. Indeed, there was no “call” placed on the Colorado River in this year. In the dry year, historical water demand (top right in Fig. 5-25) could not be satisfied at many of the structures. In the decreed demand scenario, no structure receives all the water it expects. Some of the O&G structures supplying hydraulic fracturing freshwater would receive at least some of their request while some downstream structures would not. This example demonstrates that the system is dependent on water supply and that water demand  locally exceeds supply.

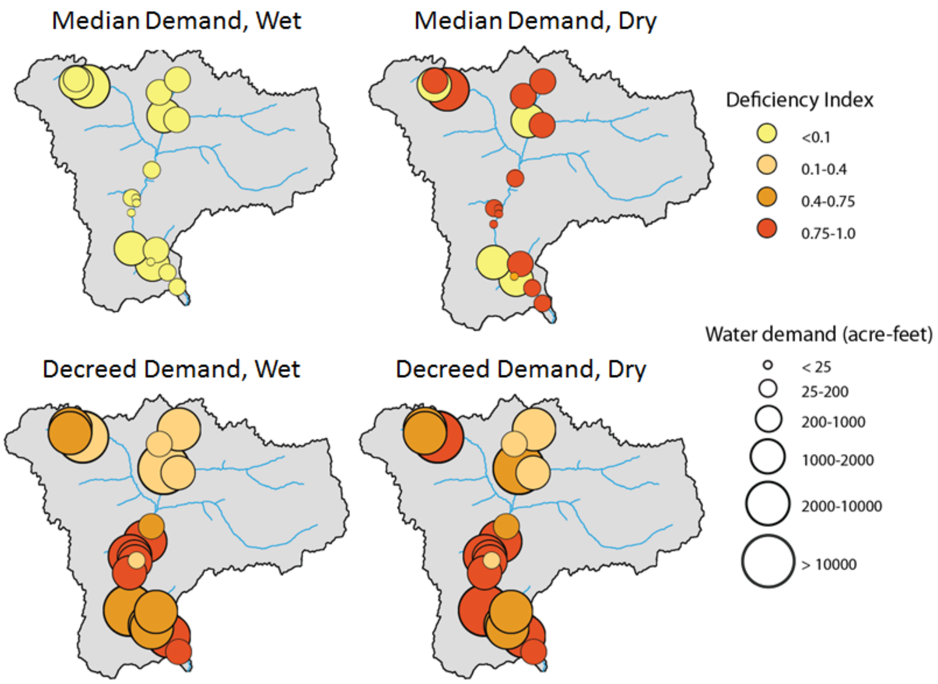


**Figure D-7. Structure deficiency in Parachute Creek for two demand and meteorological scenarios applied at each structure: (1) the median of annual withdrawal since 1950 and (2) decreed demand is the total of all water rights. The size of each circle represents the categorical water demand volume; color indicates the proportion of demand not met—"deficiency"—given streamflow. Deficiency is estimated with CODWR's water planning model StateMod (CODWR 2014e). The wet year and dry year were historical high and low flow years at the stream gage in the Colorado River at Cameo: 2011 and 2012, respectively.**

## Scenario Analyses

The EPA progress report detailing hydraulic fracturing impacts on drinking water supplies (U.S. EPA 2012) outlined a strategy for capturing future conditions and the impact of changes on water availability in the SRB and the UCRB. Scenario modeling would ensure that analyses reflected the most important factors affecting water use and availability in the study areas vis-à-vis current practices and possible future practice:

- Hydraulic fracturing activity
- Hydraulic fracturing water management (primarily recycling of hydraulic fracturing fluids)
- Land use change (population growth and public water supplier (PWS) demand)
- Meteorology variability
- Source locations

A summary of these factors and how each was addressed in this study's current scenario ("Business as Usual," U.S. EPA 2012) and high-end scenario ("Energy Plus," U.S. EPA 2012) appears in Table D-7. Hydraulic fracturing activity was addressed using current conditions and peak levels that could occur in the next 30 years, based on recent drilling trends and projections of natural gas production. Hydraulic fracturing water management looked at potential reductions in the percentage of recycled hydraulic fracturing fluid due to changes in geology of tapped plays. Population growth was simulated by increasing PWS demand, where relevant. Meteorological variability was addressed using a 26-year precipitation series (1987–2012) that captured a range of conditions for each study area. Watershed modeling allowed SUI estimation at smaller basin scales than could be thoroughly investigated with empirical data.

**Table D-7. Important factors affecting water availability and hydraulic fracturing water use in the Susquehanna River Basin (SRB) and Upper Colorado River Basin (UCRB) study areas.**

| Scenario | Hydraulic Fracturing Activity | | Hydraulic Fracturing Water Management | | Population Growth | | Meteorology | | Source Locations | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *SRB* | *UCRB* | *SRB* | *UCRB* | *SRB* | *UCRB* | *SRB* | *UCRB* | *SRB* | *UCRB* |
| Current | Median/mean withdrawals from actual sources | Current annual drilling rate, 2011–2013 | Current recycling % | Current recycling % | Current population | Current population | 1987–2012 | 1987–2012 | Modeling: 0.35–215 mi$^2$ basins | Modeling: 4.5–510 mi$^2$ basins |
| High-End | Peak annual projected drilling rate | Peak annual drilling rate, 2008 | No change: % recycling already low | Reduced recycling rate | No change: population growth not expected | Increased public water supplier demand | No change | No change | No change | No change |

## References

Ivahnenko, T., and J. Flynn. 2010. Estimated withdrawals and use of water in Colorado, 2005. USGS Scientific Investigations Report 2010-5002. Reston, VA.

Jarrett, A.R. 2002. Estimation of agricultural animal and irrigated-crop consumptive water use in the Susquehanna River Basin for the years 1970, 2000, and 2025. PSU Department of Agricultural Engineering.

PADEP 2013. http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297

PADEP 2014. http://www.pawaterplan.dep.state.pa.us/StateWaterPlan/WaterDataExportTool/WaterExportTool.aspx

Shaffer, K.H., and Runkle, D.L. 2007. Consumptive Water-Use Coefficients for the Great Lakes Basin and Climatically Similar Areas: U.S. Geological Survey Scientific Investigations Report 2007–5197.

Susquehanna River Basin Commission. 2013. http://www.srbc.net/pubinfo/index.htm

U.S. Department of Agriculture. 2007. Tables 11-17. In: Census of Agriculture. Volume 1, Chapter 2: County data.

U.S. Department of Agriculture, National Agriculture Statistics Service. 2010. Cropland data layer. Available at: http://www.nass.usda.gov/research/Cropland/Release/.

U.S. Department of Agriculture, National Agriculture Statistics Service. 2007. Tables 10, 26-29, 31, and 33; Appendix B-35. In: Census of Agriculture. Volume 1, Chapter 2: County Data (Maryland, New York, Pennsylvania).

U.S. Department of Agriculture, National Agriculture Statistics Service. 2008. Table 28: Estimated quantity of water applied and primary method of distribution by selected crops harvested: 2008 and 2003. In: Farm and Ranch Irrigation Surveys. Available at: http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.php.

U. S. Department of Commerce, Census Bureau, Geography Division. 2010. 2010 Census Population & Housing Unit Counts—Blocks. TIGER/Line Shapefile. Available at: http://www.census.gov/geo/maps-data/data/tiger-data.html

U.S. EPA (Environmental Protection Agency). 2012. Study of the potential impacts of hydraulic fracturing on drinking water resources: Progress report. EPA/601/R-12/011. Washington, DC. Available at: http://www2.epa.gov/sites/production/files/documents/hf-report20121214.pdf

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# APPENDIX E.

# QUALITY ASSURANCE **AND** QUALITY CONTROL

## Contents

## Overview

This project has followed quality assurance procedures described in the Quality Assurance Project Plan titled Modeling the Impact of Hydraulic Fracturing on Drinking Water Resources Bases on Water Acquisition Scenarios: Phase 2 Version 1.0 (US EPA, 2013b). The quality assurance project plan (QAPP) addresses:

- Data source quality and documentation
- General analytical approach applied to acquired data,
- Modeling quality assurance, and
- Data management and project archival record keeping, and
- Product review.

Project implementation involved gathering information and data from state and federal agency websites and hydrologic modeling of hydraulic fracturing withdrawal scenarios. The project generated no new data though laboratory or field projects. Acquired and modeled data were summarized according to project scientific design.

## Data Acquisition

The project team gathered information on where and how much water was acquired in each study basin by querying publicly available databases from state, regional governmental agencies, and federal data sources, augmented by databases maintained by nonprofit, or industry organizations. A comprehensive list of data sources is provided in Appendix A. All data acquired may not have been used in final data products presented in this report but have been archived with project materials.

The EPA does not make any claims as to the quality or accuracy of the data gathered from the state, federal, and industry data sources used in the project. The project team applied quality assurance and quality control measures to acquired data to ensure that the analyses performed were properly conducted and that the data used in this report faithfully represented the original data obtained from agency and non-governmental data sources. Acquired data was reviewed, but was used as received. Inspection occasionally identified significant outliers that suggested uncorrected data entry errors. The project team corrected obvious errors or consulted with source data owners to verify or correct.

A portion of the data was spatially registered in geographic information system databases, termed secondary data. Secondary geospatial was evaluated for completeness with the validation tool of the EPA Metadata Editor (EME) (https://edg.epa.gov/EME/) to determine if it met the minimum requirements of the Federal Geographic Data Committee's (FGDC) Content Standard for Digital Geospatial Metadata (FGDC, 1998) and the EPA Geospatial Metadata Technical Specification (USEPA, 2007). The project team determined whether data could be used and the results of the validations were documented. The EME was subsequently used to update the metadata records addressing any validation errors previously encountered.

## Analytics

The project QAPP described analytical approaches for assessing and summarizing water acquisition to water available. Three types of analyses were applied in each study basin: 1) the facts of water acquisition were summarized, 2) data were used to systematically quantify the water balance effects of observed hydraulic fracturing withdrawals on water bodies at the local scale, and 3) scenario analyses were applied to reduce gaps in available data related to water bodies, climate conditions, or levels of potential hydraulic fracturing activity that were not well represented in observed hydraulic fracturing withdrawals.

Estimates of water volumes at withdrawal sites was needed to perform water use intensity calculations. Most water was acquired from rivers and streams and USGS streamflow data were the primary source of information on available water volume. Various techniques were used to extrapolate streamflow volume at ungaged withdrawal locations from observed flow at gaged sites including empirical techniques and hydrological modeling using the Hydrological Simulation Program—Fortran (HSPF). Streamflow estimation procedures were outlined in U.S. EPA 2013b. Methods, calibration results and analysis of the precision of streamflow estimates are described in Appendix B of this report. Groundwater pumping was assessed at well locations in each study basin using the groundwater model GFLOW™. Modeling methods and calibration results are described in detail in Appendix C.

All statistics and graphing were performed with R Statistical Software, version 3.0.1 (R Core Team 2013) or Microsoft Excel (2007).

Data files are managed in project electronic archives as defined in the project QAPP (U.S. EPA 2013b).

## Product Review

The project quality assurance project plan (U.S. EPA 2013b) was approved by the EPA project quality assurance manager on August 30, 2013.

The project was included in a laboratory competency audit (LCA) for the ERD/NERL Division in Athens, Georgia on August 19-20, 2014, and no corrective actions were identified.

This report was independently peer reviewed using a contractor-led Letter Review, following procedures specified in U.S. EPA Drinking Water Resources Quality Management Plan (Environmental Protection Agency 2012b, Revision No. 1. (Available at: http://www2.epa.gov/hfstudy/quality-management-plan-revision-no-1-plan-study-potential-impacts-hydraulic-fracturing).

## References

FGDC (Federal Geographic Data Committee). 1998. Content Standard for Digital Geospatial Metadata, FGDC-STD-001-1998. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/metadata/base-metadata/index_html.

U.S. EPA (Environmental Protection Agency) 2007. Geospatial Metadata Technical Specification Version 1.0. Office of Information Collection Office of Environmental Information, Environmental Protection Agency, November 2007. http://www.epa.gov/geospatial/policies.html.

U.S. EPA (Environmental Protection Agency) 2012b. U.S. EPA Drinking Water Resources Quality Management Plan Revision No. 1. (Available at: http://www2.epa.gov/hfstudy/quality-management-plan-revision-no-1-plan-study-potential-impacts-hydraulic-fracturing).

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