

PART 1. RISK ASSESSMENT

AN OVERVIEW OF NATURAL GAS OPERATIONS IN GARFIELD COUNTY

Most of the natural gas extracted in the Piceance Basin comes from the Williams Fork Formation of the Mesa Verde Group (Figure 6). The gas occurs in sandstone deposits (often referred to by geologists as “sand bodies”) which are isolated from each other by non-gas bearing, impermeable shale. The sand bodies are relatively small, averaging about nine feet thick from top to bottom and about 500 feet across. Because of their low permeability, it has not been economically feasible to recover gas from the sand bodies using conventional methods. However, recent advances in well drilling and stimulation technology coupled with a strong national market for natural gas has made the Williams Fork Formation the focus of intense development.

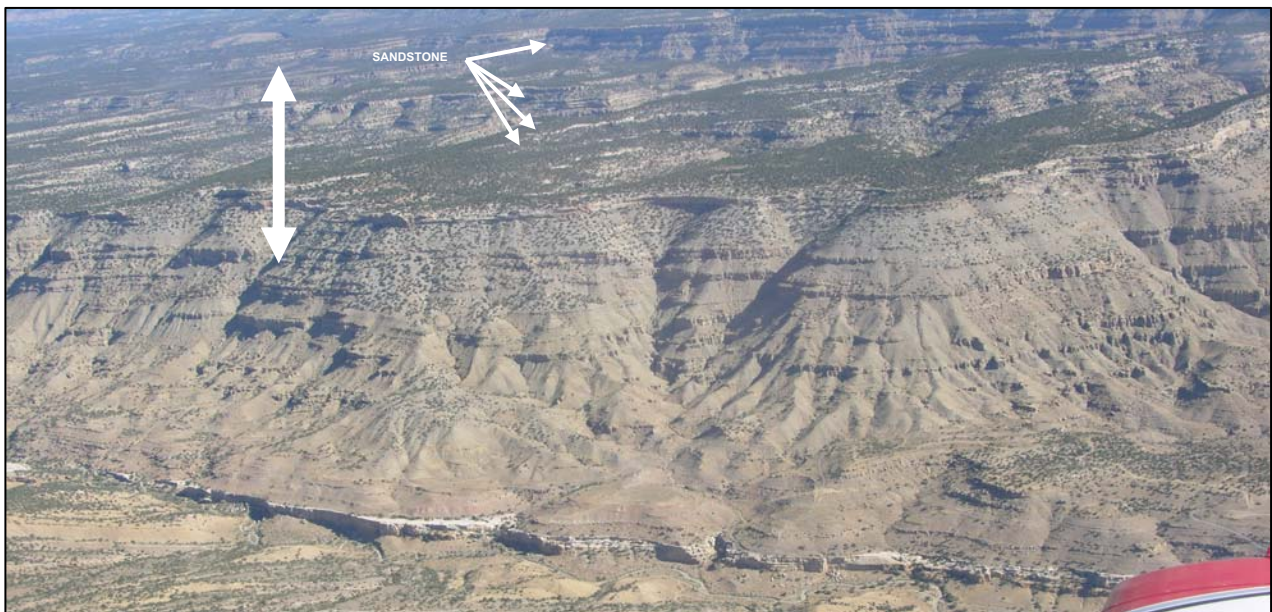


Figure 6. Piceance Basin Williams Fork Formation

Wells are commonly drilled to depths between 4,000 and 9,000 feet below the land surface. Over the last few years, directional drilling has emerged as the dominant approach. This technology allows the drillers to manipulate the direction of the borehole and target sand bodies up to 2,500 feet horizontally away from the drill rig. Each sand body must be penetrated vertically, and each well is designed to access several vertically stacked bodies. Twelve or more wells are commonly installed from the same well pad, reducing the disturbance associated with multiple pads.

A special mud is circulated through the borehole during drilling. The mud is pumped down through the center of the drill stem pipe into the borehole, where it flows back to the land

surface. The mud lubricates the drill bit, conveys cuttings up to the surface, and by virtue of its weight prevents “blowouts” of gas escaping uncontrollably upward through the borehole. After returning to the surface, the mud is passed through a shaker to separate out rock fragments and is then stored in reserve pits, which may or may not be lined. In recent years there has been increasing use of closed-loop systems that do not require a reserve pit.

The well itself is constructed according to specific requirements. A 16- to 20-inch diameter pipe or “conductor casing” is installed to a depth of 20 to 50 feet. This casing stabilizes the uppermost portion of the borehole and facilitates flow of the drilling mud. A “surface casing” about 10 inches in diameter is installed through the conductor casing. This casing isolates the natural gas, drilling mud, and other materials from shallow ground water so as not to contaminate a source of drinking water. The surface casing is required to extend from the land surface through at least 10% of the depth of the well, typically ending at a depth of 600 to 1,000 feet. The space between the casing and the borehole wall is filled with cement to prevent the migration of natural gas or drilling fluids up through this space, thus preventing the contamination of ground water that is used (or may be used in the future) as drinking water. The “production casing” is a pipe about 5 inches in diameter that is installed through the surface casing all the way down to the sand bodies. This casing is also cemented in place to prevent upward migration of gas and fluids.

Hydraulic fracturing (“fracing”) is a key step in the development of a viable well. The production casing is perforated at locations that will allow access to the sand bodies penetrated by the well. Water with proprietary additives is pumped through the perforations into the sand bodies at a pressure of about 10,000 pounds per square inch. The pressure induces fractures, which are propped open with sand or other solids that are part of the fracing fluid. These fractures provide a pathway for natural gas to flow out of the sand body into the well more easily than it could if the sand body was left intact. The fractures can extend up to 1,500 feet away from the well. It is important to note that prior to recent years, diesel fuel was routinely used as the base for the fracing fluid rather than water.

After fracing, wells undergo a completion phase. The well head assembly is installed and the well is plumbed to a pipeline. A notable part of completion is a “flow back” period of up to 30 days, in which gas is allowed to vent to the atmosphere in order to remove mud, sand, and other impurities from the well. Sometimes this gas is burned in a flare. In recent years, operators are increasing their use of “green completions”, in which the natural gas is captured rather than vented.

During the routine production phase, natural gas recovered from the well is piped to a gas processing plant for purification and distribution. Liquid hydrocarbons also flow out of the well. This “condensate” is separated from the gas stream and collected in a tank at the well head. The tank is periodically emptied into trucks and the condensate is transported to refineries. Dehydrators are also installed at the well head for removing water from the gas stream. Williams Fork wells have an expected lifetime of about 30 years.

THE RISK ASSESSMENT PROCESS

Conceptual model for pollutant migration and human exposure. A conceptual model is a useful starting point for studying human exposure to pollutants released into the environment. The conceptual model serves as a “roadmap” showing the routes by which a pollutant may come into contact with people. This roadmap becomes the basis for evaluating possible health threats and identifying ways to mitigate those threats.

The conceptual model breaks down the exposure process into a pollutant source, release mechanism, exposure medium, exposure route, and receptor.

- The *source* can be viewed as either a device (such as an internal combustion engine), a facility (such as an unlined pond for hydrocarbon-contaminated water), or a process (such as refueling) from which pollutants are released into the environment.
- A *release mechanism* is the specific manner in which the pollutant escapes. Exhaust gases are vented out of the engine; hydrocarbons evaporate from the pond, and hydrocarbon-contaminated water infiltrates into the soil below the unlined pond and possibly percolates all the way to ground water; fuel evaporates into the air during refueling and infiltrates into the ground if spills occur.
- The *exposure medium* is the environmental medium—air, surface water, ground water, or soil—that becomes polluted by the release and brings the pollutant into contact with people. The engine exhaust contaminates air; the hydrocarbons from the pond water contaminate air and possibly ground water; the hydrocarbons from refueling contaminate air and, if spilled, the surface soil.
- The *exposure route* describes how a person may take the pollutant into his or her body. Pollutants in air are inhaled; pollutants in drinking water are ingested; pollutants in soil are ingested in small amounts incidental to yard work or spending time outside on dusty days; certain pollutants in water or soil may be absorbed through the skin when the soil or water contacts the skin.
- A *receptor* is a person who makes contact with a pollutant through one or more of the exposure routes. Receptors can be residents, workers, or visitors either at the site where a release occurs or at nearby sites to which the pollutants migrate.
- *Secondary sources* may occur as a result of a primary source and release. For example, soil contaminated by a fuel spill becomes a secondary source of pollutant as the fuel hydrocarbons undergo a second release by evaporating from the soil into the air.

One can see that linking a source, release mechanism, exposure medium, exposure route, and receptor creates a roadmap by which a pollutant can travel from a particular source to a particular receptor. *Exposure* is actual contact of a pollutant with a receptor. If the journey between source and receptor is complete and exposure has occurred, we have an *actual*

exposure pathway. In many situations, the journey is not complete and there is only a *potential* exposure pathway. These potential pathways must be evaluated carefully to see if they have a significant likelihood of becoming complete and creating an exposure. One consideration is the properties of the pollutant of interest. Not all release mechanisms, exposure media, and exposure routes are relevant to each pollutant. For example, a pollutant with little or no tendency to evaporate will not occur as a gas in air, nor will a pollutant with little or no solubility in water occur at high concentrations in water.

A general conceptual model is shown in Figure 7 for natural gas operations in Garfield County. There is no single, correct way to construct such a model. The general model shown is intended to be a representative rather than exhaustive roadmap of actual and potential exposures to pollutants from natural gas operations.

Drilling and completion operations can be viewed as one source. Releases from drilling and completion include venting of natural gas from the well and exhaust gases from engines associated with the drill rig and support activities. The gases contaminate the on-site air and can migrate off-site. Both on-site and off-site receptors can be exposed.

Wellhead glycol dehydrators, condensate tanks, and condensate transfer operations may be viewed as another source. Hydrocarbons in dehydrators and condensate can evaporate and be vented to the atmosphere, where they can be inhaled by on-site or off-site receptors. Any hydrocarbon liquids that are leaked or spilled may evaporate as well. However, a portion of these liquids would likely infiltrate into the soil, then possibly percolate to the water table and contaminate ground water, which can migrate to neighboring properties where it may be captured by a well. If this contaminated ground water is used for drinking, the pollutants will be ingested. If the water is used for showering, the hydrocarbons may evaporate into the shower air and be inhaled. Absorption of pollutants through the skin may also take place during a shower, if any of the chemicals present have a significant ability to be absorbed that way.

Another source of interest may be open, unlined ponds for produced water. Hydrocarbons will evaporate from these ponds into the air, where they may be inhaled by on-site or off-site receptors. Hydrocarbons dissolved in water that infiltrates into the soil below the pond may undergo the same sequence of events as described above for hydrocarbon liquids that infiltrate into soil as a result of spills or leaks.

There is considerable interest in any threat posed by hydraulic fracturing fluids. These fluids have the potential to escape from the well into a surrounding aquifer if the well casings are breached. They also have potential to escape from the target formation through induced fractures, naturally-occurring fractures, or any other preferential flow paths that may occur in the subsurface. The resulting contaminated ground water has the potential to be used in the same manner as described above.

Some of these pathways are highly likely to be complete, if only on a transient basis. Inhalation of natural gas and of air pollutants from combustion engines is the best example. There is little question that pollutants have been emitted into the air; the question is how much pollutant is present at the location where a receptor breathes the air. Other pathways are less likely to be complete. The best example is the pathway for hydraulic fracturing fluids, which can require migration upward through the subsurface for thousands of feet, arriving in a shallow aquifer at a location in close proximity to a well used for drinking water. The details of pollutant transport through the pathways in the conceptual model are discussed in greater detail in later sections of this report.

A Conceptual Model for Contaminant Transport from Garfield County Natural Gas Operations

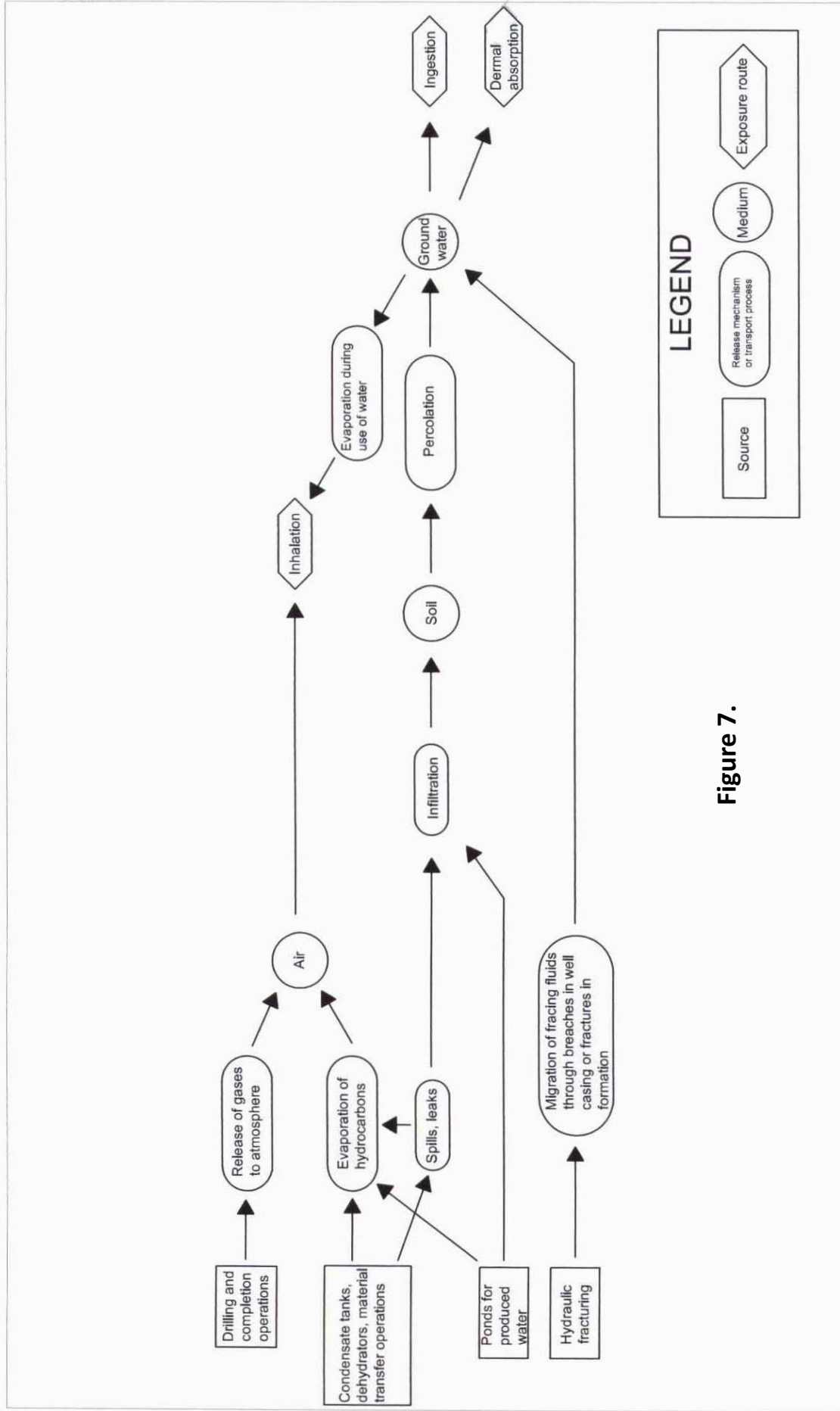


Figure 7.

Risk assessment. The U.S. Environmental Protection Agency (EPA) developed a standard process for assessing risk to human health from pollutants in the environment. The process is described in Risk Assessment Guidance for Superfund, Volume 1. Human Health Evaluation Manual (Part A) published by the EPA in 1989. While tailored to sites being investigated and cleaned up under the Comprehensive Environmental Response, Compensation, and Liability Act (also known as “Superfund”), the basic principles and procedures of the guidance are applicable to any situation in which people are exposed to pollutants. The overall risk assessment process is divided into four steps—hazard identification, exposure assessment, toxicity assessment, and risk characterization.

Hazard Identification

The purpose of this step is to identify those pollutants that have the ability to cause harm to people, and single out for further consideration those pollutants that are likely to result in the most significant exposures. Toxicity is an obvious key property, but the mobility and persistence of a pollutant are factors as well. Pollutants whose physical and chemical properties make them more likely to migrate away from their source are considered to be more of a threat to off-site receptors. For example, a high water solubility or a strong tendency to evaporate make a pollutant more mobile. Less mobile pollutants can be more of a threat to on-site receptors because the pollutants can remain near their source in high concentrations. Persistence refers to how long a pollutant remains unchanged in the environment. Many pollutants have the ability to be biodegraded (broken down into simpler, usually less toxic substances by naturally-occurring bacteria), hydrolyzed (broken down by reaction with water), or photodegraded (broken down by exposure to light). These pollutants will be less of a threat because they are less persistent. Pollutant distribution is considered as well. If more than one pollutant is present, those that occur in the most samples and at the highest concentrations are given a higher priority. Those pollutants having the greatest toxicity, mobility, persistence, and distribution are carried forward for further study.

Exposure Assessment

Exposure assessment is the second step in risk assessment. The goal of this step is to quantify the exposure experienced by a receptor to each of the pollutants of concern. The outcome of exposure assessment is a number for pollutant intake expressed as milligrams of pollutant absorbed per kilogram of body weight per day. The equations used in exposure assessment are shown in Appendix A. Much of the essence of the equations is easy to understand.

- Intuition suggests that the more contaminated the exposure medium, the greater the health threat will be. The degree of contamination is expressed as concentration—the mass of a specific pollutant in a given amount of the medium. For example, pollutant concentration in air is typically expressed as micrograms of pollutant per cubic meter of air. In water, concentration is typically milligrams of pollutant per liter of water, and in soil, milligrams of pollutant per kilogram of soil.
- Intuition also suggests that the greater the contact rate with the polluted medium, the greater the threat will be. In other words, the greater the volume of contaminated air

inhaled, or the greater the volume of contaminated water consumed, the greater the threat will be.

- The entire amount of pollutant to which a person is exposed may not be absorbed into the body. For example, when we inhale, not all of the pollutant gas molecules drawn into our lungs will pass through lung cell membranes into the bloodstream. Some will, but others will exit the lungs during the next exhalation. The degree of actual absorption is difficult to know for any particular pollutant and any particular individual. It is customary to make the protective assumption that *all* of the pollutant contacting the receptor is absorbed. If such an assumption turns out to be wrong, then we will have erred on the side of being more protective rather than less.
- Intuition suggests that the longer the duration of exposure, the greater the health threat will be. Duration can be viewed as the number of days of exposure per year combined with the number of years that a person spends at the site where exposure takes place. In general, the protective assumption is made that the exposure occurs for 24 hours each day.

The body mass of the receptor plays a role. For example, imagine that a mouse is exposed to one milligram of a pollutant, and that this amount has a definite adverse effect. Exposing an elephant to only one milligram of the pollutant may well have no effect at all. The larger the body mass of the receptor, the less the pollutant intake is on a per kilogram of body mass basis.

Averaging time is the final factor. The averaging time depends on what type of health effect the pollutant of interest causes. For a non-cancer effect, the averaging time is taken to be the duration of the exposure. For cancer, the pollutant intake is averaged over a lifetime, which is generally taken to be 70 years. The basis for this approach is the assumption that a high intake received for a short time period has the same cancer effect as a low intake received for a long time period.

Toxicity assessment

This step in the risk assessment process brings into consideration the known or estimated toxicity of the pollutants. Toxicity is primarily determined by observing what effects occur when test animals (such as mice and rats) are exposed to a pollutant in a controlled laboratory setting. The use of animals rather than people is a fundamental limitation in toxicity testing because of possible differences between the response in humans compared with the response in a test species. However, when similar effects are observed across numerous test species and for exposure by both oral ingestion and inhalation, the relevance of these studies to humans becomes more convincing.

Toxicity tests are conducted by dividing the test animals into groups, with each group receiving a different exposure to the pollutant. At the end of a specific period of time (anywhere from four days to a lifetime), each animal is examined for adverse effects. Not every animal in a group will show an effect because individual response varies with a variety of factors, such as

age, sex, health status, genetics, prior exposures to that pollutant, and co-exposures to other toxic substances. We generally find that the percentage of animals in each group that experience an adverse effect is greater for greater exposures. A notable exception to this generalization occurs for pollutants that exhibit endocrine disrupting effects. These effects sometimes appear to occur at lower exposures but not at higher exposures.

Panels of toxicology experts are convened by the EPA to evaluate the results and reliability of laboratory toxicity studies. When available, information from epidemiological and clinical studies of humans is also considered. For non-cancer effects, the panels determine a “reference concentration” or “reference dose” for the pollutant. These reference values are a minimum daily exposure level that is highly unlikely to produce an adverse effect, not only in the general population but for sensitive sub-populations as well. Separate reference values are developed for acute (one to 14-day), intermediate (15- to 365-day), subchronic (2 weeks to 7 years), and chronic (7- to 70-year) exposures, and for exposures by oral ingestion and by inhalation. This approach reflects the experimental observation that non-cancer effects show a threshold exposure level—below that threshold, no adverse effects are observed, while above that threshold effects occur with increasing frequency as the exposure increases beyond the threshold. The smaller the reference concentration or reference dose, the more toxic the pollutant is.

Similar testing and evaluation is conducted for cancer as the adverse effect. However, a pollutant’s cancer potency is expressed as a “slope factor” rather than a reference concentration or dose. The greater the slope factor, the greater the probability that a receptor will develop cancer for a given exposure. Inherent in the slope factor is a protective assumption by the EPA that exposure to *any* amount of a carcinogen will increase an individual’s chance of developing cancer. In other words, unlike non-cancer effects, cancer is not considered to have a threshold exposure level below which no cancer will occur.

The EPA classifies chemicals according to their carcinogenicity using an approach based on “weight of evidence”. If it is the opinion of expert toxicologists that epidemiologic studies of humans establish a cause and effect relationship between exposure to the chemical and the occurrence of cancer, the chemical is classified as a Category A human carcinogen. If the evidence from human studies is judged to be limited or inadequate, but there is sufficient evidence of carcinogenicity in animals, the chemical is classified as a Category B probable human carcinogen. Category C, possible human carcinogens, is for chemicals with even less evidence of carcinogenicity than Category B chemicals. Category D chemicals are unclassifiable due to inadequate study. Class E chemicals are those for which evidence suggests they are not carcinogenic.

The primary source of toxicity information for risk assessment is the EPA Integrated Risk Information System (IRIS). This extensive data base provides reference doses, reference concentrations, and slope factors for over 500 substances along with an explanation of how these quantities were determined. A discussion is also provided regarding the level of

confidence in the toxicity values and supporting studies. The complete IRIS data base can be accessed at www.epa.gov/iris.

Risk characterization

This is the final step in the risk assessment process, where toxicity assessment and exposure assessment are integrated into an expression of the degree of health threat.

To evaluate the threat from non-cancer effects, the intake determined in the exposure assessment is compared with the reference dose or reference concentration for the pollutant. The duration of the exposure is taken into account. For example, the intake from a chronic exposure is compared with a reference value derived from chronic exposure studies. The reference value is considered to be safe by a wide margin, so that if the intake is less than the reference value, it is highly unlikely that even a sensitive subpopulation will experience adverse health effects. Intakes that exceed the reference values are considered to be unacceptable and usually trigger actions that will reduce the exposure. An alternate way of making the comparison is to divide the intake by the reference value to obtain a “hazard quotient”. A hazard quotient greater than one corresponds to an unacceptable exposure, based on the possible occurrence of non-cancer health effects.

To evaluate the threat of cancer, we perform a calculation to determine cancer risk for an individual experiencing the exposure of concern. The equation for this calculation is shown in Appendix A. Cancer risk is often expressed as a probability, such as “a 1 in 10,000 chance of developing cancer from this exposure”. This probability statement can be interpreted in two ways—as the chance that an individual experiencing the exposure will develop cancer from this exposure, or that one person out of every 10,000 people experiencing this exposure will develop cancer from this specific exposure. The risk obtained from this procedure is considered to be an “upper bound estimate”; in other words, the true risk is likely to be less than the calculated value. The EPA uses a cancer risk of 1 in 1,000,000 (one in one million) as a regulatory goal, meaning that regulatory programs are generally designed to try to reduce risk to this level. When it is not feasible to meet this regulatory goal, the EPA considers cancer risks lower than 1 in 10,000 to be acceptable.

It is important to note that cancer occurs at a poorly characterized “background level” due to natural causes beyond our control. Ionizing radiation is one such cause; we are constantly exposed to a low level of radiation from the earth’s crust and outer space. Naturally occurring chemical carcinogens (such as certain polynuclear aromatic hydrocarbons, which can occur in soot from natural fires) are another cause. Random mutations in DNA are also a factor. The cancer risk calculated in a risk assessment is an additional risk on top of the background risk.

It is often the case that a receptor is exposed to more than one pollutant at the same time. As a first approximation of the threat from a combined exposure, the hazard quotients calculated for non-cancer effects are added together to obtain a “hazard index”, which is interpreted in the same manner as a hazard quotient—an index greater than one is considered unacceptable. Similarly, the total cancer risk from multiple carcinogenic pollutants is obtained by adding the

risks calculated for the individual pollutants, with total risk values greater than 1 in 10,000 considered to be unacceptable. A more refined approach to multiple pollutants is to segregate the pollutants according to their major effect, summing only those pollutants with similar effects. This approach requires advanced knowledge of toxicology and must be done with care so as to avoid underestimating health threat.

A report on the results of a risk assessment must always include a discussion of the uncertainties inherent in the results, of which there can be many. Among these uncertainties are the degree to which actual exposure parameters (pollutant concentration, contact with polluted media, duration of exposure, body mass of receptor) match those used in the risk calculations and uncertainties caused by the limitations of toxicity testing.

The *Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment* (available at <http://www.garfield-county.com/index.aspx?page=1098>) demonstrates the applicability of this risk assessment process to natural gas operations in Garfield County. This study, conducted by the Disease Control and Environmental Epidemiology Division of the Colorado Department of Public Health and Environment, focuses on data collected in the *Garfield County Ambient Air Quality Monitoring Report* (available at the same site).

The present study complements the *Garfield County Air Toxics* study. Rather than relying solely on monitoring data that presents only a partial picture of air quality, this study uses pollutant transport modeling as a way of augmenting our understanding of possible human exposures to hydrocarbons in air from natural gas operations. Risk calculations are then based on the results of modeling rather than on actual air monitoring data. The present study also includes a qualitative examination of possible threats from pollutants in water and soil.

HEALTH EFFECTS OF SELECTED HYDROCARBONS

Benzene, toluene, and *m,p*-xylenes are hydrocarbons that are prominent environmental pollutants associated with natural gas operations. Their health effects are summarized below based on information shown in IRIS.

Benzene. Benzene is considered to be a known human carcinogen (Category A in the weight-of-evidence system) both by oral ingestion and inhalation based on reliable human evidence as well as supporting animal studies. There is clear causation between exposure to benzene and the occurrence of leukemia. Hematologic neoplasms, aplastic anemia, and Hodgkin's lymphoma are other cancer-related effects associated with benzene. An increased risk of oral and nasal cancer as well as liver, stomach, lung, ovary, and mammary gland cancer is associated with benzene through animal studies. The non-cancer effects of benzene include neurotoxicity and depression of bone marrow function, resulting in blood disorders (decreased counts of specific blood cells, such as erythrocytes, leukocytes, and thrombocytes) and impairment of the immune system.

Toluene. The available study results for toluene are inadequate to determine the ability of toluene to cause cancer (Category D in the weight-of-evidence system). Non-cancer effects observed in human studies include many of a neurological nature, such as impaired color vision, impaired hearing, changes in nerve conduction, headache, dizziness and possible respiratory irritation.

***m,p*-Xylenes.** There are no adequate human data on the carcinogenicity of *m,p*-xylenes and animal studies are inconclusive (Category D in the weight-of-evidence system). Non-cancer effects include mild neurological impairment (such as reduced motor coordination) based on human and animal studies, and possible developmental effects in animals (such as cleft palate, observed in mouse studies.)

AIR POLLUTION EFFECTS

Air pollutant transport. Of the three exposure pathways—air, water, and soil—air is likely to be the most significant pathway related to natural gas operations in Garfield County. In general, people experience relatively little contact with soil outside of their own property, hence their exposure to soil is limited. Many people do not consume a great deal of water from their home tap, and thus have a limited exposure to ground water. However, everyone breathes the air and has considerable opportunity to be exposed to air pollutants.

Whether a specific pollutant contributes to the air pathway when released into the environment depends on the pollutant's tendency to evaporate. Substances that are gases at normal temperatures and pressures (i.e., ambient conditions) will be found in the air when released to the environment. The lighter hydrocarbons, such as methane, ethane, and propane behave in this manner. Substances that are liquids at ambient conditions may also occur in the air. If the liquid has a low boiling temperature and high vapor pressure, at least a portion of that liquid readily evaporates into the atmosphere. Hydrocarbons that are somewhat heavier, such as benzene, toluene, and *m,p*-xylenes are good examples of liquids that readily evaporate. The chemicals known as "volatile organic compounds (VOCs)" have a strong tendency to evaporate and we expect them to occur as air pollutants. This holds true regardless of whether the VOCs are released into the environment as hydrocarbon liquids or dissolved in water.

Once a pollutant enters the atmosphere, it does not remain at the release location for long. If there is any wind, the pollutant is carried with the wind in a process called advection. As the pollutant moves downwind, the turbulent motion of the wind disperses the pollutant from side to side (perpendicular to the wind direction) and up and down. The region of contaminated air (the "plume") takes on the approximate shape of a cone, with the point of the cone at the location of the release. At any given distance from the release location, the highest concentration of pollutant is on the centerline of the cone. The concentration along the centerline decreases with increasing distance from the release location. Higher wind speeds

spread the pollutant over a larger volume of air, resulting in smaller pollutant concentrations than would be observed for lower wind speeds.

This description of air pollutant transport is an idealized picture. Real conditions result in a more complex shape for the contaminated region of air, and a more complex pattern of pollutant concentrations within that shape. Variability in wind direction results in dispersal of the pollutant over a greater volume of air. The presence of hills, valleys, trees, and buildings influences both the horizontal and vertical movement of air and air pollutants. Atmospheric conditions are an important factor as well. When temperature inversions occur, pollutants are trapped in a distinct layer of air whose thickness is typically anywhere from a few tens of feet to hundreds of feet. The development of the cone-shaped region of contaminated air is limited when the upper edge of the cone reaches the top of the inversion layer of air.

Air pollutant concentrations determined by sampling and analysis. As described in the preceding section on risk assessment, the magnitude of the health threat posed by a pollutant depends on the concentration of the pollutant that a person is exposed to. The best way to obtain pollutant concentrations for risk assessment is to collect and analyze samples that are representative of the range of concentrations and conditions that occur while an exposure is taking place. In the absence of such samples, mathematical models of pollutant transport can be used to predict pollutant concentrations that occur for specific conditions. Modeling is the primary approach used in the present study.

The Garfield County Ambient Air Quality Monitoring Study, June 2005–May 2007 focused on particulate matter less than 10 microns in diameter (PM₁₀) and VOCs. Measurements of PM₁₀ occurred every three days for two years at seven sites in Garfield County, including urban areas, rural areas, and both urban and rural areas close to natural gas operations. A summary of the results is shown below (Table 3). Average PM₁₀ concentrations found at each location ranged from 9.2 to 27.0 micrograms per cubic meter. The maximum concentrations found at each location ranged from 28 to 92 micrograms per cubic meter.

Table 3. Summary of PM₁₀ Monitoring Results

Site	Overall Arithmetic Average (µg/m ³)	Overall 24-Hour Maximum (µg/m ³)	Possible Number of Sample Days	Number of Samples Recovered	Percent Data Recovery (%)
Glenwood-Courthouse	14.4	36	243	235	97%
New Castle-Library	22.8	92	243	238	98%
Silt-Bell	10.7	34	243	237	98%
Silt-Daley	9.2	28	243	231	95%
Silt-Cox	13.6	62	243	223	92%
Rifle-Henry Bldg.	27.9	72	243	240	99%
Parachute	27.9	76	243	234	96%

From Garfield County Ambient Air Quality Monitoring Study, June 2005 – May 2007.

Samples of air for analysis of VOCs were collected over a 24-hour period on 232 occasions over the course of the Ambient Air Quality Monitoring Study from the same sampling locations used for PM₁₀. An additional twenty-seven “grab samples” were collected over a 15-second period from seven additional rural sites close to natural gas operations on occasions when odors were reported by the public. Two additional grab samples were collected in the immediate vicinity of a condensate tank as condensate was being transferred from the well pad tank to a tank truck. Of the forty-three VOCs covered by the EPA-approved methods used for analysis, fifteen were detected in at least one sample. Only six of these VOCs were detected in more than 20% of the total number of samples: acetone, vinyl acetate, 2-butanone (MEK), benzene, toluene, and *m,p*-xylenes. A summary of the results is shown in Table 4.

Of the VOCs shown in Table 4, benzene, toluene, and *m,p*-xylenes are expected to have the strongest association with natural gas. They are known to occur in unpurified natural gas, albeit in concentrations well under 1%. Their association with natural gas is supported by the high frequency of occurrence (93%) observed for the complaint-driven grab samples for each of these three VOCs, as well as the high concentrations found in samples of condensate vapors.

It is difficult to obtain air samples that are representative of benzene, toluene, and *m,p*-xylenes at locations of interest, such as a property line or residence near a natural gas well. The difficulty lies in the inherent variability of pollutant concentrations at the location of interest because of variations over time in emissions from the well along with variations in meteorological factors that affect pollutant transport through the air.

During the life of a well, emissions of natural gas components into the air are highly variable. Few, if any, emissions occur from the borehole until it is extended into natural gas-producing zones. Then, during a period of well conditioning called “flow back”, natural gas may be vented from the well into the air. Once the well goes into its routine production phase, the natural gas is piped to a local facility for processing and injection into regional and transcontinental pipelines. However, a fraction of the heavier, non-methane gases emerging from the well are captured at the well head as “condensate” and diverted to an on-site storage tank. About 10% of condensate is benzene, toluene, and *m,p*-xylenes, and thus condensate tank emissions are a source of these compounds in air.

Table 4. Summary Statistics for Detected VOCs

<u>Detected compounds</u>		Overall 24-Hr Samples (232 samples, 14 sites)				Overall Grab Samples (27 samples)			
CAS #	Compound	Avg µg/m³	Max µg/m³	Min µg/m³	% Detect s	Avg µg/m³	Max µg/m³	Min µg/m³	% Detect s
74-87-3	Chloromethane				0.0%	1.5	15.0	0.7	3.7%
67-64-1	Acetone	18.5	80.0	3.6	81.9%	26.0	81.0	3.7	77.8%
75-69-4	Trichlorofluoromethane	1.0	26.0	0.7	0.4%	1.5	15.0	0.7	7.4%
75-09-2	Methylene chloride	1.0	8.4	0.7	1.7%				0.0%
108-05-4	Vinyl Acetate	2.1	15.0	0.7	23.3%	2.5	15.0	0.7	14.8%
78-93-3	2-Butanone (MEK)	2.2	12.0	0.7	55.2%	3.0	15.0	0.8	70.4%
67-66-3	Chloroform				0.0%	1.5	15.0	0.7	3.7%
71-43-2	Benzene	2.2	49.0	0.8	39.2%	28.2	180.0	0.8	92.6%
79-01-6	Trichloroethene	0.9	2.7	0.7	0.4%				0.0%
108-88-3	Toluene	7.4	130.0	0.8	89.7%	91.4	540.0	0.8	92.6%
591-78-6	2-Hexanone	1.0	4.4	0.7	3.0%	1.7	15.0	0.7	14.8%
127-18-4	Tetrachloroethene	0.9	2.3	0.7	0.9%				0.0%
100-41-4	Ethylbenzene	1.0	3.4	0.7	3.4%	8.3	96.0	0.8	63.0%
136777-61-2	<i>m,p</i> -Xylenes	3.9	24.0	0.8	64.2%	106.6	1500.0	0.8	92.6%
100-42-5	Styrene	0.9	6.0	0.7	0.9%				0.0%
95-47-6	<i>o</i> -Xylene	1.1	4.3	0.7	10.3%	18.1	260.0	0.8	81.5%
106-46-7	1,4-Dichlorobenzene	1.1	12.0	0.7	3.4%				0.0%

<u>Detected compounds</u>		Condensate Load-out Grabs (2 samples)		
CAS #	Compound	Vent Outlet µg/m³	50' distance µg/m³	% Detect s
71-43-2	Benzene	590000	360	100.0 %
108-88-3	Toluene	770000	480	100.0 %
100-41-4	Ethylbenzene	37000	29	100.0 %
136777-61-2	<i>m,p</i> -Xylenes	250000	200	100.0 %
95-47-6	<i>o</i> -Xylene	49000	43	100.0 %

NOTE: 1/2 of the Minimum Reporting Level was substituted for non-detect values for statistical calculations.
 From Garfield County Ambient Air Quality Monitoring Study, June 2005 – May 2007, November 2007.

Meteorological conditions also change with time. Wind speed undergoes considerable variation, with greater speeds dispersing pollutants more effectively than lesser speeds, leading to lower concentrations at the location of interest. Wind direction at most sites varies through all the compass directions, so that pollutants are transported toward the location of interest only part of the time. Nighttime temperature inversions and multi-day winter inversions trap pollutants in a relatively thin layer of stable air from the land surface upward, with the top of the inversion layer just a few tens of feet above the surface early in the evening (leading to high pollutant concentrations) but rising to several hundred feet before sunrise (leading to lower pollutant concentrations, providing the inversion does not persist for an extended period of time). In contrast, on a clear, sunny afternoon in mid-summer, pollutants may be dispersed by convection currents throughout a larger volume of air, from the ground to elevations of several thousand feet (creating lower pollutant concentrations). Given the complexity and variability of real conditions, air at a location of interest would need to be characterized at least hourly for a year or more to develop an accurate knowledge of the range and distribution of pollutant concentrations.

Samples collected over a 24-hour period provide a “snapshot” of the average concentration for that time period; samples collected over just a 15-second period provide more of a “snapshot” of transient conditions. Unless samples are collected continuously (e.g., a 24-hour sample every day), neither sampling approach provides a reliable indication of concentrations over longer periods. As discussed in Section 1, we are interested in concentrations representative of longer periods in order to evaluate the degree of health threat from exposure to a pollutant.

The variability in emissions, wind speed, and air stability along with the relatively small number of samples collected at natural gas-affected locations during the Garfield County Ambient Air Quality Monitoring Study suggests that we cannot draw conclusions about natural-gas related pollutant concentrations with the desired degree of confidence. Do the results of the study reflect high-end pollutant concentrations? Or averages? Or conditions somewhere else on the spectrum between maximum and minimum concentrations? Without knowing, we are handicapped in our ability to make a reliable assessment of the degree of health threat experienced by Garfield County residents. However, we can use mathematical modeling to estimate or predict pollutant concentrations and, in effect, generate “missing” data, giving us a better idea of the range and distribution of concentrations. That said, one must bear in mind that mathematical models have limitations. Modeling inevitably requires that a number of simplifying assumptions be made in order to make the calculations feasible. These assumptions do limit the ability of the model to accurately reflect real conditions, but as long as the limitations of modeling are understood and taken into account when interpreting the results, modeling can provide a useful “ball park” level of accuracy that helps to illuminate the degree of threat and provides guidance to decision-makers.

Air pollutant concentrations determined by modeling. The Gaussian plume model is the simplest approach to predicting pollutant transport from a single, well-defined “point source” of air pollutant emissions (such as a well or condensate tank). A Gaussian plume is the qualitative picture described earlier—the cone-shaped region of contaminated air extending

downwind from the pollutant release point. The result of Gaussian plume modeling is an estimate of pollutant concentration at any specific location of interest downwind of the pollutant source. The model is based on user-specified values for pollutant emission rate, position of the location of interest relative to the source, wind speed, and atmospheric stability (*Air Pollution Modeling*, Paolo Zannetti, Van Nostrand Reinhold, 1990). The mathematical equations used in this model are shown in Appendix B.

The Gaussian plume model was used to estimate concentrations of benzene, toluene, and *m,p*-xylenes in air for meteorological conditions characteristic of Garfield County.

Wind speeds were based on data collected during the Garfield County Ambient Air Quality Monitoring Study for five sites: Silt-Bell, Silt-Cox, Silt-Daley, Parachute, and Newcastle Library. Data from all five sites were combined to generate an average proportion of time over the course of a typical year that each wind speed range occurred, with separate averages for day and night (Appendix C).

The wind direction data from the Ambient Air Quality Monitoring Study were examined to determine the maximum proportion of time in which the wind blew in any given direction (Appendix D).

- One of the factors that determines air stability is insolation – the intensity of sunlight. Assuming a clear sky, strong insolation occurs when the angle between the horizon and the sun is greater than sixty degrees; moderate insolation occurs for angles between thirty-five and sixty degrees; and weak insolation occurs for angles between fifteen and thirty-five degrees. Sun angle tables were consulted to determine the proportion of the year in which the sun was in each of these three angle ranges (Appendix E).

Air stability is also determined by the degree of cloudiness. No cloud cover information was available for Garfield County. The best available information was a month-by-month breakdown of the average number of days classified as clear, partly cloudy, and cloudy developed by the National Weather Service for Grand Junction. These data were converted to the proportion of a year in each cloud cover category (Appendix F).

- The Gaussian plume model requires that meteorological conditions be characterized as falling into one of six air stability classes. The information on wind speed, insolation, and cloudiness described above was combined so as to determine the proportion of time during a typical year that could be classified as falling into each of these six stability classes (Appendix G).

Generic pollutant concentrations were calculated for each stability class for distances ranging from 25 meters to 4,800 meters directly downwind of the source for a convenient, arbitrary emission rate of 1 gram per second. The concentration results for each stability class were combined into a single set of results by weighting each class according to the proportion of a typical year in which that stability class occurs

(Appendix H). The result was a set of concentrations for various distances downwind from the pollutant source. These generic concentrations, which are characteristic of meteorological conditions over a typical year, were used as the basis for calculating specific concentrations for each of the pollutants and emission scenarios described below.

Five specific emission scenarios were examined using the Gaussian plume model:

- “Flow back” is a stage in the conditioning of a new natural gas well prior to production. In the traditional flow back process, gas is allowed to vent from the well to the atmosphere for as long as thirty days. Typical gas emission rates and composition were used to calculate representative emission rates specifically for benzene (0.07 grams per second), toluene (0.07 grams per second), and *m,p*-xylenes (0.07 grams per second) (Appendix Ia).
- In recent years, more companies are turning to “green completions,” in which the natural gas vented during flow back is captured and processed for sale. A typical capture rate and gas composition were used to calculate representative emission rates under this scenario for benzene (0.0049 grams per second), toluene (0.0049 grams per second), and *m,p*-xylenes (0.0049 grams per second) (Appendix Ia).
- Glycol dehydration units are used at the wellhead during routine production to remove water from the gas stream before injecting it into a pipeline for transport to a local processing facility. A typical emission rate and composition for dehydration emissions was used to calculate representative emission rates for benzene (0.0036 grams per second), toluene (0.01 grams per second), and *m,p*-xylenes (0.01 grams per second) (Appendix Ib).
- During routine production, heavier hydrocarbons are captured at the wellhead and separated from the gas stream as “condensate.” The condensates are stored at the wellhead in condensate tanks, from which they are periodically collected and transported to refineries. Emissions from condensate tanks vary with the rate at which condensate is produced by the well, which varies from one well to another as well as during the lifetime of the well. In Weld County, Colorado, condensate tank emissions are limited to 20 tons per year of total volatile organic hydrocarbons (VOCs) as part of the effort to reduce the formation of ozone in Front Range air. As a point of reference, this emission rate was used along with typical condensate emission composition to calculate representative emission rates for benzene (0.0081 grams per second), toluene (0.0415 grams per second), and *m,p*-xylenes (0.0415 grams per second) (Appendix Ic).
- Condensate tanks can be outfitted with combustors to destroy VOC emissions. These combustors can typically operate with a destruction efficiency of 98%, leading to lower emission rates for benzene (0.00016 grams per second), toluene (0.00083 grams per second), and *m,p*-xylenes (0.00083 grams per second) (Appendix Ic)

The Gaussian plume model was used to calculate air concentrations for benzene, toluene, and *m,p*-xylenes at multiple distances ranging from 25 meters (82 feet) to 4,800 meters (approximately 3 miles) for each of the five emission scenarios. The results of the model calculations are shown in Tables 5A – 5C.

Of the five scenarios, flow back with no gas recovery produces the highest concentrations of each of these pollutants. In this emission scenario, benzene concentrations ranged from 358 micrograms per cubic meter at a location 25 meters downwind of the source to 0.1 micrograms per cubic meter at a distance 4,800 meters downwind. Benzene concentrations reported for actual air samples in the Garfield County Ambient Air Quality Monitoring Study had a maximum of 49 micrograms per cubic meter for 24-hour samples and 180 micrograms per cubic meter for 15-second grab samples. These concentrations predicted by the model are similar to the range of concentrations found through sampling and analysis.

In this same emission scenario, toluene and *m,p*-xylenes were calculated to range from 215 micrograms per cubic meter at a location 25 meters downwind to 0.1 micrograms per cubic meter at a location 4,800 meters downwind. Toluene concentrations reported in actual air samples collected for the Ambient Air Quality Monitoring Study were as high as 130 micrograms per cubic meter in the 24-hour samples and 540 micrograms per cubic meter in the 15-second samples, although the concentrations averaged only 7.4 and 91 micrograms per cubic meter, respectively. It is noteworthy that the 15-second maximum value exceeds the maximum calculated using the model. *m,p*-Xylenes concentrations were as high as 24 micrograms per cubic meter in the 24-hour samples and 1,500 micrograms per cubic meter in the 15-second samples, with averages of 3.9 and 107 micrograms per cubic meter, respectively. Again, the maximum 15-second value exceeds the range calculated using the model.

For any specific location, time, and conditions, actual concentrations may vary from those predicted by the model for several reasons. The model is based on wind speeds, wind directions, cloudiness, sun angles, and atmospheric stability averaged over the course of a specific year. However, conditions at any specific time can be considerably different than the average. For example, pollutant concentrations in air can be especially high in early evening as a nighttime inversion begins to develop. Emissions are trapped in a layer of air that, for a limited period of time, may be no thicker than a few tens of meters above the land surface, confining the pollutants to a smaller volume of air leading to high concentrations. Topography in the form of hills and valleys can sometimes channel air flow and alter pollutant dispersion.

Table 5B. Toluene Concentrations in Air Resulting from Selected Natural Gas Development Operations

(Concentrations in micrograms per cubic meter)

Downwind distance (meters)	Concentrations in micrograms per cubic meter			Condensate emissions at 20 tons per year <u>total VOCs</u>	Condensate emissions with 98% removal of 20 tons per year <u>total VOCs</u>
	Flow back, no recovery	Flow back, 93% recovery	Wellhead glycol dehydration		
25	214.5	15.0	30.6	127.2	2.5
50	96.5	6.8	13.8	57.2	1.1
75	58.5	4.1	8.4	34.7	0.7
100	39.4	2.8	5.6	23.3	0.5
125	28.3	2.0	4.0	16.8	0.3
150	21.5	1.5	3.1	12.7	0.3
175	16.9	1.2	2.4	10.0	0.2
200	13.7	1.0	2.0	8.1	0.2
250	9.6	0.7	1.4	5.7	0.1
300	7.2	0.5	1.0	4.2	0.1
350	5.6	0.4	0.8	3.3	0.1
400	4.4	0.3	0.6	2.6	0.1
500	3.1	0.2	0.4	1.8	0.0
600	2.3	0.2	0.3	1.3	0.0
700	1.7	0.1	0.2	1.0	0.0
800	1.4	0.1	0.2	0.8	0.0
900	1.1	0.1	0.2	0.7	0.0
1000	1.0	0.1	0.1	0.6	0.0
1100	0.8	0.1	0.1	0.5	0.0
1200	0.7	0.0	0.1	0.4	0.0
1300	0.6	0.0	0.1	0.4	0.0
1400	0.6	0.0	0.1	0.3	0.0
1500	0.5	0.0	0.1	0.3	0.0
1600	0.4	0.0	0.1	0.3	0.0
3200	0.2	0.0	0.0	0.1	0.0
4800	0.1	0.0	0.0	0.1	0.0

Table 5C. *m,p*-Xylenes Concentrations in Air Resulting from Selected Natural Gas Development Operations

(Concentrations in micrograms per cubic meter)

Downwind distance (meters)	Flow back, no recovery		Flow back, 93% recovery		Wellhead glycol dehydration		Condensate emissions at 20 tons per year		Condensate emissions with 98% removal of 20 tons per year	
	no recovery	93% recovery	no recovery	93% recovery	no recovery	93% recovery	total VOCs	total VOCs	total VOCs	total VOCs
25	214.5	15.0	30.6	127.2	2.5	1.1	57.2	1.1	34.7	0.7
50	96.5	6.8	13.8	57.2	0.7	0.1	23.3	0.1	16.8	0.5
75	58.5	4.1	8.4	34.7	0.5	0.1	12.7	0.1	10.0	0.3
100	39.4	2.8	5.6	23.3	0.4	0.1	8.1	0.1	5.7	0.1
125	28.3	2.0	4.0	16.8	0.3	0.1	4.2	0.1	3.3	0.1
150	21.5	1.5	3.1	12.7	0.2	0.1	2.6	0.1	1.8	0.1
175	16.9	1.2	2.4	10.0	0.2	0.0	1.3	0.0	1.0	0.0
200	13.7	1.0	2.0	8.1	0.1	0.0	1.0	0.0	0.8	0.0
250	9.6	0.7	1.4	5.7	0.1	0.0	0.7	0.0	0.7	0.0
300	7.2	0.5	1.0	4.2	0.1	0.0	0.6	0.0	0.6	0.0
350	5.6	0.4	0.8	3.3	0.1	0.0	0.5	0.0	0.5	0.0
400	4.4	0.3	0.6	2.6	0.1	0.0	0.4	0.0	0.4	0.0
500	3.1	0.2	0.4	1.8	0.0	0.0	0.4	0.0	0.4	0.0
600	2.3	0.2	0.3	1.3	0.0	0.0	0.3	0.0	0.3	0.0
700	1.7	0.1	0.2	1.0	0.0	0.0	0.3	0.0	0.3	0.0
800	1.4	0.1	0.2	0.8	0.0	0.0	0.3	0.0	0.3	0.0
900	1.1	0.1	0.2	0.7	0.0	0.0	0.3	0.0	0.3	0.0
1000	1.0	0.1	0.1	0.6	0.0	0.0	0.3	0.0	0.3	0.0
1100	0.8	0.1	0.1	0.5	0.0	0.0	0.3	0.0	0.3	0.0
1200	0.7	0.0	0.1	0.4	0.0	0.0	0.3	0.0	0.3	0.0
1300	0.6	0.0	0.1	0.4	0.0	0.0	0.3	0.0	0.3	0.0
1400	0.6	0.0	0.1	0.3	0.0	0.0	0.3	0.0	0.3	0.0
1500	0.5	0.0	0.1	0.3	0.0	0.0	0.3	0.0	0.3	0.0
1600	0.4	0.0	0.1	0.3	0.0	0.0	0.3	0.0	0.3	0.0
3200	0.2	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.0
4800	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.0

Exposure scenarios. Three standard exposure scenarios for non-cancer effects were considered: acute exposures lasting from one to fourteen days; intermediate exposures lasting from fifteen to 364 days; and chronic exposures lasting from seven years to a lifetime. Three exposure scenarios tailored to natural gas operations in Garfield County were used in the evaluation of cancer risk:

Lifetime exposure (seventy years) to on-going natural gas development—A person lives for seventy years in one or more locations where he or she is always downwind of natural gas operations. Because on-going development of new wells appears to be unlikely for such an extended time in Garfield County, this is unlikely to occur for exposures due to flow back. However, this scenario may be more realistic for exposure to condensate tank emissions and glycol dehydration unit emissions, which may continue as long as the well is in production. The lifetime exposure scenario will result in the greatest cancer risk and is included primarily as a possible worst case.

Two-year exposure to natural gas development—A person lives for two years in a location downwind of natural gas operations. This scenario includes situations in which multiple well pads are developed in proximity to this person, with the total duration of development being two years.

One-year exposure to natural gas development—A person lives for one year in a location downwind of a well pad that is developed over the course of that year.

The *Draft Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment* identified two sites, Cox and Daley, as representative of rural “background” locations representative of areas unaffected by natural gas operations. The exposure point concentrations for benzene identified in Table A7 of that study are 1.9 micrograms per cubic meter for the Cox site and 0 for the Daley site. An average of 1.0 micrograms per cubic meter was thus used as a background concentration applicable to all three of the above exposure scenarios for cancer risk. In addition to the seventy-year, two-year, and one-year exposure to benzene from natural gas operations, a seventy-year exposure to the background concentration of benzene was included.

Each of these three exposure scenarios also includes a lifetime exposure to background concentrations of benzene in air reported for rural areas in the Garfield County Ambient Air Quality Monitoring Study.

Threat of non-cancer effects from air pollutants. The threat of non-cancer effects from PM₁₀ is below any level of concern. The EPA has established a National Ambient Air Quality Standard for twenty-four hour average concentrations of PM₁₀ that is protective of not only the general population but sensitive subpopulations as well. As discussed in Section 2.2 of the *Garfield County Ambient Air Quality Monitoring Study*, there were no exceedances of this standard.

The threat of non-cancer effects from exposure to benzene, toluene, and *m,p*-xylenes was evaluated using the risk assessment procedure described in Section 1. Pollutant concentrations were generated using the Gaussian plume model, as described above. Exposures to benzene, toluene, and *m,p*-xylenes may produce non-cancer health effects if the exposures are high enough. “Reference concentrations” are pollutant concentrations in air that represent thresholds below which health effects are not expected to occur. Reference concentrations have been developed for acute exposures (one to fourteen days), intermediate exposures (fifteen to 364 days), and chronic exposures (seven years to a lifetime). Table 6 shows reference concentrations used in this study.

Table 6. Reference Concentrations (in micrograms per cubic meter)

	<u>Acute</u>	<u>Intermediate</u>	<u>Chronic</u>
Benzene	30	20	30
Toluene	3,766	none available	5,000
<i>m,p</i> -xylenes	9,000	3,037	100

From Draft Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment, December 2007.

Tables 7A–E show the following situations in which one or more reference concentrations are exceeded:

- For flow back with no gas recovery, the acute reference concentration for benzene is exceeded for distances up to 125 meters downwind.
- For flow back with no gas recovery, the intermediate reference concentration for benzene is exceeded for distances up to 150 meters downwind.
- For flow back with no gas recovery, the chronic reference concentration for benzene is exceeded for distances up to 125 meters downwind.
- For flow back with no gas recovery, the chronic reference concentration for *m,p*-xylenes is exceeded for distances up to twenty-five meters downwind
- For emissions of VOCs at twenty tons per year from condensate tanks, the chronic reference concentration for *m,p*-xylenes is exceeded for distances up to twenty-five meters downwind.

Flow back with no gas recovery is the only operation that exceeds reference concentrations at distances beyond twenty-five meters. Of the three pollutants whose emissions were modeled, benzene is the only one that exceeds reference concentrations at distances beyond twenty-five meters. These results suggest that emission of benzene during uncontrolled flow back is the situation that presents the greatest threat of non-cancer effects. These effects may occur in

people who spend one day or more within a distance 125 meters downwind of the natural gas well.

The threat of non-cancer effects was also examined in the *Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment*. That study was based on pollutant concentrations generated by sampling and analysis using a reasonable estimate of the concentration likely to be contacted over time (i.e., the 95% upper confidence level on the arithmetic mean). One of the fourteen sites evaluated (Brock) exceeded the acute reference concentration for benzene. That site and one other (Newcastle Library) had an excessive level of intermediate exposure, mostly due to benzene.

Cancer risk from air pollutants. Of the three pollutants that are the focus of this study, benzene is the only carcinogen. According to the U.S. Environmental Protection Agency (EPA) Integrated Risk Information System, benzene has a slope factor that ranges from 0.000077 up to 0.00027 per microgram per kilogram per day. The higher of the two slope factors was used in this study.

Tables 5A–E show the benzene cancer risks for each of the above exposure scenarios applied to each of the five emission scenarios. The EPA advocates as a goal that cancer risk for a specific exposure be no more than 1 chance in 1 million. However, the EPA further specifies that cancer risk for a particular exposure be considered acceptable when it is between 1 chance in 1 million and 1 chance in ten thousand. Of the risks shown in Tables 5A–E, the following exceed the upper end of the EPA acceptable range:

For flow back with no gas recovery, the seventy-year exposure exceeds the acceptable range for distances up to 200 meters downwind of the well.

For flow back with 93% recovery of gas, the seventy-year exposure exceeds the acceptable range for distances up to twenty-five meters downwind of the well.

For VOC emissions of twenty tons per year from condensate tanks, the seventy-year exposure exceeds the acceptable range for distances up to twenty-five meters downwind of the well.

Benzene emissions during uncontrolled flow back present the greatest risk of cancer. However, the risk of cancer exceeds the EPA acceptable range only for a seventy-year exposure. An exposure of that duration appears unlikely.

Cancer risk was also examined in the *Draft Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment*. Three sites—Brock, Parachute, and Glenwood Springs—were determined to have cancer risk exceeding the upper end of the EPA acceptable range for a seventy-year exposure. Brock, identified as a site affected by natural gas operations, had a cancer risk slightly over the upper end of the range due entirely to benzene. Parachute was identified as urban, with the usual urban sources of VOCs, as well as being directly affected by natural gas operations. Cancer risk in Parachute was from cumulative exposure to

Table 7A. Benzene Cancer Risk Resulting from Flow Back with No Gas Recovery

(Benzene emission rate of 0.07 grams per second)

Downwind distance (meters)	Concentration (micrograms per cubic meter)	Rural background cancer risk (chances per million)	70-Year exposure, total benzene cancer risk (chances per million)	2-Year exposure, total benzene cancer risk (chances per million)	1-Year exposure, total benzene cancer risk (chances per million)
25	214.5	7.8	1680.6	55.6	31.7
50	96.5	7.8	760.2	29.3	18.5
75	58.5	7.8	463.8	20.8	14.3
100	39.4	7.8	314.7	16.6	12.2
125	28.3	7.8	228.8	14.1	11.0
150	21.5	7.8	175.3	12.6	10.2
175	16.9	7.8	139.7	11.6	9.7
200	13.7	7.8	114.7	10.9	9.3
250	9.6	7.8	82.7	9.9	8.9
300	7.2	7.8	63.6	9.4	8.6
350	5.6	7.8	51.1	9.0	8.4
400	4.4	7.8	42.5	8.8	8.3
500	3.1	7.8	31.7	8.5	8.1
600	2.3	7.8	25.3	8.3	8.0
700	1.7	7.8	21.3	8.2	8.0
800	1.4	7.8	18.6	8.1	8.0
900	1.1	7.8	16.7	8.1	7.9
1000	1.0	7.8	15.3	8.0	7.9
1100	0.8	7.8	14.2	8.0	7.9
1200	0.7	7.8	13.3	8.0	7.9
1300	0.6	7.8	12.7	7.9	7.9
1400	0.6	7.8	12.1	7.9	7.9
1500	0.5	7.8	11.7	7.9	7.9
1600	0.4	7.8	11.3	7.9	7.8
3200	0.2	7.8	9.0	7.8	7.8
4800	0.1	7.8	8.5	7.8	7.8

Table 7C. Benzene Cancer Risk Resulting from Operation of Wellhead Glycol Dehydration Units

(Benzene emission rate of 0.0036 grams per second)

Downwind distance (meters)	Concentration (micrograms per cubic meter)	Rural background cancer risk (chances per million)		70-Year exposure, total benzene cancer risk (chances per million)	2-Year exposure, total benzene cancer risk (chances per million)	1-Year exposure, total benzene cancer risk (chances per million)
		7.8	93.8			
25	11.0	7.8	93.8	93.8	10.3	9.0
50	5.0	7.8	46.5	46.5	8.9	8.3
75	3.0	7.8	31.2	31.2	8.5	8.1
100	2.0	7.8	23.6	23.6	8.2	8.0
125	1.5	7.8	19.2	19.2	8.1	8.0
150	1.1	7.8	16.4	16.4	8.0	7.9
175	0.9	7.8	14.6	14.6	8.0	7.9
200	0.7	7.8	13.3	13.3	8.0	7.9
250	0.5	7.8	11.7	11.7	7.9	7.9
300	0.4	7.8	10.7	10.7	7.9	7.8
350	0.3	7.8	10.0	10.0	7.9	7.8
400	0.2	7.8	9.6	9.6	7.8	7.8
500	0.2	7.8	9.0	9.0	7.8	7.8
600	0.1	7.8	8.7	8.7	7.8	7.8
700	0.1	7.8	8.5	8.5	7.8	7.8
800	0.1	7.8	8.4	8.4	7.8	7.8
900	0.1	7.8	8.3	8.3	7.8	7.8
1000	0.0	7.8	8.2	8.2	7.8	7.8
1100	0.0	7.8	8.1	8.1	7.8	7.8
1200	0.0	7.8	8.1	8.1	7.8	7.8
1300	0.0	7.8	8.0	8.0	7.8	7.8
1400	0.0	7.8	8.0	8.0	7.8	7.8
1500	0.0	7.8	8.0	8.0	7.8	7.8
1600	0.0	7.8	8.0	8.0	7.8	7.8
3200	0.0	7.8	7.9	7.9	7.8	7.8
4800	0.0	7.8	7.8	7.8	7.8	7.8

Table 7D. Benzene Cancer Risk Resulting from Condensate Tanks Emitting 20 Tons Per Year of Volatile Organic Hydrocarbons

(Benzene emission rate of 0.0081 grams per second)

Downwind distance (meters)	Concentration (micrograms per cubic meter)	Rural background cancer risk (chances per million)		70-Year exposure, total benzene cancer risk (chances per million)	2-Year exposure, total benzene cancer risk (chances per million)	1-Year exposure, total benzene cancer risk (chances per million)
		7.8	201.4			
25	24.8	7.8	201.4	201.4	13.3	10.6
50	11.2	7.8	94.9	94.9	10.3	9.0
75	6.8	7.8	60.6	60.6	9.3	8.6
100	4.6	7.8	43.3	43.3	8.8	8.3
125	3.3	7.8	33.4	33.4	8.5	8.2
150	2.5	7.8	27.2	27.2	8.4	8.1
175	2.0	7.8	23.1	23.1	8.2	8.0
200	1.6	7.8	20.2	20.2	8.2	8.0
250	1.1	7.8	16.5	16.5	8.0	7.9
300	0.8	7.8	14.2	14.2	8.0	7.9
350	0.6	7.8	12.8	12.8	7.9	7.9
400	0.5	7.8	11.8	11.8	7.9	7.9
500	0.4	7.8	10.6	10.6	7.9	7.8
600	0.3	7.8	9.8	9.8	7.9	7.8
700	0.2	7.8	9.4	9.4	7.8	7.8
800	0.2	7.8	9.0	9.0	7.8	7.8
900	0.1	7.8	8.8	8.8	7.8	7.8
1000	0.1	7.8	8.7	8.7	7.8	7.8
1100	0.1	7.8	8.5	8.5	7.8	7.8
1200	0.1	7.8	8.4	8.4	7.8	7.8
1300	0.1	7.8	8.4	8.4	7.8	7.8
1400	0.1	7.8	8.3	8.3	7.8	7.8
1500	0.1	7.8	8.2	8.2	7.8	7.8
1600	0.1	7.8	8.2	8.2	7.8	7.8
3200	0.0	7.8	7.9	7.9	7.8	7.8
4800	0.0	7.8	7.9	7.9	7.8	7.8

Benzene, 1,4-dichlorobenzene, and trichloroethene. Cancer risk in Glenwood Springs, identified as having only urban characteristics, was from cumulative exposure to benzene, 1,4-dichlorobenzene, and methylene chloride.

Uncertainties in non-cancer threat and cancer risk. There are a number of uncertainties in the non-cancer threat and cancer risks determined using pollutant concentrations based on the Gaussian plume model. Some of these uncertainties have the effect of reducing threat and risk.

- Actual pollutant emission rates may be less than those used in the model calculations. There is some variation in emission rates from one well pad to another. There may be variation from one company to another as well, if different operating practices are used.
- Site-specific meteorological conditions and topography may differ from the average conditions upon which the model is based. If site-specific conditions and topography enhance the dispersion of pollutants, there will be less exposure to residents at that site and less likelihood of health effects.
- Cancer risk would be less if the less potent of the two slope factors provided in the EPA *Integrated Risk Information System* was used.

Other uncertainties have the effect of increasing threat and risk.

- Actual pollutant emission rates may be greater than those used in the model calculations, for the same reasons identified above that rates may be less.
- Similarly, if site-specific meteorological conditions and topography limit pollutant dispersal, the likelihood of health effects would be increased. This situation is most likely to apply to acute exposures, which may occur from transient or short-term conditions, such as a multi-day winter inversion.
- The presence of other natural-gas related sources of these pollutants may increase the likelihood of health effects. Benzene, toluene, and *m,p*-xylenes are components of fuel and exhaust from vehicles or engines that are used on well pads. This emission source was not included in the model.
- If multiple well pads are in development at the same time in the same vicinity, their effects will be additive for any site that receives pollutant emissions from each site.
- The presence of other carcinogens in outdoor air, not included in the model, will increase cancer risk. For example, 1,4-dichlorobenzene was occasionally observed in the Garfield County Ambient Air Quality Monitoring Study. This consideration applies as well to the presence of other air pollutants having non-cancer effects.

- The presence of other pollutants in indoor air may increase the likelihood of non-cancer effects and cancer. Combustion devices (such as gas and wood stoves), tobacco smoke, paints, furnishings, and building materials all emit pollutants.

Discussion. Given the above uncertainties, the use of modeling as a substitute for sampling and analysis is no panacea. However, modeling can provide pollutant concentrations that can be used to illuminate an approximate understanding of the likelihood of health effects.

The results presented above suggest that the single operation creating the greatest threat from exposure to benzene, toluene, and *m,p*-xylenes is flow back with no recovery of natural gas. Until recently it was routine to conduct flow back in this manner. However, at this time companies are making increasing use of “green completions,” in which over 90% of the natural gas is recovered during flow back. This practice is an effective way to reduce the single most significant exposure to benzene, toluene, and *m,p*-xylenes. For cases in which the green completion approach is not used, a setback requirement is desirable.

WATER POLLUTION EFFECTS

Pollutant transport in ground water. A useful starting point is to consider the general behavior of pollutants in ground water. Contamination in ground water has several possible origins. Liquids that are spilled, leaked, or dumped onto the land surface may infiltrate into the soil and percolate downward to ground water. These can be organic liquids, such as gasoline or condensate, or water-based liquids containing dissolved pollutants. Liquids may leak into the subsurface soil from pits, ponds, underground tanks, and pipelines. These liquids can also percolate downward to ground water. Solid materials that are spilled, leaked, or dumped onto the land surface may undergo the same process, provided they are water soluble, by dissolving into rain water that infiltrates into the soil.

As any liquid moves through the subsurface, it may leave behind a thin film of itself on the soil and rock surfaces. This effect gradually decreases the amount of liquid that continues to flow downward, and releases of small volumes of liquid are less likely to reach the ground water than releases of larger volumes. Another complicating factor is the tendency of most pollutant molecules to undergo sorption to the rock and soil surfaces through physical and chemical interactions. The sorbed pollutant becomes a residue that is left behind as the rest of the liquid continues to percolate. This residue can act as a secondary source of contamination. When clean rain water percolates through the subsurface, pollutant molecules in the residue can desorb or redissolve (“leach”) into this water and be carried downward to the ground water.

When polluted water reaches the water table, it mixes with the ground water and creates a “slug” or “plume” of contaminated ground water. When a hydrocarbon liquid reaches ground water, a large portion of the hydrocarbon liquid will float on the water table. Over time, hydrocarbon molecules from this floating hydrocarbon layer will dissolve into the ground water, creating a slug or plume of contamination.

Ground water typically flows slowly through an aquifer. The contaminant plume is carried along with the moving ground water by advection. The velocity of the ground water depends on the hydraulic gradient of the ground water the hydraulic conductivity of the aquifer. (Hydraulic gradient can be pictured as the slope of the water table, with ground water flowing from an area of high water table to an area of low water table. Hydraulic conductivity refers to how readily the water can move through the aquifer. High values of gradient and conductivity lead to a higher velocity of ground water flow.) The contaminant plume itself usually moves at a slower velocity than the ground water due to the sorption process described above. Any particular dissolved pollutant molecule will sorb at some random time. While the pollutant molecule is sorbed, it is stationary. When it desorbs at some later random time, the pollutant becomes mobile and resumes advection. Overall, any given pollutant molecule will spend part of its time stationary rather than all of its time mobile, and thus will move at a slower velocity than the ground water itself, which is mobile all of the time.

Initially, the plume is small and the pollutant concentrations within the plume are relatively high. As the plume moves, it spreads out in all directions by hydrodynamic dispersion, and pollutant concentrations within the plume decrease over time because the pollutant mass is distributed over a larger volume of water. Many organic pollutants, including most of the smaller hydrocarbons, are susceptible to biodegradation. Naturally-occurring bacteria can use the pollutants as a source of “food” (that is, as a source of carbon for growth and energy for metabolism). The biodegradation process breaks down the hydrocarbon molecules into simpler hydrocarbons or to carbon dioxide and water. The rate of biodegradation depends on the chemical structure of the pollutant molecule, the type of bacteria, the amount of dissolved oxygen present in the ground water, and the availability of nutrients for the bacteria. Biodegradation can be a valuable asset if it works at a fast enough rate. Taken together, the effects of dispersion and biodegradation are often referred to as “natural attenuation”.

The ground water pathway in Garfield County. Natural gas operations have the potential to create ground water contamination. One potential source of contamination is an improperly constructed gas well, which can allow the escape of natural gas, drilling fluids, or produced water into the surrounding geologic formation at the breach. Another potential source is seepage from unlined pits used to store water that may be contaminated with hydrocarbons or chemicals used in different stages of the well installation and completion process. Hydraulic fracturing creates fractures having the potential to act as conduits for the flow of water contaminated with hydrocarbons and substances used in the fracturing process. Surface spills or leaks of materials such as condensate can allow hydrocarbons to eventually reach ground water, as described on the preceding page. From the standpoint of evaluating the threat to human health, the key question (as explained in the earlier section on risk assessment) is whether or not a given exposure route is complete.

Rural residents of Garfield County have expressed concern about possible effects on ground water used for drinking and other domestic purposes. With the exception of the well-known contamination problem near West Divide Creek caused by faulty well construction, available

data from sampling and analysis do not show the presence of natural gas-related pollutants in ground water. Ground water characterization required by Garfield County for new subdivisions has not revealed any contamination problems (J. Rada, Garfield County Health Department). Similarly, examination of the ground water data base maintained by the Colorado Oil and Gas Commission revealed no contamination outside the vicinity of the problem in West Divide Creek.

Can ground water be contaminated even though no contamination has been revealed by results from sampling and analysis? Given that there is no exhaustive ground water monitoring program in place, the possibility exists that undetected contaminant plumes may be present. Rural water wells could be an important source of water quality data. However, landowners must bear the cost of analyzing their water, and most landowners likely do not have their water analyzed because of cost.

How likely is it that a plume will affect a water well? The likelihood of a contaminant plume in the drinking water aquifer reaching a private well used by rural residents is strongly dependent on location- and release-specific factors. Most ground water used in rural areas of Garfield County is from 20 to about 250 feet below the land surface (D. Dennison, Garfield County Oil & Gas Liaison). Pollutant releases that occur within this zone do have the potential to reach water wells. Whether the contaminant plume does so depends first on the direction of ground water flow—a well must be in the path of the plume in order to be affected. The vertical location of the release must also be a match for the point where the well draws water. A pollutant release at a given depth can result in a plume that may not travel vertically to a depth that would allow it to enter the well. Even if a well is in the path of the plume, the distance between the release location and the well is also a key factor. The greater the distance that the plume travels, the more the plume spreads out by hydrodynamic dispersion, reducing the maximum pollutant concentrations found in the plume. Biodegradation can cause further reductions in pollutant concentrations within the plume to the extent that the pollutant may no longer be a threat. Therefore the degree of threat posed by a release to ground water depends strongly on the location of the release relative to nearby water wells, in terms of both direction and distance.

There is public concern about the possibility of hydraulic fracturing leading to ground water contamination. Part of this concern is derived from the unknown composition of the materials pumped through the gas well into the gas-bearing formation during the hydraulic fracturing process; the detailed composition of these materials is treated as proprietary information by the natural gas industry. Concern also stems from the possibility that the new fractures may promote the movement of natural gas and hydraulic fracturing fluids toward water wells.

Natural gas wells in Garfield County range in depth from about 2,000 feet below the land surface to as much as 18,000 feet below the land surface (2006 Phase I Hydrogeologic Study by URS, Inc.), with most typically falling in the range from 4,000 to 9,000 feet (D. Dennison, Garfield County Oil & Gas Liaison). Thus, considerable transport must take place to bring hydraulic fracturing chemicals from such great depths up to the surficial aquifer used by rural residents. Given that the gases and fluids in these deep formations are under great pressure,

there is a tendency for upward migration of pollutants towards lower pressure zones at shallower depths. The rate of migration can be very slow because of the low permeability of formations between the gas-bearing zones and the surficial aquifers. However, fractures and faults can provide preferential flow paths that offer less resistance to pollutant transport. Evidence of deep ground water mixing with shallow ground water in the Mamm Creek gas field in southeastern Garfield County was presented in the 2006 Phase I Hydrogeologic Study performed by URS, Inc., demonstrating that the potential for pollutant transport from deep zones to shallow ground water is real. Due to the complexity and heterogeneity of the subsurface across Garfield County, it is difficult to predict with any confidence when and where this kind of migration may occur.

A risk assessment for ingestion of contaminated ground water was not performed. Without data showing contaminant concentrations in water currently used or potentially useable for drinking, there is no basis for calculating risk. Similarly, available information is insufficient to permit the use of modeling to predict contaminant concentrations. However, the maximum contaminant levels described below in the discussion of surface water are also a useful guide for ground water used for drinking. Even though these levels are legally enforceable only for public water systems, residents who monitor their private well may use these levels as a guideline for unacceptable contaminant concentrations.

The surface water pathway in Garfield County. There are several ways in which natural gas operations may contaminate surface waters (i.e., rivers, streams, lakes, ponds, and wetlands). Hydrocarbons and other materials involved in natural gas operations can enter the water directly through spills, such as those that sometimes occur in transportation accidents. Spills or leaks that occur some distance away from surface water may still enter the water as a result of overland flow across the land surface. Spilled or leaked materials that don't flow all the way to surface water on their own may be washed into the water by rain or snowmelt flowing across the land surface. Some bodies of surface water are fed by seepage from ground water. In these situations, ground water contaminant plumes described in the preceding section may also affect surface water. In contrast, some surface waters act as a source of recharge for ground water. In these situations, contaminated surface water can lead to a plume of contaminated ground water.

The Colorado River and certain tributaries are used as a source of drinking water by the public water systems operated by the City of Rifle and the Towns of Parachute and Silt.

Public water systems are regulated by the EPA under the Safe Drinking Water Act and are thus subject to the National Primary Drinking Water Regulations, which can be viewed at <http://www.epa.gov/safewater/contaminants/index.html>. These regulations set "maximum contaminant levels" for a variety of microorganisms and chemicals in water that is supplied to the public. Four of the most prominent petroleum hydrocarbons have been assigned maximum contaminant levels: benzene at 0.005 milligrams per liter, toluene at 1 milligram per liter, ethyl benzene at 0.7 milligrams per liter, and total xylenes at 10 milligrams per liter. Barium, which is a component of drilling muds, has a maximum contaminant level of 2 milligrams per liter.

Public water systems are required to monitor the water for these contaminants on a regular basis and, if violations occur, provide notice to the public and take corrective action.

The requirements of the Safe Drinking Water Act provide Garfield County residents supplied by public water systems with significant protection from drinking water contaminants associated with natural gas operations. In order for this regulatory system to be effective, it is imperative that the public water systems meet all the requirements for monitoring. Should benzene, toluene, ethyl benzene, xylenes, or barium be discovered at unusually high concentrations through this monitoring, the public water systems should consider additional monitoring for other contaminants that are associated with natural gas operations.

SOIL

Soil can become contaminated by spills, leaks, or overflows onto the land surface. Liquids (both hydrocarbons and water-based liquids) can flow down-slope across the land surface, spreading pollutants across a larger area of surface soil. Some portion of the liquids will infiltrate into the soil, spreading pollutants from the surface downward. Sorption of pollutants to soil results in a residue that persists until rain and snowmelt have leached the pollutants off the soil and carried them farther away across the land surface or farther down into the subsurface. Water soluble solid materials that are spilled or leaked onto the land surface may undergo the same process by dissolving into rain and snowmelt that infiltrates into the soil.

The primary manner in which people are exposed to pollutants in soil is through ingestion. While it is certainly not the case that adults intentionally “eat dirt”, a small amount of incidental ingestion is plausible. For example, soil on hands from gardening or other outdoor activities can be transferred into a person’s mouth. Young children are more likely to ingest soil as a result of their hand-to-mouth habits. The EPA recommends making the assumption that an adult ingests an average of one-tenth of one gram (less than four one-thousandths of an ounce) of soil per day (*Risk Assessment Guidance for Superfund, Volume 1. Human Health Evaluation Manual*). For children, the recommendation is two-tenths of a gram of soil per day. There is a possibility for dermal absorption of pollutants from soil on hands. However, this is limited to the relatively small number of pollutants that have this ability.

There is little to no information available on pollutants in soil from natural gas operations (R. Chesson, Colorado Oil and Gas Conservation Commission). This precludes the possibility of doing a risk assessment for an actual, polluted site.

The Colorado Oil and Gas Conservation Commission requires that soil contaminated with greater than 1,000 milligrams of total petroleum hydrocarbons per kilogram of soil be treated or removed and properly disposed of. Soil with this level of contamination resulting from a condensate spill was assessed for risk as a way of illuminating what kind of hydrocarbon concentrations would present a significant threat. Only benzene, toluene, and *m,p*-xylenes were included because toxicity values for other hydrocarbons in condensate are not available.

The EPA-recommended values for a reasonable-maximum exposure were used in the calculation, which is shown in Appendix J. The hazard quotients are 0.011, 0.0031, and 0.0014 respectively for benzene, toluene, and *m,p*-xylenes. The sum of the hazard quotients is 0.016. All of these numbers are well under one, which is the threshold for unacceptable exposure leading to non-cancer effects. The cancer risk due to benzene is one chance in one million, which meets the EPA regulatory goal for acceptable cancer risk. That 1,000 milligrams of total petroleum hydrocarbons per kilogram of soil presents an acceptable health threat is not surprising—the level was deliberately set at a “safe” value.

RECOMMENDATIONS

As described in this report, there are numerous gaps and uncertainties in our understanding of pollution from natural gas operations in Garfield County. The motivation for the following recommendations is to reduce these uncertainties and fill data gaps. Better information is needed in order to make a complete and accurate evaluation of threats to human health.

- *Conduct a thorough study of air emissions during drilling*—At least three well pads should be selected for study, with different companies, drilling approaches, and operations represented. A scenario believed to be a worst case from an air emission standpoint should be among the three. Daily 24-hour grab samples of ambient air should be collected at the boundary of the well pad at each of sixteen equally-spaced compass directions. Samples should be analyzed for volatile organic compounds, carbon monoxide, and ozone. The duration of the study at each well pad should cover the drilling and completion of at least three wells. On-site measurements of wind speed, wind direction, and temperature should be made at 15-minute intervals in order to understand elements of the basic meteorology of the site. The results of this study should provide a much-improved picture of air pollutant concentrations representative of drilling operations in general.
- *Identify the components of hydraulic fracturing fluids and other materials used in well installation*—There is considerable public concern about the chemical composition of these materials. The industry maintains that hydraulic fracturing fluids are not a threat but has offered only incomplete evidence in the form of material safety data sheets, which are not required to include the identity of all components. Disclosure of the fracturing fluid composition would allow monitoring of ground water for fluid components, evaluation of the potential health threat, and the potential for improved public acceptance of the industry. Similarly, the chemical composition of used drilling muds and produced water should be determined and revealed.
- *Establish a monitoring program for protection of the private well users*—As described in the section on water, Garfield County presents a difficult situation to assess for ground water contamination. The subsurface is complex, and the behavior of any specific contaminant plume may make contamination difficult to locate. It may not be possible

to implement a ground water monitoring network at a feasible cost that would provide a high degree of confidence for detecting contamination.

However, the principal goal is to detect any contamination that may be affecting private wells, where exposure to contaminants would actually take place. The most direct way to accomplish this goal is to collect quarterly or semiannual samples from private wells. The monitoring program should be funded, organized, and operated by either Garfield County or the Colorado Department of Public Health and Environment. Well water should be analyzed for methane, benzene and other volatile organic compounds, and selected components of hydraulic fracturing fluids that have the greatest potential to affect human health.

- *Inspection of surface soils at well pads after drilling activities are complete*—Colorado Oil and Gas Conservation Commission staff should inspect well pads for contamination of surface soil and collect samples of any areas where contamination is suspected based on observation of discolored soil or odor. Inspections should occur frequently and in particular should be timed so as to allow observation of empty pits prior to backfilling when drilling operations area complete. Samples should be analyzed for petroleum hydrocarbons and any metals (such as barium) that are used or occur in drilling fluids. Soils exceeding the spill cleanup criterion for total petroleum hydrocarbons or typical action levels for metals should be remediated. This practice should ensure that landowner exposure to soil contaminants is minimized.
- *Use green completions and applicable best management practices*—The industry can accomplish a significant reduction in pollutant emissions by continuing to adopt more environmentally friendly practices. As described in this report, the capture of gas during flow back should eliminate the most serious pollutant emissions.