Some Concerns about Hydrofracturing in Shale-Gas Production

Arthur N. Palmer
Professor Emeritus
State University of New York
Oneonta, NY 13820

Introduction

There are several compelling arguments in favor of gas drilling of shale beds in eastern states, with yields enhanced by hydraulic fracturing:

It's good for the economy.
It creates jobs.
It will supply the country with much-needed (and relatively clean) energy.

But there are arguments against this plan:

It's bad for the economy (not to mention infrastructure and quality of life).
Jobs will be mainly for trained outsiders.
We don't need the energy at present (there's now a glut of natural gas).
It endangers water supplies.

I'd like to briefly outline the economic aspects, but also explain the serious dangers of hydrofracturing from a hydrologic standpoint. I should point out that I am a professional groundwater hydrologist (see CV at end), and that I have also worked as a consultant to several oil and gas companies (e.g., ARCO, Plano, TX, now part of BP Group; Stone Energy Corp., Columbus, OH) and know and collaborate with hundreds of petroleum geologists. Therefore, I have no inherent bias against the oil industry.

A Few Economic Points

There is a great rush to drill now, not later. From the standpoint of petroleum companies and a number of lucky landowners, this makes economic sense from the standpoint of capital gains. But from the standpoint of state and local government, long-term prosperity, drilling and monitoring standards, and economic benefit, this is the worst time to drill.

1. The price of fuel is relatively low now. Think the price is high now? Just wait and see.
2. There is now such a glut of natural gas from drilling in the East that it is being piped to states farther west, and there are plans to sell it overseas.
3. Strategically, it makes economic sense to wait until there is a real need. The gas is not going to go away, and its value will only appreciate – until a cheap and reliable source of renewable energy is developed.
4. By waiting, instead of rushing in, it's possible to learn from early mistakes. Technology and safety will improve, and strategies for optimizing yield will have matured.

A Cultural Point

Gas drilling is pitting neighbor against neighbor, towns against the state, etc. This is an unhealthy situation where a few people benefit and everyone else suffers. This point can be exaggerated, but the effects are already being felt even where fracking has not yet begun.

And a Serious Message about Water Quality

Gas drilling and fracking have been given the green light in many areas, with three conditions: (1) the state environmental agency (e.g., DEC in New York and West Virginia, DEP in Pa.) will oversee the operation and ensure that their regulations are being followed; (2) that water quality will be monitored in the vicinity; and (3) that if contamination is detected, remedial measures will be taken. Why doesn't this satisfy the anti-frackers?

1. State agencies are underfunded and understaffed, and although they are fine and dedicated professionals, they are being placed in an impossible situation. There is nowhere near enough time, enough money, and enough expertise to adequately fulfill any (let alone all) of the mandates.
2. Problems around the country center on degraded water supplies and inadequate remediation and/or compensation. Monitoring of water quality involves measuring a few key contaminants (and many irrelevant items). Many people in and around drill sites, including neighbors with no financial involvement, complain about degraded water supplies – their water "tastes funny" is one of the most common complaints – and yet more often than not their water passes EPA standards. The problem is that not all the fracking fluids are known (for proprietary reasons), although this situation is improving. What do you test for? Methane itself is not a health risk except at very high concentrations (when explosions are among the risks). It is not even on the EPA list of drinking-water standards (*water.epa.gov/scitech/drinkingwater*). Non-threatening problems involving smell, taste, turbidity, etc., are apparently not technically considered contamination.
3. There are several scenarios for contamination: (a) spills at the wellhead; (b) breaks in the casing; (c) deep-seated contamination that migrates over time; (d) spills during transport.
4. If contamination is detected, what are the remedial measures? Just the surface contamination alone can be difficult to monitor and remediate. The deeper ones are far more serious, because not only are they very widespread, but complete remediation is impossible (given present technology and budgets). Even after most of the fracking fluids have been recovered, many contaminants will linger and disperse. By the time contamination is detected, it is often too late to remediate the entire zone of contamination. And more often than not, when contaminants are found, they still lie within the standards for drinking water.

These scenarios have recurred in many areas (e.g., Pa., Texas, Wyoming….). People are stuck with water that's "OK" but which they can't stand to use. Air quality is degraded by a persistent smell. But everything is fine because the standards for air quality are not exceeded. These problems also affect people who object to gas drilling in their region.

The weak standards to which gas drillers are held is a travesty. No private individual would be allowed to violate EPA standards in the way that fracking operations do legally. Since fracking and fracking fluids are presently exempt from EPA standards (thanks to lobbying efforts), and their compositions are proprietary, how can effective monitoring methods be established?

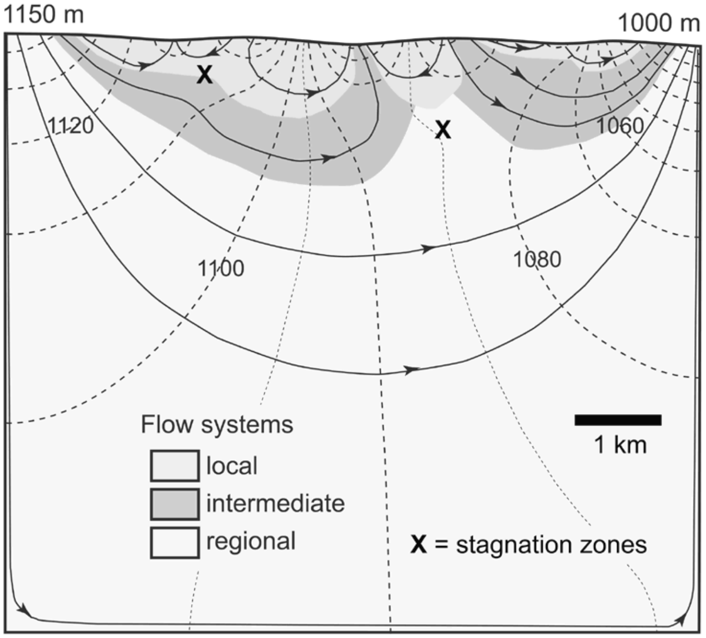
… and the Most Serious Problem of All

Fracking fluids are injected at depths of thousands of feet, way below the depth of water wells. Also, most of the fluids are extracted after the fracking. But residual fracking fluids remain – it is almost impossible to pump them all out. These supposedly remain in place, deep beneath the surface. Not true – they move.

Any groundwater hydrologist knows that groundwater flow is not limited to shallow depths. The patterns and physics of flow have been quantified since the early 20th century and have been verified many thousands of times in the field. Even if there are no problems in and around drilling sites, the contaminants will move slowly but inevitably down-gradient to the major river valleys. In the Appalachians, that happens to be where most of the population centers and highest-yielding aquifers are located. Drilling will probably not take place in the valleys, but they are the areas in most serious danger from the contaminants. This is not raising a false alarm, but as close to a scientific fact as it is possible to get in the field of subsurface geology.

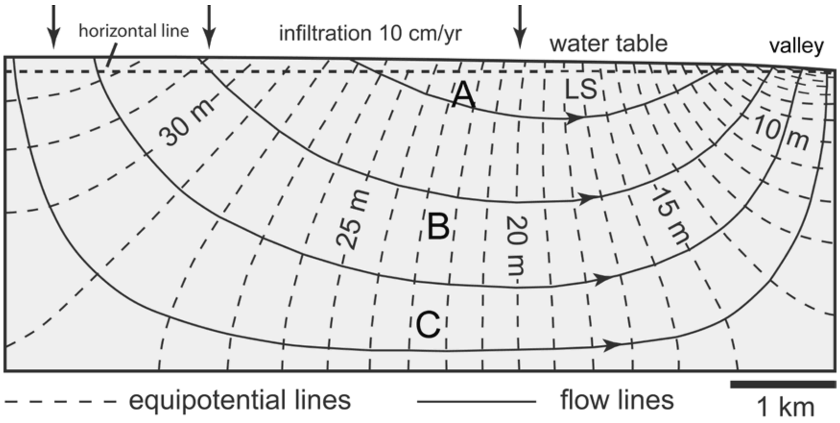
This needs to be put in perspective. Thick plumes of deadly toxic waste will not overwhelm these areas, but instead there will be small amounts of leakage over many decades and even centuries. It's possible that the contaminants will become so diluted that they will remain below drinking-water standards. But why should we impose this kind of low-level contamination on a large percentage of our population? This kind of contamination has a vile history. There are many examples where the toxic effects of contaminants were not realized until far too late – remember DDT, PCBs, thalidomide, etc? Remember Times Beach, Missouri? Love Canal, New York? The CDC lists hundreds of low-level contaminants in human bodies just from casual exposure. Just what we need is additional contaminants injected into the ground, where it will be literally impossible (both physically and economically) to remove them. If fracking becomes like a gold rush, with landowners grabbing for royalties to keep ahead of their neighbors, there will be widespread plumes of chemicals at depth. They will lie below the level of water wells, but that does not solve the problem.

Patterns of groundwater flow have been recognized for well over a century, and for the past 70 years or so they have been quantified with the aid of physical laws and validated all over the world (early references: Hubbert, 1940; Tóth, 1963). Below is an example of Tóth's determination of groundwater flow patterns, showing local, regional, and intermediate-scale flow systems. Contaminants simply follow the arrows. They cannot disperse in the upstream direction unless there is almost no flow. Water infiltrates through upland surfaces and flows downward, laterally, and finally upward toward valleys:



The dotted lines show the distribution of hydraulic head, across which the flow moves (from high head to low head). Follow any of the solid lines to see where the flow and contaminants will go. The vertical scale is not exaggerated.

How fast do the water and contaminants move? This also involves well-established physical laws, but detailed answers are difficult to obtain because the behavior of subsurface rocks is known precisely only where there are many wells and dye traces. A simplified example shows examples of how fast the contaminants can move in a typical groundwater system:



This was designed with the computer software package MODFLOW (U.S. Geological Survey). There is no vertical exaggeration. It represents the typical pattern of groundwater flow from an upland into a valley (left to right). The land surface is not shown, because only the groundwater pattern is critical. Groundwater is fed by infiltration throughout the region, and emerges in a valley at the upper right-hand corner. The water-table slope is the result of 10 cm/yr infiltration into rocks with an average hydraulic conductivity of 10^{-4} cm/sec. This is typical of sandstone, one of the most common subsurface materials in the Appalachians. In shale the conductivity is usually about 100 times lower, but hydraulic fracturing would increase this value. Furthermore, most contaminants would move out of the shale into adjacent more permeable rocks such as sandstone. In the Appalachians the infiltration rate may be up to about 5 times greater, depending on the local climate, soil type, and topography. A higher infiltration rate would produce a higher mounding of the water table above the valley, and proportionally faster groundwater flow, but the flow patterns would not change much.

How fast will contaminants move? Assume a typical porosity of 0.1 (10%). This is probably a little high, but a smaller porosity results in *faster* flow. Hydraulic conductivity (K), or permeability, is assumed to be 10^{-4} cm/sec (typical for sandstone, the most common aquifer material in the Appalachians). At A: local velocity is about 1.37 meters/year (4.5 ft/yr), and the average velocity all the way to the outlet is about 4.6 m/yr (15 ft/yr). At B and C the local velocities are a little lower, but all of the velocities increase greatly toward the valley because the flow is converging into a smaller area.

These velocities seem rather low. It would require several hundred years for contaminants to travel a mile. This sounds good if you don’t mind your grandchildren having to deal with the problem. But this estimate is based on diffuse flow through a homogeneous material. The most rapid flow takes place through major fissures (joints, faults), and because the hydraulic head is lower in these efficient channels, groundwater in surrounding areas converges toward them, and they provide major channels for contaminants (see p. 8–11).

Consider a fracture system with an average width of 1 millimeter (0.1 cm), and a hydraulic gradient of 0.1 (100 m per km, common in the Appalachians). Flow velocity through a fissure is calculated by squaring the width (cm^2), multiplying by specific weight of water (980 dynes/cm^3) and hydraulic gradient (no units), and dividing by 12 and by the viscosity (about 0.013 dyne-sec/cm^2 at 50 deg. F). The velocity through this fissure will be approx. 6.28 cm/sec, which is equivalent to a flow of one kilometer in less than 5 hours! This gradient and fissure width are higher than average. At a gradient of 0.01 (10 m/km) the flow would be 1/10 as fast, and it would take 50 hours – not much consolation. Most fissures are narrower, more like 0.1 mm (0.01 cm), and in combination with the smaller gradient this would provide a flow rate of 5000 hours per kilometer, or about 200 days. This gives us enough time to relax before the contaminants arrive.

But these fast-moving contaminants will still be fairly limited in volume, and some may degrade into harmless by-products. They could rapidly cause problems in some wells, but it will take hundreds of years for the entire contaminant load to drain. The contaminant level will rise slowly to a peak, and then subside even more slowly. In the meantime all the sand and gravel aquifers in the valley are susceptible to contamination. And residents in the valley will have no idea where the contaminants came from. The pollutants may be at only a low concentration, but this depends on how much has been injected into the ground and not retrieved. How much contamination takes place, and what it consists of, is beyond our control.

Typical groundwater models (such as the one used to construct the flow diagram) rely on average permeabilities from pumping tests. These inevitably underestimate the maximum rates of flow, which take place through interconnecting fractures. This discrepancy can be shown by comparing dye traces with the output of traditional groundwater models. Worthington et al. (2003) describe an example of aquifer contamination that cost 7 lives and caused sickness (some chronic) in 2000 people, where traditional groundwater models *underestimated* the flow rate by 50 to 70 times. The true rate of contaminant travel was demonstrated with dye tracing.

How common are these fractures? Do they really affect groundwater contamination? I live in Oneonta, New York, between the Susquehanna River and Otego Creek. Both river valleys have suspiciously straight patterns over long distances, which suggest fault control. But the valley bottoms are covered by up to 400 feet of glacial and river sediment, so its nearly impossible to determine the presence of faults. However, some water wells in the Susquehanna Valley south of Cooperstown contain measurable concentrations of methane, some (I am told) that are at flammable levels. A line of water wells in the Otego Creek valley have salt concentrations so high that the water is way past undrinkable (many thousands of parts per million). I was asked to investigate these. I figured that road salt was the source, until I found that the wells lay uphill from any roads. The only likely source of salt of this concentration is the Salina beds of Silurian age – which lie about halfway between the Marcellus Shale and the Utica Shale. Remediation is impossible in both areas, because the sources and dispersion are so widespread. Treating the problem where the groundwater emerges is like trying to cure blindness with a windshield wiper.

The impact of fracking fluids cannot be easily predicted from short-term measurements of water quality in the vicinity of the wells. Although the impact of individual fractures delivering wastes to nearby river valleys cannot be predicted so easily as suggested here, this analysis shows that there is real potential for contamination in surrounding river valleys well within our own lifetimes.

Cited References

Hubbert, M.K., 1940, Theory of groundwater motion: Journal of Geology, v. 48, no. 8, p. 785–944.

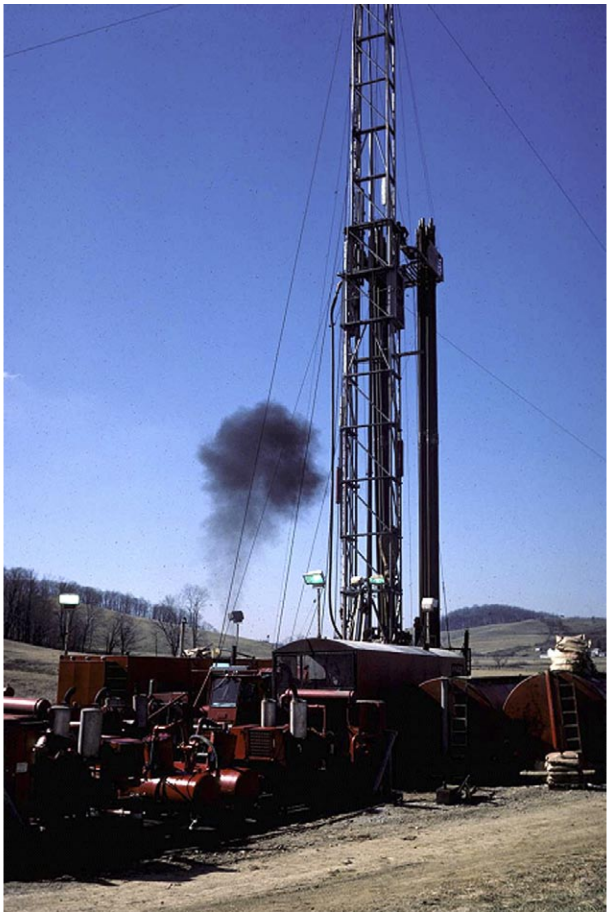
Tóth, J., 1963, A theoretical analysis of groundwater flow in small drainage basking: Journal of Geophysical Research, v. 68, p. 4795–4812.

Worthington, S.R.H., Smart, C.C., and Ruland, W.W., 2002, Assessment of groundwater velocities to the municipal wells at Walkerton, Ontario: Proceedings of 2002 joint annual conference of the Canadian Geotechnical Society and Canadian chapter of the International Association of Hydrogeologists, Niagara Falls, Ontario, p. 1081-1086.

A.N. Palmer: Brief Credentials

Former director of Water Resources program at SUNY Oneonta: largest program of its kind in the Northeast (*www.oneonta.edu/academics/earths/*).
Internationally recognized as an authority in the field of groundwater in fractured bedrock (see *www.iah.org/karst/members.html*).
Author of about 100 technical papers in groundwater flow in soluble rocks (e.g. Geological Soc. of Amer. Bulletin, v. 103, Jan. 1991, p. 1–21) and author or editor of several books.
Development of several computer software packages designed to model groundwater flow and water chemistry (see GSA Bulletin article above).
Fellow of American Association for the Advancement of Science; Fellow and Kirk Bryan Award recipient, Geological Society of America.
Consultant for City of Oneonta, N.Y., concerning placement and testing of several municipal water wells.
Occasional consultant for several petroleum companies, e.g. ARCO (now part of BP group), Plano, TX, and Stone Energy Corp. (branch in Columbus, OH).

Photos on next page.



Gas drilling rig, Coshocton Co., Ohio, 1986

“Roughnecks” connecting drill stems

Gas drilling at night

Part of 4” drill core retrieved from ~8000 ft depth

These photos show the drilling of a vertical gas well, with no fracking. Photos by Margaret V. Palmer.

ADDENDUM: SHALE-GAS PRODUCTION IN KARST

Arthur N. Palmer

The conclusion in the previous document is that hydraulic fracturing poses a serious threat to groundwater quality, not only in the vicinity of the drilling site, but also in the entire down-gradient part of the groundwater flow system. Although the main injection of contaminants takes place thousands of feet below the surface, groundwater flow inevitably carries them laterally and then upward into major neighboring river valleys over periods of years to hundreds of years, tailing off for possibly thousands of years. In the Appalachians, the valleys are where most people live. The contaminants are widely dispersed, but they pose a low-level threat to health, especially when thousands of fracked wells are involved. This is a huge gamble. Perhaps the contaminants will pose no health hazard or will degrade to harmless materials with time. But if problems do develop – and they will take time to be recognized – there is no hope of remediating the situation. It is impossible, both physically and economically.

This addendum considers the influence of bedrock on groundwater flow, with emphasis on karst.

Effect of Rock Types and Structure

Recoverable shale gas is most concentrated in areas of relatively flat-lying beds, such as those of the Appalachian Plateaus. Bedding-plane partings are favorable for groundwater flow. Fractures that cut across the beds are equally favorable to flow. Competent rocks such as sandstone and limestone contain major fractures that are relatively widely spaced. They are also cleanly fractured, with well-defined walls, so that water can travel through with little resistance. Bedding-plane partings behave in the same way, and their spacing is proportional to the bed thickness. In shale, fractures and partings are closely spaced and narrow. Also, they tend to get clogged with disintegrated rock so that they resist fluid flow. This is why fracking is used so often for recovery of natural gas from shale – to increase the number of fractures, and to widen and prop them open.

The problem is not so much the leakage of contaminants through the shale, but leakage along the vertical fractures produced or enlarged by fracking, into adjacent high-permeability beds. From there, the groundwater flow is concentrated and relatively rapid. Groundwater flow (and any contaminants) are concentrated in the most transmissive rocks, as water in adjacent less-permeable rocks flows toward them. This principle has been known for more than a century and can be demonstrated with any groundwater analysis or well-field examination.

Problems in Karst

Caves and solution conduits in soluble rock (limestone, dolomite, evaporites) form along zones where groundwater flow is already most rapid. This means that most of them lie at shallow depth below the surface. However, deep caves can also form where rocks are faulted or folded. Cave systems that loop more than 1000 feet below the surface and emerge at springs are common in thick, deformed limestone such as that in Mexico. This is not common in the U.S., because limestones are rarely thick enough; and where they are (as in western Virginia) there are fewer reliable sources of shale gas. Most such areas are folded as well as faulted, so that much of the shale gas has been expelled or sequestered into small zones. In general, there is little problem of upward leakage of fracking contaminants exclusively through caves.

However, some deep caves and solutional zones have formed near the surface and were later buried by younger rocks, to form paleokarst. There is only one major paleokarst zone in the eastern U.S., at the boundary between Lower and Middle Ordovician rocks. The productive shales lie mainly above this zone; but downward leakage can take place into underlying paleokarst zones, where contaminants can be conveyed great distances laterally, and eventually to valley outlets. This is of concern mainly in the central and southern Appalachians, where the paleokarst is most extensive.

In typical karst areas in the East, most groundwater flow is shallow. This poses a problem for constraining the dispersion of contaminants at drill sites, e.g., from accidental spills, routine minor leakage, or from ruptured seals around wells (see reports by Paul Rubin, of Hydroquest). Ordinarily contamination from such spills moves slowly through low-permeability soil and rocks. But where karst is present, groundwater velocities are up to hundreds or even thousands of times greater. This has been shown with innumerable dye traces. Traditional computer models of groundwater flow fail to predict flow patterns and velocities in karst with any helpful degree of accuracy. The case history described on page 5 (Worthington et al., 2002) involved dolomite karst, where a quarter-million-dollar study with well tests and computer modeling, by one of the most trusted companies in the field, underestimated the flow velocity by 50 to 70 times and completely misinterpreted the contaminant catchment area.

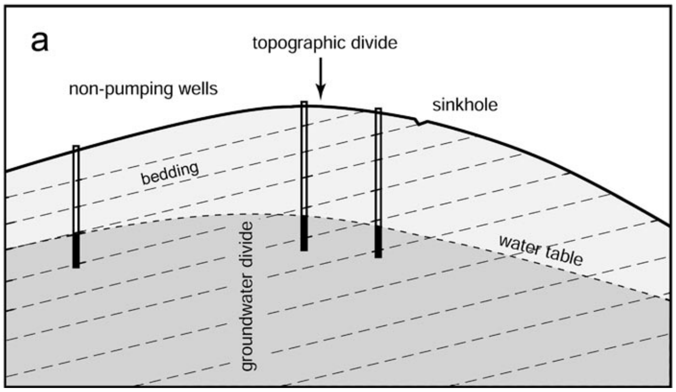
There are several problems with dispersion of contaminants in karst:

1. Concentration of flow along major flow paths. This is not necessarily bad, since it aids remediation – except that the contaminants will have flowed to surface springs before detection and remediation can take place.

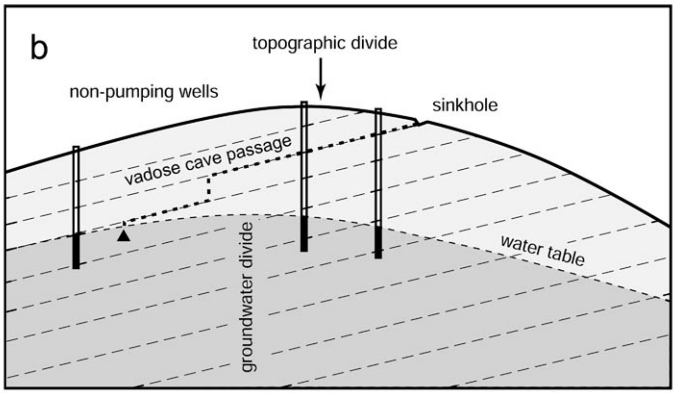
2. High flow velocities (see #1).

But here are the really serious problems in karst:

3. At shallow depth, above the water table, underground water and contaminants move by gravity. They tend to get hung up on relatively low-permeability beds and move down the dip of the strata. This problem is greatest where the dip is small – as in the Appalachian Plateaus – because the contaminants can be dispersed over large distances. This gravitational water is independent of normal groundwater potential fields, so its presence cannot easily be detected. It can move beneath topographic divides, and even across groundwater divides that have been mapped by well data, and hit the water table far from where the surface contamination took place:

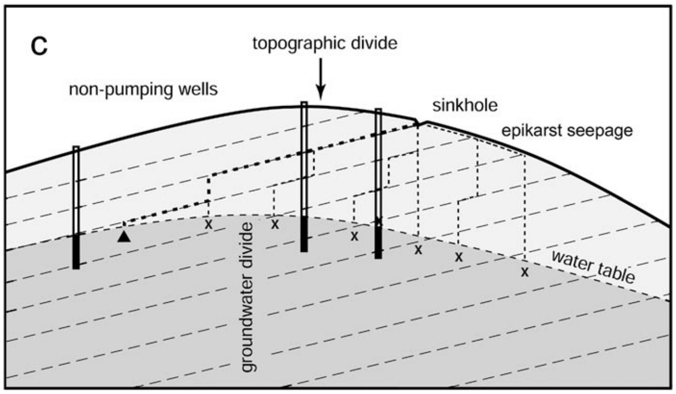


a. Information from drilling.

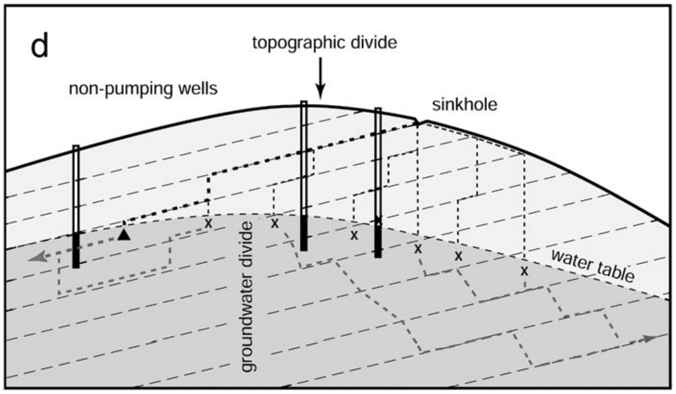


b. Contamination enters a cave through a sinkhole or adjacent spill. Note that in well-bedded rocks the main flow can easily cross beneath the topographic divide and over the groundwater divide. Even though it may jog downward along major fractures, it can reach the water table at remote points such as the triangle. Cave mapping and dye tracing in karst show this to be very common, and therefore somewhat predictable – but only to those who are aware of the problem. See next page....

Source: A. Palmer, 2007, Cave Geology: Dayton, OH, Cave Books, p. 390.

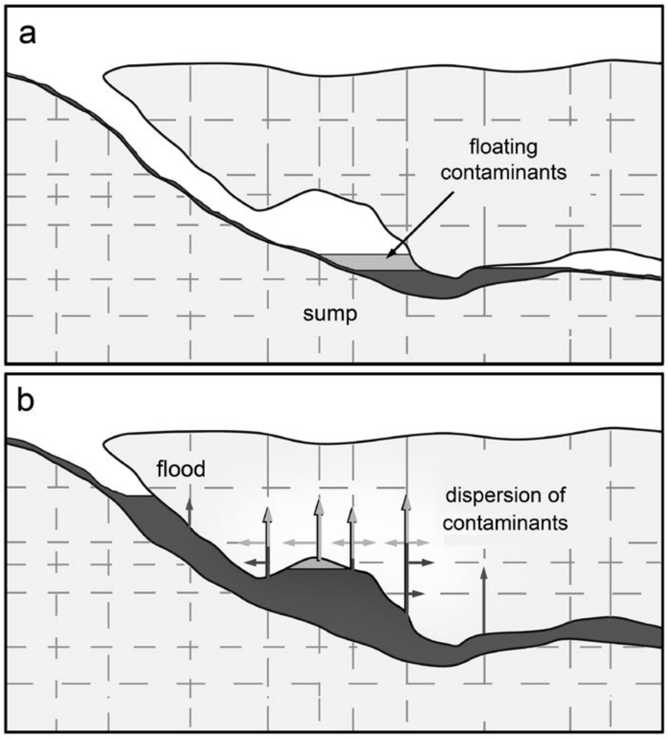


c. But downward seepage also takes place through all of the minor fractures, so some of the contaminants become widely spread and reach the water table at many points (X). This is a problem in all bedded rock, but is most serious in karst.



d. From those points of contamination (X), groundwater moves slowly down the hydraulic gradient along paths that are somewhat predictable, to valleys on either side of the plateau. But the contaminants are way beyond remediation, least of all at the spill site.

4. Many contaminants are "floaters" – liquids that are less dense than water. In karst conduits these tend to accumulate at sumps where cave water reaches a sump (ceiling drops below the water level). This material can remain and accumulate with time, with volatiles able to escape from solution and seep upward along fractures to the surface. This problem becomes much worse during floods, when water fills the caves and forces the contaminants upward through many fractures, spreading them out. As a result the escape of volatiles can be much greater:



This can be a serious problem. Examples have been documented where accumulation of flammable volatiles (e.g., gasoline fumes) have reached potentially explosive levels in overlying buildings. Examples sites include Bowling Green, Kentucky (Crawford, 2001).

Methane (CH_4) is the lightest hydrocarbon and the least soluble of the common gases. By itself it is less likely to contribute to this kind of contamination, since the problem is with spills near the surface. However, leakage of methane from below can contribute to the problem illustrated here.

Source: A. Palmer, 2007, Cave Geology: Dayton, OH, Cave Books, p. 391.

Conclusion

Groundwater contamination from hydraulic fracturing of shale poses a serious threat to groundwater supplies. This contamination cannot be remediated, because its magnitude and wide dispersion make it physically and economically impossible to do so. The problem is complicated by karst, in which contaminant dispersion can take place rapidly and unpredictably, as well as into adjacent non-karst aquifers.

Supplementary Reference

Crawford, N., 2001, Environmental problems associated with urban development upon karst, Bowling Green, Kentucky, *in* B.F. Beck and J.G. Herring (eds.), Geotechnical and Environmental Applications of Karst Geology and Hydrology: Lisse, Netherlands, A.A. Balkema, p. 397–424.