Frequently Asked Questions (FAQ) About Natural Gas Transmission Pipelines Through Karst Terrains

By the Virginia Cave Board

The construction of new natural gas transmission pipelines through Virginia karst landscapes was recently proposed, and numerous questions and concerns have arisen regarding the potential risks that these pipelines may have upon human health, safety, and the karst environment. One of the core missions of the Virginia Cave Board is to provide information on matters relating to karst lands in Virginia, therefore the Board has developed answers to some potentially common questions on the topic.

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Q. Is the limestone and dolomite dissolving away to form caverns and conduits?

Q. Have sinkholes ever formed during the installation of a high pressure natural gas pipeline?

Q. Sinkholes do form suddenly in our region, don't they? We read about road closures and building foundation failures. How could this have happened?

Q. Can soil being carried into sinkholes or caverns during the process of excavation negatively affect the karst environment?

Q. How can one predict where collapse of sediment into voids in the bedrock might occur?

Q. Can blasting have an effect upon karst aquifers and groundwater supplies?

Q. Can trenching negatively affect water wells and springs?

Q. Won't the pipeline trench, even if backfilled, become an artificial "conduit," diverting water away from its previous natural flow path through the subsurface?

Q. Can the on-going operation of natural gas transmission pipelines on karst affect water quality?

Q. Besides leaking natural gas, are there other potential water quality challenges from natural gas transmission pipelines located in karst terrain?

Q. Can a preliminary karst survey help reduce potential risks to the pipeline's integrity and safeguard water supplies, water quality, and the subsurface environment?

Q. How effective are natural gas pipeline inspections?

Q. Where can I learn more about karst?

Q. What exactly is karst?

A. The term "karst" refers to a landscape type, not unlike "desert," "marsh," "tundra," "steppe" or "montane." It was named for a province in Slovenia that was dominated by sinkholes, caverns, irregular "pinnacled" bedrock surfaces, and large springs. The term "karst" was later applied to other landscapes dominated by similar features. However, modern definitions usually apply the term to landscapes in which surface and groundwater flow systems occur within bedrock modified by chemical solution, regardless if there are sinkholes or other surface features historically associated with karst landscapes. Therefore, if surface and groundwater is flowing over and through soluble rocks, such as limestone, the presumption is that karst is present. The main difference in karst versus non-karst systems is:

1) Groundwater flow is non-uniform, and primarily through conduits formed by bedrock dissolution. As such, groundwater flow in karst is not as predictable as groundwater flow in unconsolidated sediment; therefore, many computer models of groundwater flow are not reliable;

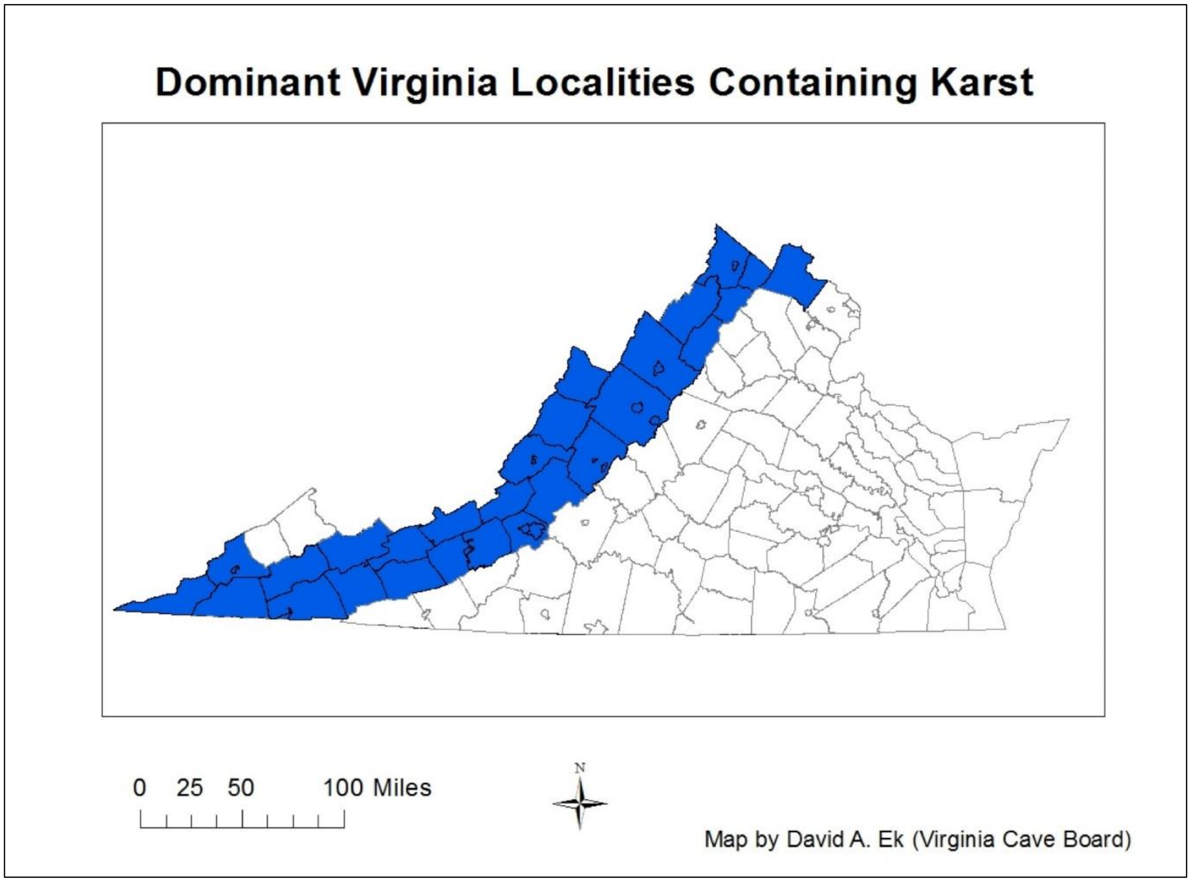
2) These conduits slowly change over time due to chemical solution and alteration of the bedrock and aquifer characteristics;

3) Groundwater can flow rapidly through solution channels, carrying pollutants and sediment with little or no filtration or treatment commonly associated with groundwater flow; therefore, the risk of contaminant transport is generally higher within karst terrain; and

4) Some aquatic and terrestrial organisms have adapted to the caves and conduits within karst systems, and their confinement to these systems has created a high degree of specific adaptation to these environments. These organisms' dependence upon this environment, coupled with their often low numbers, and their tendency to evolve into distinct species, has created a situation in which they are often highly susceptible to impact and environmental degradation.

Q. Where is karst located in Virginia?

A. It has been estimated that one-third of all of the United States east of the Mississippi River, and 18 percent of Virginia, contains karst. Karst can be located wherever there are soluble rock strata, and this includes sandstones that are cemented with calcite. While many areas of Virginia contain some karst, the dominant karst region within Virginia is the Valley and Ridge Physiographic Province located near the western portions of the state, bordering West Virginia and Kentucky. The following map provides an approximation of the major karst regions in Virginia.



Q. Are there currently any natural gas pipelines in Virginia located in karst terrain?

A. Yes, there are several companies that operate and maintain natural gas transmission pipelines located within Virginia karst terrains. Of the 27 Virginia counties that contain significant karst resources, 20 of them (74 percent) appear to have at least one natural gas transmission pipelines that traverses the county and is likely located on karst. These counties are: Alleghany; Augusta; Botetourt; Clarke; Frederick; Lee; Loudoun; Montgomery; Page; Pulaski; Roanoke; Rockbridge; Rockingham; Russell; Shenandoah; Smyth; Tazewell; Warren; Washington; and Wythe. The seven Virginia counties containing significant karst resources that do not currently contain any current natural gas transmission pipelines are: Bath; Bland; Craig; Giles; Highland; Scott; and Wise.

Q. Is locating natural gas transmission pipelines in karst inherently dangerous?

A. While natural gas pipelines are often the safest means of transporting natural gas, there are dangers associated with carrying pressurized flammable gas. According to the U.S. Department of Transportation's Pipeline and Hazardous Material Safety Administration (PHMSA), there were 1,270 "significant" "gas transmission" pipeline incidents from 1995 to 2014 in the United States, resulting in 42 fatalities and 174 injuries. For this same time period in Virginia, there were 58 incidents (from all types of pipelines, not just gas transmission), resulting in four fatalities and 28 injuries. The causes of these incidents ranged from pipe damage during excavations, pipe corrosion, flood damage, to weld failures.

There is no cave or karst category, but cave or karst-related incidents appear to be an insignificant percentage of incidents.

The biggest safety threat associated with the on-going operations of a natural gas transmission pipeline in karst terrain is due to its potential ability to swiftly and widely transport pollutants through karst conduits, thereby potentially affecting a wider array of people and resources. Gas can move along a karst conduit faster than a person can walk. There have been instances in which teenagers have died from entering a cave a long distance from an unsuspecting gasoline spill. In these situations, the gasoline vapors traveled long distances through the cave and karst conduits before coming into contact with an ignition source or created a situation in which the unsuspected cave explorer became asphyxiated. There are incidents in which flammable vapors degassed and vented into crawlways and basements under existing homes and structures. These are rare incidents, but it is important to keep natural gas or other flammable gases out of cave and karst conduits and other confined locations. Corrosion is a ubiquitous concern for all pipelines; however, there are some situations that may lead to an increased risk for pipelines located in karst. Some rock layers contain pyrite, and pyrite can lead to the production of sulfuric acid, which would then accelerate limestone dissolution as well as pipeline corrosion. To reduce pipeline corrosion, some common industry practices include special sealants and the passing of a weak electrical current through the pipeline.

Q. Are there specific laws guiding the construction of natural gas pipelines in karst terrain?

A. Virginia does have a law specifically focused upon protecting caves (the Virginia Cave Protection Act, Code of Virginia Section 10.1-1000 to 1008); there is no corresponding law that specifically protects karst. In addition, there are regulations governing pipelines; however, these regulations provide no separate consideration for karst or karst impact.

It is important to understand, that caves and karst contain interrelated systems of physical, chemical and biologic processes. Virginia caves and karst not only provide pathways for water, they also support the economy, contain irreplaceable cultural resources, and provide critical habitat for rare and protected species. As such, there may be other laws that may be applicable to caves and karst, ranging from the Federal Cave Resources Protection Act, Endangered Species Act, Clean Water Act, and the Archeological Resources Protection Act, to name a few. From a project-to-project perspective, some of these laws may apply due to the specific resources and issues involved, not necessarily because of the presence or absence of sensitive karst resources. It should be noted that several of these environmental laws contain specific exemptions for targeted elements of the oil and gas industry.

Just as diverting or modifying water flowing into a karst system may interrupt the karst's natural flow regime, it may also disrupt or even seriously harm sensitive cave organisms. There are a variety of rare, threatened and endangered species that inhabit Virginia caves, some, such as the Lee County isopod, Madison Cave amphipod, Madison Cave isopod, and Holsinger's cave beetle, are restricted to caves and karst. Therefore, most cave and karst-related laws are due to the presence of protected species or artifacts that may be in caves and karst, and not due to the karst landscape per se.

Q. Is the strength of the bedrock a challenge for predicting the behavior of karst feature development?

A. It is true that the bedrock underlying the karst terrain of Virginia varies considerably, depending on how it was deposited and whether it underwent modification by solution action of acidic water in the distant past. However most of the rock within Virginia's karst regions is hundreds of millions of years old, and in general is structurally sound. In fact, most of the regional highway commissions consider ten---feet of solid limestone to be sufficient to support "critical structures" such as highway overpasses and viaducts. It should be noted that the famous Natural Bridge of Virginia's Rockbridge County is 50---feet thick, yet it carries U.S. Route 11 over an open void over 200 feet in height without collapsing.

But more importantly, it is often not the collapse of the bedrock that causes sudden, catastrophic formation of sinkholes in our region; rather; it is the collapse of sediment overlying the bedrock voids that commonly occurs. These are called "cover collapses." Cases in which a bedrock cavern roof suddenly gives way are rare in Virginia. Since the geographic setting, geologic history, climate and local environmental conditions vary widely from one karst region to the next, transferring the risk assigned to a karst setting in one part of the country and applying it to a Virginia karst setting may not be a valid assumption.

Although natural cave collapses are rare within Virginia, there are human-induced activities that can increase the likelihood of problems within a karst setting, this is one of the reasons that proper geophysical studies, site specific evaluations, and karst assessments prior to construction is important. Situations that would greatly increase this potential risk, especially within karst settings, are poorly designed on-site water and stormwater management, and diverting and impounding water. These poor practices can greatly increase the likelihood of unintended consequences, including the potential for sinkhole and cover collapse. This is why it is especially critical to have water and stormwater management designs and plans for projects within karst settings to be prepared by professionals who have demonstrated experience in karst stormwater management; and that developers should be held accountable for implementing these recommendations responsibly.

Q. Is the limestone and dolomite dissolving away to form caverns and conduits?

A. Yes, but the process of dissolution is imperceptibly slow. In our area, the limestone is dissolved by carbonic acid, which is the result of atmospheric and soil carbon dioxide mixing with percolating water. However, the actual rate of limestone dissolution underground is extremely slow. For instance, to dissolve an inch of limestone under natural conditions, may take many decades to several hundred years. In addition, the caves in our region are likely several millions of years old. Limestone and other carbonate rock and conduits and caves within karst terrain are not likely to catastrophically collapse merely from the placement of a pipeline, building or other structure on karst surfaces. It should be noted that since the founding of our country, there have perhaps been millions of people and hundreds of communities in the United States that have lived on karst- this is not a rare or unusual situation. Pipelines within karst terrain can be structurally stable, if properly designed, constructed and maintained.

Q. Have sinkholes ever formed during the installation of a high pressure natural gas pipeline?

A. Yes, they have, and in fact this occurred in a well---documented incident (click here for a reference: http://www.karstportal.org/node/11809) during the installation of a natural gas pipeline system in Florida. Unfortunately, this incident has been used as evidence by critics that all pipelines installed in karst are inherently unsafe and may induce sinkhole formation. However, the Florida incident occurred while the pipeline was under construction using a process called "Horizontal Directional Drilling" (HDD); and in the relatively soft and poorly consolidated limestone that occurs in that region. HDD requires enormous "tip pressure" to advance the borehole, and as a result of this it caused a "blow out" of the soft limestone and soil above it. It is for this and other reasons that the Virginia Cave Board does not recommend horizontal directional drilling within karst settings.

Q. Sinkholes do form suddenly in our region, don't they? We read about road closures and building foundation failures. How could this have happened?

A. This certainly does happen, but usually not because the rock has collapsed. It more commonly occurs where soil and sediment that fills the pre---existing network of solution---enlarged voids and conduits in the bedrock begins to move downward. This can happen due to natural causes, such as periods of drought that lowers the water table, thus creating an air---filled void beneath the soil plug in a vertical chamber. In these situations, the water that was supporting the soil is gone; thereby allowing the soil to subside into the hollow below, forming a sinkhole on the surface. It can also occur when water that used to infiltrate in a dispersed manner has later been channelized into a concentrated area. As new sinkholes are created, it provides an effective conduit to transport sediment and other debris that falls into the sinkhole from the surrounding unstable land surface, and carry this material away by the water flowing through the karst conduit. This is how a catastrophic sinkhole can grow quickly engulfing objects on the surface and collapsing into itself. While these catastrophic sinkholes can be created by natural processes, more often they are due to human activity. Over---pumping of groundwater from shallow wells, quarry dewatering, and channeling of stormwater into narrow drainage paths, can all wash underlying soil and loose unconsolidated sediment away, thus leaving the surface structurally unstable and susceptible for the creation of additional sinkholes. Something as simple as improperly directing the water from roof drains and gutters away from the foundation of a structure can eventually cause a sinkhole to form along the footer or even below the slab.

Q. Can soil being carried into sinkholes or caverns during the process of excavation negatively affect the karst environment?

A. Yes, it can. That is why the preliminary karst survey is so important. The most vulnerable karst features are cave entrances and "open throat" sinkholes (i.e. sinkholes that have an opening into the subsurface bedrock). Soil, uncontrolled stormwater and pollutants absorbed into soil particles can flow into these openings and directly into the subsurface without the benefit of any filtration. Therefore, the preliminary survey identifies karst features so that the pipeline's route may be relocated accordingly. If they cannot be avoided, strict sediment and erosion control measures should be taken during construction and continue after construction until such time that the surrounding soil has stabilized. Every effort should be taken to direct soil and construction site runoff from these openings.

Q. How can one predict where collapse of sediment into voids in the bedrock might occur?

A. One cannot predict exactly where a sinkhole might form, but the pattern of existing sinkholes gives clues as to where the pre---existing structural features such as intersecting joints and fractures, faults, and olds in the bedrock, have allowed sinkholes to form with greater frequency and density over time. In addition, potential causative factors, such as ponded water or greater volumes of water being channeled into karst settings, would be particularly noted and inspected by knowledgeable professionals performing karst assessments. This is why preliminary surveys are so important. In addition, experienced karst geologists and soil scientists are aware that certain rock units tend to form cohesive, clay---rich soil layers that are prone to the development of so---called "covered karst" where these soils tend to bridge over underlying voids and hollows in the subsoil and bedrock. Known areas with this type of cohesive soil must be scrutinized very carefully during development, especially after the process of vegetation clearing (i.e. "stripping and grubbing") which destroys the entangled root mass holding the surface soil together.

Q. Can blasting have an effect upon karst aquifers and groundwater supplies?

A. Blasting is a common excavating tool, and it has wide applications, ranging from the breaking and fracturing of the maximum amount of material that may occur in a quarry operation, to the minor sculpting and finish work that you may see on a cliff above a highway. In many situations, trenching is the more common excavating tool for pipeline construction. When blasting is needed for pipeline construction, it is more common to use the lower- impact "finishing" end of the blasting spectrum.

Water in karst aquifers primarily moves along solution channels; therefore, flow is highly dependent upon the direction and characteristics of these conduits. This is also true for fracture flow aquifers in non-karst settings. The impact from blasting can alter and disrupt these solution channels, thereby causing the water to flow along different conduits. This creates situations in which the water flows in different directions, or that water quality and quantity is altered. If these water quality or hydrologic changes occur, it is highly improbable that the previous groundwater conditions can be restored.

Blasting may affect localized depth to groundwater, recharge characteristics and water quality. Many of these potential effects are similar for karst versus non-karst settings. It should however be noted that since karst groundwater flow is highly dependent upon localized structural characteristics, any disturbance, such as blasting, that can affect localized structural characteristics have therefore a greater chance of altering groundwater flow in surficial karst aquifers. If these impacts do not directly affect deeper wells, they may still affect the well's recharge characteristics.

There are many factors that contribute to the potential for blasting to affect karst resources; some of these are a function of the on-site karst characteristics, while others are factors of the blasting. Blasting parameters that may contribute to karst impacts are usually the same that would affect non-karst groundwater resources, such as: specific objective, proximity, intensity, use of cover material, duration and timing of charges, drilling characteristics, geologic considerations, handling and storage, and blasting material used.

Depending upon the explosive charge used, blasting can release a wide variety of soluble chemicals, such as nitrates, nitrites, perchlorates, and semi-volatile organic compounds, to name a few. These products can enter the local surface waters or groundwater and therefore contribute to water pollution.

Other potential complications with blasting include the incomplete combustion of explosive material, improper selection of explosive product, the "leaking" of chemical charges into surrounding cracks and fractures prior to detonation, increased turbidity within wells and karst conduits, geochemical reactions caused by the exposure of fresh geologic surfaces, airborne gas and particles, and improper transportation and storage. These all can be minimized by a properly written and implemented blasting plan.

Q. Can trenching negatively affect water wells and springs?

A. Trenching is a much more common form of excavation for pipeline construction than blasting. In most cases, the rock can be excavated using trenching equipment (i.e., rock saws) and hoe rams, which exert much less force and do not generally have enough power to collapse the strong regional bedrock. In addition, the trench can be inspected after rock removal to check if the more obvious karst conduits have been intercepted or disturbed. If intersected conduits are observed, they should be mitigated. It should be noted that just because a trench did not intersect any existing conduits, does not mean that the karst's groundwater flow characteristics have not been altered.

While trenching has the potential to create less impact to natural water flow through karst systems than blasting, trenching still can create karst impacts and these are not easily predicted. Ground disturbance of any kind in karst terrain can lead to complications, and trenching involves a lot of ground disturbance.

In addition, an excavated trench can lead to either diverted or ponded water, which can modify natural pathways, and can create ponding of water that could lead to accelerated sinkhole development. Professional karst assessment, proper construction techniques, the use of best management practices, and follow-up monitoring can greatly lessen the chance of negative effects from trenching, but it cannot be eliminated.

Q. Won't the pipeline trench, even if backfilled, become an artificial "conduit," diverting water away from its previous natural flow path through the subsurface?

A. Design steps should be taken to minimize this from happening. On slopes, water breaks should be installed on the surface to direct water away from flowing down the pipeline alignment. Within the trench itself, clay dams and collars are often installed and are intended to prevent the pipe's outer edge from acting like a continuous conduit for water flow. The dams and collars interrupt the water flow and promote the percolation of water vertically into the subsurface; however, the ponding of water behind the dams and collars can create unintended consequences by interrupting natural flow-paths and the acceleration of sinkhole development in karst areas.

Q. Can the on-going operation of natural gas transmission pipelines on karst affect water quality?

A. The presence or absence of karst does not add or diminish the likelihood of negative impacts to waters as a result of natural gas transmission pipelines. However, should a problem occur, say a leaking contaminant, then this contaminant, may travel further and quicker within a karst environment compared with many non-karst systems. This may create situations in which the impact is more widespread and may affect the karst environment and cause greater project management complications.

While pipelines are generally considered the safest means of transporting natural gas, problems can and do occur. One problem that can occur is leaks. Karst is especially susceptible to problems associated with leaking liquid chemicals, so there is a fundamental difference between pipelines carrying liquid products from those carrying gas products. Since natural gas (methane) is lighter than air, many problems associated with pipelines leaking liquid products are significantly reduced. However, natural gas pipelines are typically under a lot of pressure, and as such, minor or incipient leaks are common and therefore, may or may not be detected, reported, or mitigated.

If a natural gas pipeline leaks within a ventilated location, the methane is dissipated to the air and will likely not have any direct impact to karst, unless there is a cave entrance located immediately upslope of the leak. Many large caves "breathe" by either expelling air or drawing in air due to pressure and temperature differences between the cave's atmosphere and the localized surface atmosphere. Therefore, there may be rare instances in which methane leaking into the air immediately downhill from a cave is drawn into the cave environment. While this occurrence is likely very rare, should it actually occur, it could result in a potentially hazardous situation with the possibility of explosion. Every effort should be made to mitigate against the possibility of natural gas leaking into enclosed karst cavities or other closed spaces.

If the leak should occur from a section of the pipeline in contact with groundwater, then the water may pick up and transport the methane either in the dissolved state or as entrapped gas. Eventually within the water's flow- path, the entrapped gas or a portion of the dissolved methane will be vented to the air. Perhaps the biggest hazard in this situation is dependent upon where this venting occurs. If the venting occurs within a cave passage that has poor air circulation, then the methane concentration can build up to levels that could cause flammable and explosion hazards if the gas should come into contact with an ignition source. This risk may be reduced by:

- proper engineering and or design within higher-risk or sensitive areas (such as caves or karst);
- pipeline inspections (to detect leaks) and prompt reporting of suspected leaks;
- reducing the occurrence of pipelines being in contact with groundwater;
- an understanding of groundwater flow in the pipeline's vicinity;
- identifying and inventorying potential locations and situations in which gas may accumulate in down- gradient locations of the pipeline, and potential ignition sources;
- ensuring proper ventilation of managed facilities in areas of higher risk; and
- notifying the Virginia Department of Natural Heritage of any known leaks or spills within karst environments.

Q. Besides leaking natural gas, are there other potential water quality challenges from natural gas transmission pipelines located in karst terrain?

A. While pipeline construction poses a wide variety of potential threats to karst waters, few if any of these are specific to karst. In addition, most of these potential impacts are not even specific to pipeline construction, but are also valid for most any construction projects ranging from the construction of schools, and roads, to individual homes. For the discussion of karst impacts, it is instructive to categorize them according to risk, and threat. Risk refers to the likelihood of a situation happening, while threat refers to the harm that would result if that situation actually occurs. For instance, the risk of nuclear plant melt-down is extremely low, since it would have an extremely low probability of occurring. However, the threat of such a situation would be extremely high, since the damage from a nuclear catastrophe is extreme. Applying these categories to pipeline construction in karst areas, the risk to groundwater from pipeline construction is the same for karst and non-karst settings; however, since the possibility to quickly transport spills and contaminants to a higher degree in karst than in non-karst settings, the threat in karst landscapes is higher.

Constructing any structure creates a lot of short-term localized ground disturbance. If not properly managed, these disturbances can affect surrounding environments. This is true for karst and non-karst settings. This is the reason that Virginia has strict erosion and sediment-control regulations.

Besides the quantity of ground disturbance, new construction often requires equipment use, which therefore introduces gasoline, diesel, antifreeze, and oil into the project site. In addition, construction and repair of pipelines may include the use of on-site solvents, epoxy and other sealants used to waterproof pipe joints.

Once the pipeline is constructed, on-site equipment will occasionally be needed to perform inspections, for repair and maintenance, to conduct occasional replacements, and to perform routine vegetation management. Part of vegetation management may include the spraying of herbicides. Herbicide and other chemical usage in karst settings has a greater potential to affect off-site locations through unintended transport through solution conduits.

Q. Can a preliminary karst survey help reduce potential risks to the pipeline's integrity and safeguard water supplies, water quality, and the subsurface environment?

A. Yes, it can. Preliminary karst surveys should take into account a number of factors: the known locations of caves, sinkholes and springs, the type of carbonate rock and the structural geology of the area through which the pipeline is planned; documentation of bedrock deformation, including faults, folds and other structural features; and mapped water flow patterns that have been determined by existing studies of the local and regional hydrology. This survey should be augmented by careful karst mapping to obtain an idea of where there may be a dense concentration of karst features that may indicate significant karst development that would have the potential to influence planned facilities and construction activities. Changes in pipeline routing should be based on the findings of the survey and subsequent analysis. However it is important to emphasize that the preliminary survey is only the first step. It must be followed up with continuous observation and monitoring during the construction phase of the project. A comprehensive and robust inspection and evaluation program is also recommended throughout the life of the pipeline's operation.

Q. How effective are natural gas pipeline inspections?

A. Inspections are a critical component of a pipeline's safety management program. However, it is not enough simply to state or require monitoring, since there is a multitude of monitoring techniques that have been employed and each has their own advantages and disadvantages, as well as specific applicability. A few examples of natural gas pipeline monitoring techniques include the following: gas sampling, acoustic sensors, broad-band absorption, Lidar surveys, backscatter imaging, thermal imaging, soil monitoring, and dynamic monitoring. A good paper summarizing the advantages and disadvantages of many of these techniques is “Technology status report on natural gas leak detection in pipelines”, by Yudaya Sivathanu; prepared for the U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, WV. The web address of this document is listed in the “Where Can I Learn More about Karst” section.

Q. Where can I learn more about karst?

A. There are many excellent references on karst and related matters. The following are a few examples:

<u>Karst-Specific References Regarding Sinkholes and “Living on Karst”:</u>

A Reference Guide for Landowners in Limestone Regions (the Virginia Speleological Survey)
http://www.virginiacaves.org/lok/page1.htm
Commonwealth of Virginia Hazard Mitigation Plan (Section 3.14 deals with Karst Topography)
http://www.vaemergency.gov/em-community/recovery/haz-mit-plans
Living on Karst (Cave Conservancy of the Virginias)
http://www.caveconservancyofvirginia.org/livingonkarst/livingonkarst.htm
Living with Karst (American Geosciences Institute)
http://www.americangeosciences.org/sites/default/files/karst.pdf
Sinkholes- The USGS Water Science School
http://water.usgs.gov/edu/sinkholes.html
Sinkholes- Virginia Division of Geology and Mineral Resources
http://www.dmme.virginia.gov/DGMR/pdf/sinkholes.pdf
Sinkholes and Karst Terrain
http://www.dmme.virginia.gov/DGMR/sinkholes.shtml
Sinkhole Formation Assoc. with Installation of a High-pressure Natural Gas Pipeline, West-central FL
http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1116&context=sinkhole_2013

<u>General Information on Karst:</u>

Cave Conservancy of the Virginias
http://www.caveconservancyofvirginia.org
Karst Water Institute
http://karstwaters.org
National Cave and Karst Research Institute
http://www.nckri.org
National Speleological Society
http://caves.org
Virginia Cave Board
http://www.dcr.virginia.gov/natural_heritage/cavehome.shtml
Virginia Natural Heritage Karst Program- Virginia Department of Conservation and Recreation
http://www.dcr.virginia.gov/natural_heritage/karsthome.shtml
Virginia Speleological Survey
http://virginiacaves.org

Pipeline Safety Information:

Pipeline Safety Trust
    http://pstrust.org

Technology status report- natural gas Leak detection in pipelines
    http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/
    scanner_technology_0104.pdf

U.S. Department of Transportation Pipeline and Hazardous Material Safety Administration
    http://www.phmsa.dot.gov