# Evaluating System for Ground-Water Contamination Hazards Due to Gas-Well Drilling on the Glaciated Appalachian Plateau

**by Samuel S. Harrison**[a]

## ABSTRACT

Recent drilling for natural gas in the Glaciated Appalachian Plateau area of northwestern Pennsylvania has caused limited, but increasing ground-water contamination. By evaluating hydrogeologic parameters at a proposed gas well site, such as the ground-water flow system, permeability of surficial sediments, and the presence of fracture zones, the contamination hazard of the site can be assessed. Three case studies document that the most hazardous sites are generally located on or near valley walls of major drainageways. The relatively steep hydraulic gradient, the frequent presence of highly permeable surficial sediments, and the low to moderate dilution of contaminants along the intermediate-length flow paths at these sites all contribute to a relatively high pollution hazard. In addition to locating gas wells in high-hazard hydrogeologic zones, allowing the annulus of gas wells to become pressurized is the other major factor contributing to aquifer contamination.

## INTRODUCTION

Drilling activity for natural gas has increased dramatically during the past three years in the Glaciated Appalachian Plateau area of northwestern Pennsylvania (Figure 1). Increased drilling activity in response to a general increase in demand for domestic natural gas was amplified locally by the designation of the Silurian Medina Group as a "tight sand." Because of the low natural permeability of the Medina in this area, stimulation, normally by hydrofracturing, is necessary to increase the production rate. The "tight sand" designation permits developers to market Medina gas at approximately double the normal price for new gas, making Medina wells profitable despite high drilling and development costs.

Because of the significant increase in drilling activity, there has been limited but increasing ground-water contamination. This paper briefly describes the various contaminant sources associated with gas-well drilling, and discusses in detail factors affecting the movement of these contaminants into and within shallow aquifers. A qualitative model is presented for evaluating the hazard of aquifer contamination in the Glaciated Appalachian Plateau. Case histories demonstrate the application of the model. Finally, suggestions are made for decreasing the hazard of aquifer contamination.

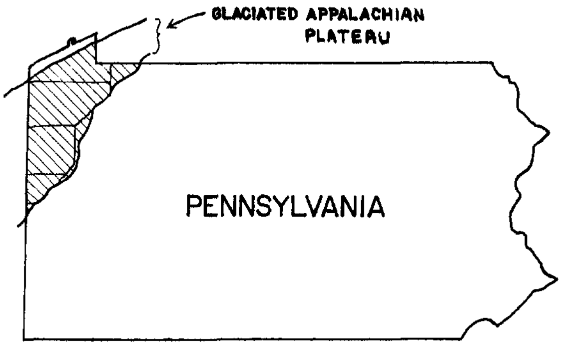


**Fig. 1. Location of the Glaciated Appalachian Plateau in Pennsylvania.**

## SOURCES OF CONTAMINATION

Fresh-water aquifers can be contaminated by: (1) brines or oil from formations which lie below the zone of ground-water circulation, (2) various chemicals used in drilling muds, fracturing operations, and well servicing, and (3) natural gas, itself. The possible pathways along which these contaminants may enter an aquifer are depicted in Figure 2.

Two general pathways of contaminant entry into a shallow fresh-water aquifer are surface and subsurface. Examples of contaminants that gain surface entry are those that are discharged into surface slush pits, those blown off during fracturing or servicing operations, or brines spread on roads for dust or ice control (Figure 2, modes a, b, c).

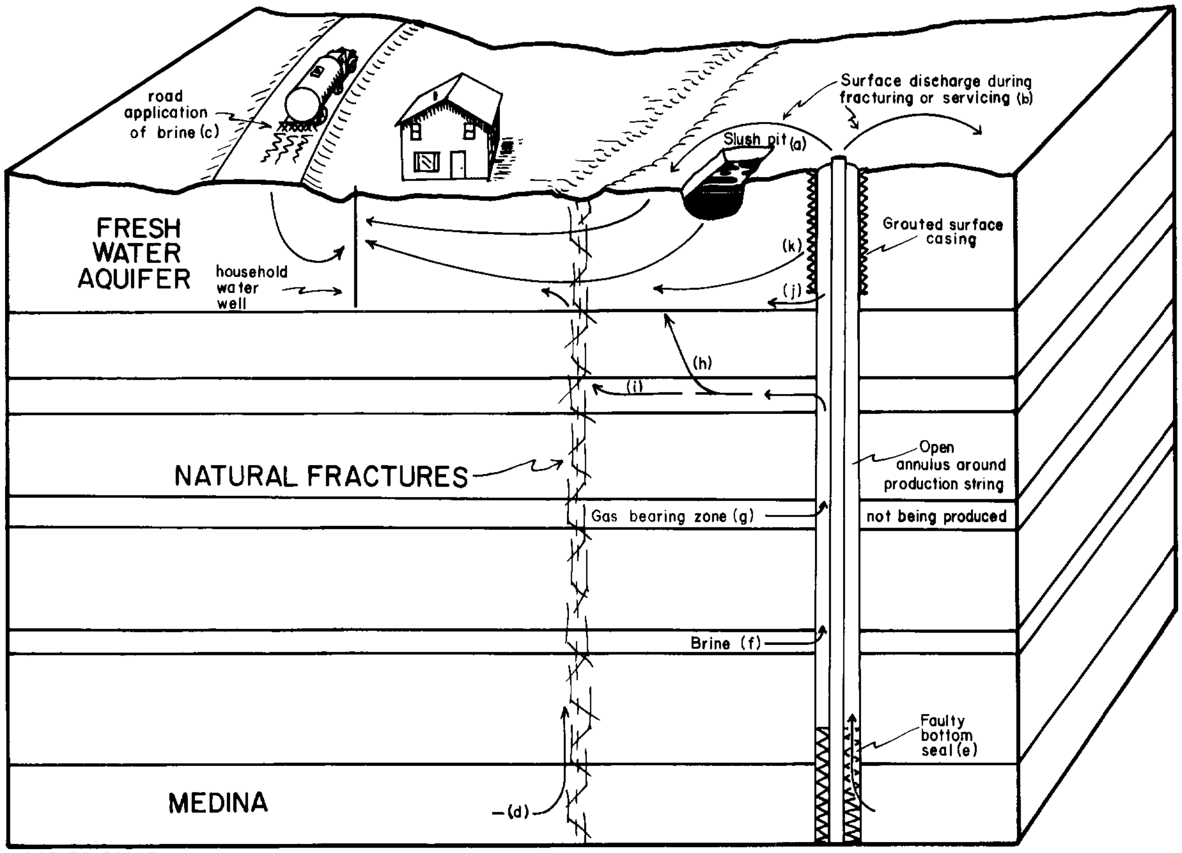
Contaminants reaching a shallow fresh-water aquifer by subsurface migration may have moved upward toward the aquifer along: (1) fracture zones having high secondary permeability, (2) improperly plugged abandoned gas and oil

---

[a] Professor of Geology and Environmental Science, Allegheny College, Meadville, Pennsylvania 16335.

Received February 1983, revised July 1983, accepted July 1983.

Discussion open until May 1, 1984.



NOT TO SCALE

**Fig. 2. Possible sources of aquifer contamination due to gas-well drilling and production activities.**

wells, or (3) the annulus of the well. Although not very likely at depths of several thousand feet, the elevated pressures used in the fracturing process might be sufficient in some cases to increase fracturing of rocks overlying the producing horizon. This may enhance permeability along a naturally-occurring fracture zone causing brine and/or gas in the producing horizon to move upward along that fracture zone (Figure 2, mode d).

An important factor in subsurface migration of contaminants is the pressure maintained in the gas reservoir. Pressures in excess of natural reservoir pressure may cause upward migration from an imperfectly sealed reservoir. As a result, the Pennsylvania Legislature has limited maximum pressure in gas storage operations so that the pressure which exists in the reservoir naturally cannot be exceeded.

Contaminants (e.g., gas, oil, brine, stimulation fluids) can enter the open annulus of a gas well through a leak in the bottom seal above the producing horizon (Figure 2, mode e), or from strata producing either brines (f), or natural gas (g) above the producing horizon and below the zone of fresh-water circulation. Possible routes of contaminants within the annulus to a shallow fresh-water aquifer are: (1) lateral migration through highly-permeable strata and then upward movement through less-permeable strata (Figure 2, mode h), (2) lateral movement through permeable strata to a fracture zone which can provide a highly-permeable pathway upward (i), (3) movement directly into the shallow aquifer where a surface casing is of insufficient depth (j), or through a leak in a surface casing (k).

The migration of contaminants within an open annulus into a fresh-water flow system is greatly influenced by pressure within the annulus. If an annulus is not left open to the atmosphere, and as a result, pressure which exceeds normal hydrostatic pressure builds up within the annulus, a pressure gradient between the near-surface fresh-water aquifer and the contaminants in the annulus will develop. This pressure gradient results in: (1) movement of contaminants upward toward the surface, and (2) greatly increased rates of migration. Thus, natural contaminants that exist beneath a fresh-water aquifer but do not naturally move in that direction may suddenly be caused to migrate rapidly along an artificially created pressure gradient if an annulus is pressurized. The importance of not allowing elevated pressures to develop in an annulus will be demonstrated in the case histories discussed later in this paper.

## HYDROGEOLOGIC FACTORS AFFECTING THE CONTAMINATION HAZARD

### Ground-Water Flow Systems

The movement of contaminants within the zone of fresh-water circulation is controlled by the ground-water flow system. The flow system (unless modified by elevated pressure in a gas well) is in turn essentially controlled by topography in areas underlain by flat-lying, undeformed bedrock. Upland areas are recharge areas and the lowest areas (stream valleys and lakes) are discharge zones. Flow systems of various dimensions can occur in the same area, with local shallow short-flow-path flow systems superimposed on deeper, longer-flow-path intermediate or regional flow systems (Figure 3).

The movement of contaminants originating at the surface is controlled by the flow path that exists directly beneath them. For example, in the Glaciated Appalachian Plateau, contaminants at or near the surface from a well drilled at point "a" (Figure 3) would follow a deep flow path toward the regional discharge zone (e.g., a stream in a major valley). The hydraulic gradient would be low to moderate compared to other, shorter-flow paths. Because of the length of the flow path, dilution caused by hydraulic dispersion would be great.

Contaminants entering the ground water in a recharge area of a local flow path ("c" and "d"), on the other hand, would in most cases follow a relatively high hydraulic gradient with much less dilution occurring before being discharged back to the surface. Intermediate-length flow paths, such as the one which is recharged in area "b" in Figure 3, would follow a moderate to high hydraulic gradient which in most cases would be greater than that of the regional flow path. By the time the contaminant reached the discharge area, dilution would be intermediate between that of the local and regional discharges.

Contaminants originating at the surface in any of the discharge zones (Figure 3, zone "e") would

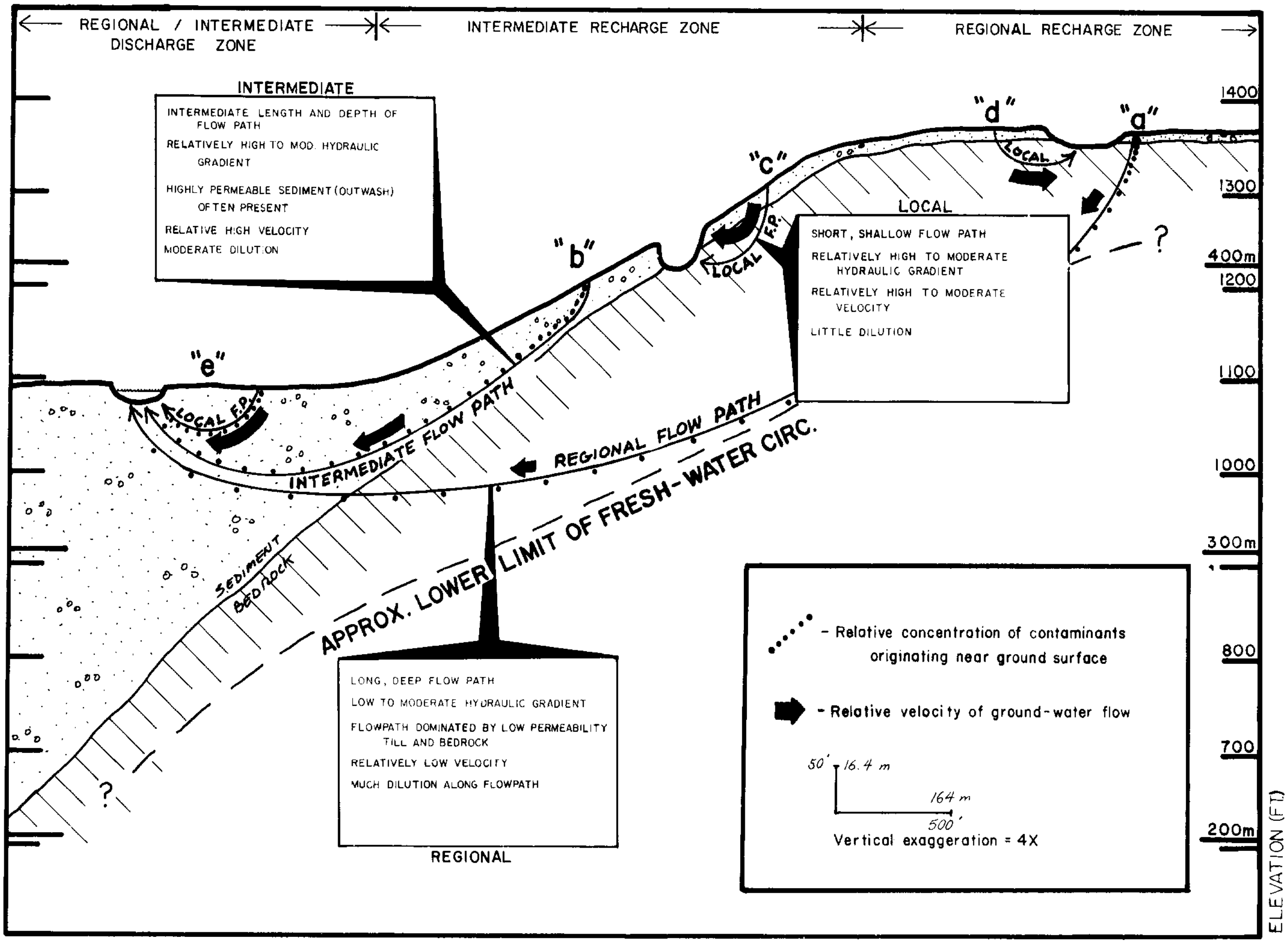


Fig. 3. Influence of natural ground water flow systems on movement and dilution of contaminants originating at or near the land surface.

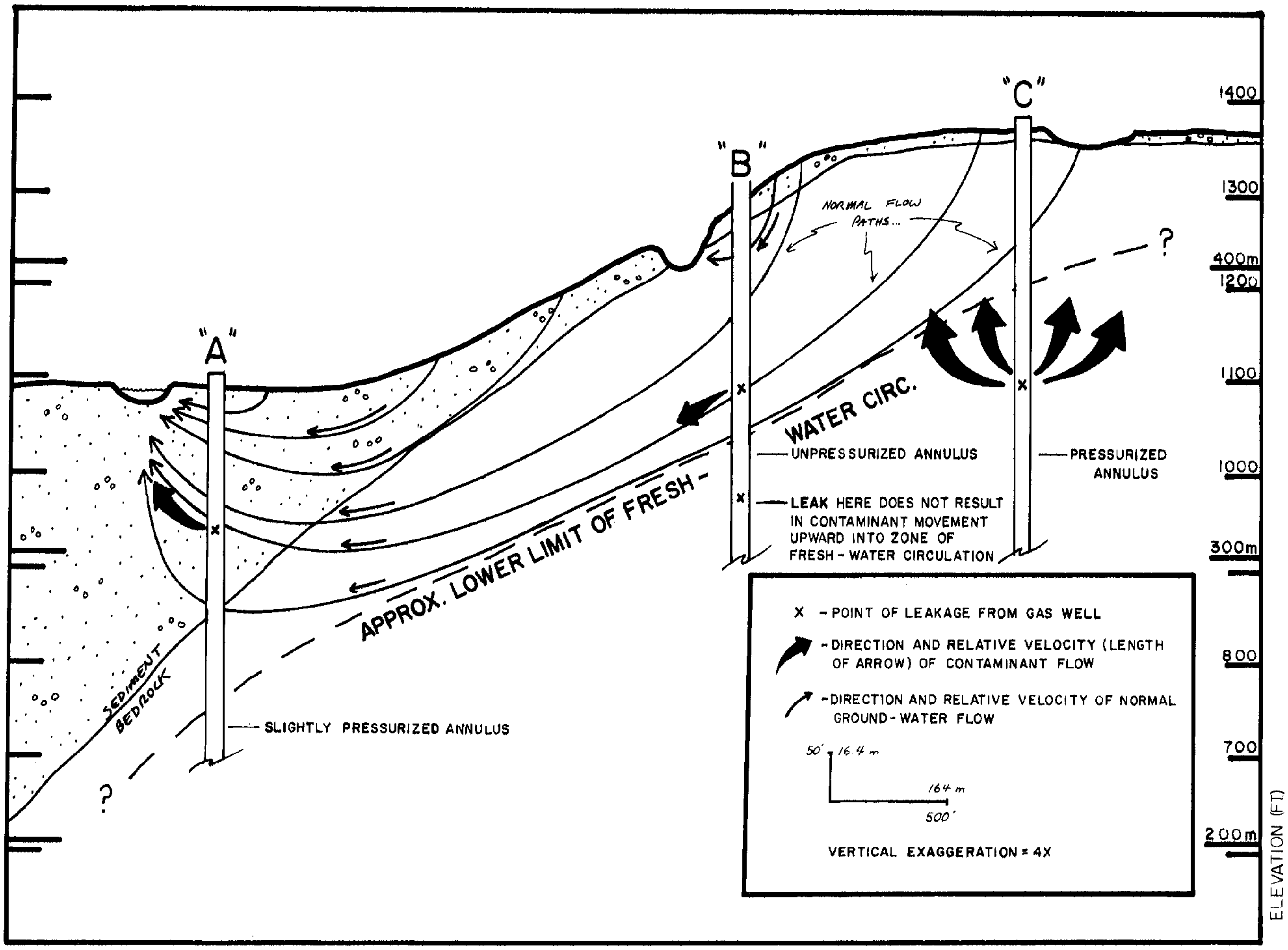
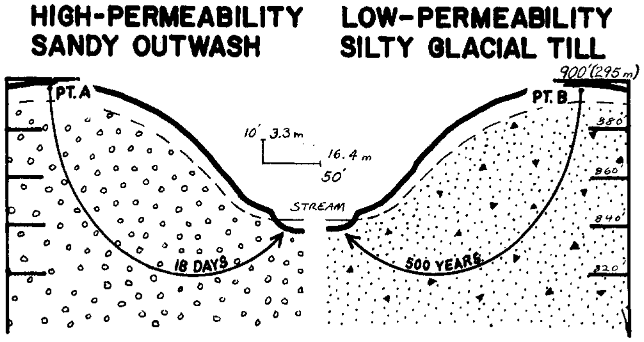


**Fig. 4. Movement of contaminants originating below land surface from gas wells: (A) elevated pressure, resulting in new directions of flow at high velocity, (B) slightly elevated pressure, normal flow path at slightly increased velocity, (C) normal pressure, normal flow paths at normal velocity. Note that contaminants entering ground below the zone of fresh-water circulation move upward into the circulation zone only under elevated pressure.**

have very little impact on ground-water quality, as ground-water flow would have a strong upward component in these areas. In discharge areas, the hazard of contamination shifts from ground water to nearby surface water. Although losing stream reaches are not common in the Glaciated Appalachian Plateau, contaminants flowing through a losing stream segment could be reintroduced into the ground water after considerable dilution in the stream.

Contaminants that originate below the surface at gas wells have a more complex relationship to natural ground-water flow systems than do surface-origin contaminants. Contaminants originating below the ground but within the zone of fresh-water circulation (e.g., leaking from the gas-well surface casing) will simply be incorporated into the flow system which surrounds them if: (1) the contaminants are not under elevated pressure, and (2) they are not so dense as to cause them to travel independently of the surrounding ground water. However, those subsurface-originating contaminants which are under elevated pressure (e.g., pressurized annulus) may not only travel with relatively great velocity, but new directions of flow may be established including local reversal of flow paths under high pressures.

Under elevated pressure, the point where the contaminants enter the ground water (i.e. the "leak") acts like a recharge area with flow radiating outward (Figure 4). The extent to which a flow path would be reversed or even follow new paths to the surface depends on many variables. These include the pressure at the point of contaminant origin and the hydraulic gradient of the natural flow system which the contaminants enter. For subsurface-originating contaminants under pressure, entrainment of contaminants into an existing flow path (Figure 4, well b) accompanied by movement at relatively high velocities will occur



**HIGH-PERMEABILITY EARTH MATERIAL**
(e.g. sandy glacial outwash)
- velocity = 20 ft./day (6.6 m/day)
- travel time from pt."A" to stream = 18 days

**LOW-PERMEABILITY EARTH MATERIAL**
(e.g. silty glacial till)
- velocity = .002 ft./day (0.0006 m/day)
- travel time from pt."B" to stream = 180,000 days

**Fig. 5. Effect of permeability on velocity and travel time of ground water.**

more often than will reversal of flow direction. As with surface-originating contaminants, the zone of ground-water contamination will be smallest if subsurface-originating contaminants enter a flow system in a discharge area and greatest if they enter in a recharge area.

### Permeability of Earth Materials

Under a given hydraulic gradient, the more permeable the earth material, the greater the velocity of contaminant flow along a flow path. For example, contaminants entering a flow path at point "a" in Figure 5 would travel at 20 ft/day (6.6 m/day) through relatively permeable glacial outwash, reaching the discharge point (stream) in about 18 days. On the other hand, in the example shown, it might take contaminants a few hundred years to reach the discharge point if they were following the same flow path through relatively low-permeability glacial till.

The direction of flow of contaminants can also be affected by the areal distribution of relatively highly-permeable sediments. Contaminants originating at point "a" on the surface in Figure 6 will flow through the more highly-permeable sediment in a flow path which differs from the normal expectation. Rather than following a path normal to the slope (e.g., from "c" to "d"), flow in this case is diagonal to the slope, following the relatively highly-permeable lens of sediment from "a" toward "b." Thus, when ground-water flow systems include earth materials of differing permeabilities, flow paths may vary somewhat from those depicted earlier (e.g., Figures 3 and 4).

### Fracture Zones

In addition to formation permeability, a second variable that causes departures from "normal" flow paths is the presence of fracture zones. The surface expressions of these zones are commonly referred to as fracture traces. Within a fracture zone an abnormally high density of vertical hairline fractures (joints) occur within the strata resulting in a greater permeability than the less-fractured earth material around it. Thus, these zones can influence the direction and velocity of ground-water flow much the same as a highly-permeable lens of sediment. Contaminants originating at the surface at point "a" (Figure 7) will tend to follow a flow path along the high-permeability fracture trace (toward "b") rather than a more normal path straight down the slope ("c" to "d"). An important difference between the influence of fracture zones and a lens of high-permeability sediment is that fracture zones can extend downward a few thousand feet. Thus, fracture zones may provide relatively high-permeability avenues for upward movement of pressurized subsurface-origin contaminants (Figure 7).

## A HYDROGEOLOGIC MODEL FOR EVALUATING CONTAMINATION HAZARD

The model shown here is based on the generalized geology and hydrogeology of the

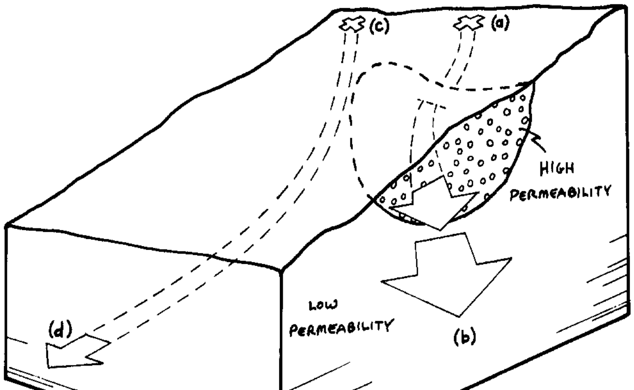


**Fig. 6. Influence of permeability on direction of contaminant flow. Path C to D is normal flow. Path A and B is refracted from normal flow path by a high-permeability sediment body located within low-permeability sediment.**

Glaciated Appalachian Plateau. Hydrogeologically, this area has three major components: (1) valley bottoms of major valleys which serve as regional discharge areas, (2) broad undulating uplands which are regional recharge zones, and (3) sloping valley walls along the major valleys (Figure 8). Superimposed on all of these major components are small stream valleys that are usually local discharge zones.

The major valley bottoms are typically underlain by up to 500 feet of clay-to-gravel-size alluvium and glacial outwash in northwestern Pennsylvania (Figure 8) (Schiner and Gallaher, 1979, p. 8). Gravel layers in these valleys are known to yield several hundred gallons/minute to properly constructed municipal and industrial wells. Disruption of drainage patterns by glaciation resulted in some major valleys which now contain only marshes or relatively small, underfit streams, though they may be underlain by major glacio-alluvial aquifers.

Valley walls along the major valleys are under-

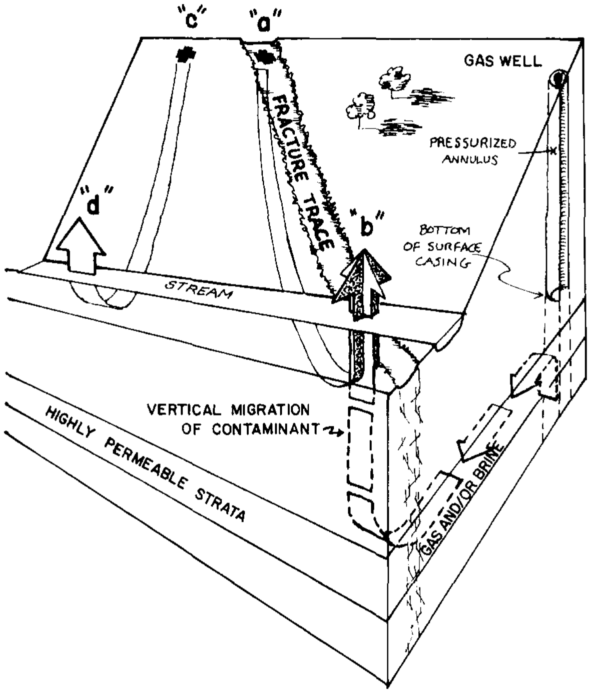


**Fig. 7. Influence of fracture traces on the velocity and flow path of surface- and subsurface-origin contaminants.**

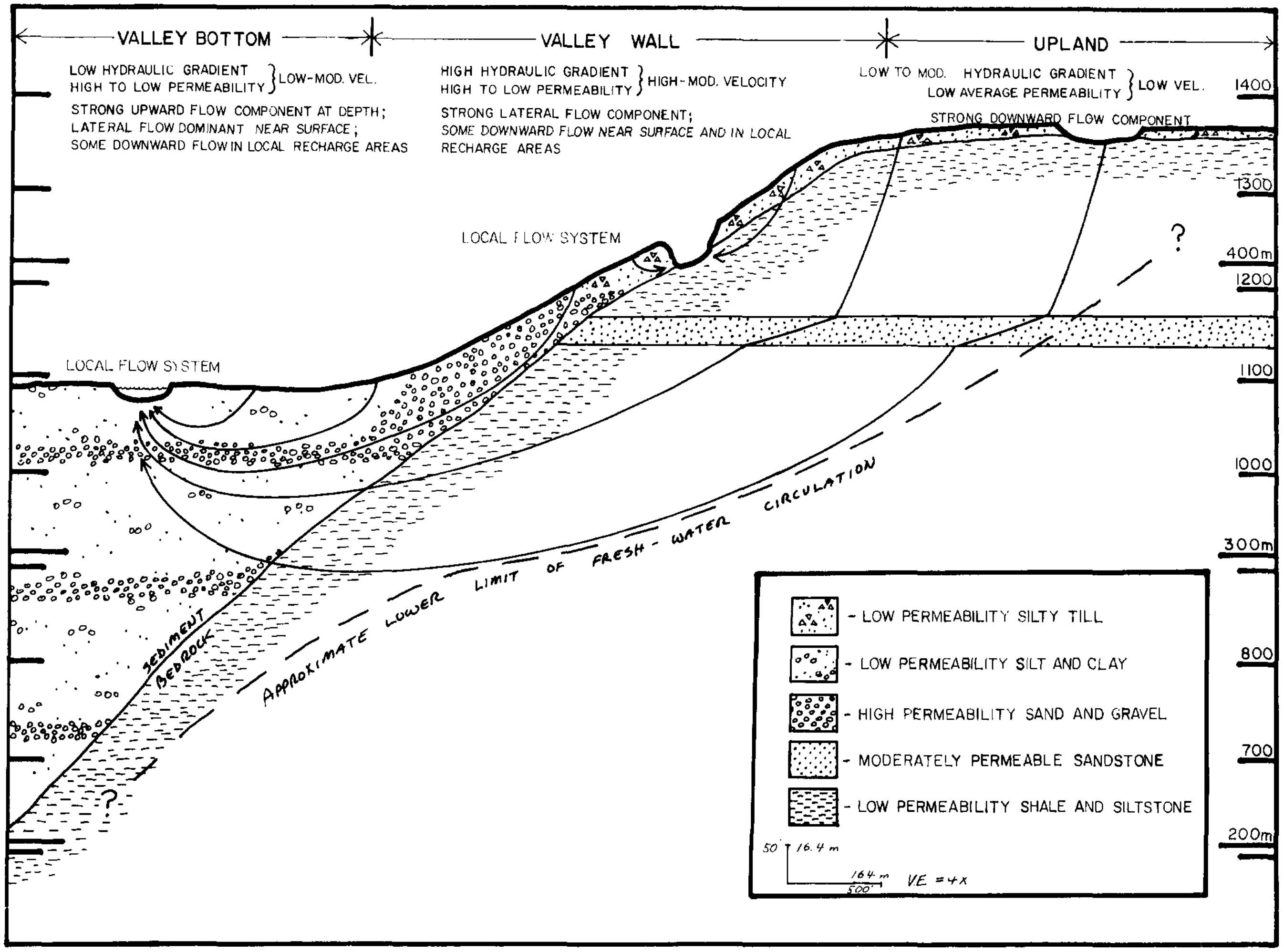


**Fig. 8. Model of major factors affecting contamination hazard of gas wells in various hydrogeologic zones on the Glaciated Appalachian Plateau.**

**Table 1. Summary of Contamination Hazard for Gas-Well Sites on the Glaciated Appalachian Plateau**

| *Contamination-hazard factors* | *Hydrogeologic zone*<br>*Valley bottom (major valleys)* | *Valley wall* | *Upland* | *Local flow system (upland or valley wall)* |
|---|---|---|---|---|
| Velocity of contaminant flow*. | Low to moderate velocity. | High to moderate velocity. | Low velocity. | High to moderate velocity. |
| Dilution along flowpath before discharging to surface water. | Low to moderate dilution. | Low to moderate dilution. | High dilution. | Low dilution. |
| Dominant component of shallow ground-water flow. | Upward at depth, lateral near surface. | Downward component usually present, but lateral component dominates. | Downward. | Usually downward where gas wells drilled. Difficult to site wells in local discharge areas. |
| Types of water wells present. | Shallow, household cased wells dominate. High-yield industrial and municipal wells also present. | Both open-hole bedrock and cased alluvial household wells present. | Low-yield household wells cased several ft into bedrock, then open hole. Few high-yield wells tap good aquifers, especially on fracture traces. | Household wells likely to penetrate local flow system and tap deeper flow system. |
| Relative volume of fresh-water zone potentially contaminated. | Small volume. | Moderate volume. | Large volume. | Small volume. |
| Overall hazard assessment. | *Overall hazard low* due to low to moderate velocity and upward flow component which results in a small area potentially affected. *High hazard* may exist locally near high-yield industrial or municipal water wells or in local recharge areas on valley bottom. | *Overall hazard high* due to rapid lateral flow component, low to moderate dilution, and moderate size of area affected. | *Overall hazard low* (except near fracture traces) due to dilution and long travel times. Problems might not be recognized for years. Large volumes of fresh-water zone could be affected if concentration of contaminant is high enough. | *Overall hazard low* due to small area of aquifer affected and low housing density. Hazard of surface-water (stream) contamination moderate. |

* Assuming nonpressurized contaminant source. Relative velocity designations based on permeability and hydraulic gradient in the hydrogeologic zone.

lain by a few to several tens of feet of low-permeability glacial till and relatively permeable sand and gravel deposits. The sand and gravel is thought to be of kame-terrace and delta-kame origin. Locally, these deposits are shallow household aquifers and commercial sources of aggregate. Soils are frequently well drained. Major transportation routes have often been built along the lower portion of the valley walls. As a result, these areas are often fairly heavily populated. Household wells may tap either the shallow outwash or, where glacial till occurs, the deeper bedrock, aquifers.

The broad, gently rolling uplands are underlain by a thin veneer (usually less than 20 ft) of low-permeability glacial till (Figure 8). Despite poorly-drained soils and a seasonally high-water table, farms and rural homesites are moderately dense. Wells are usually fairly low yield (less than 25 gpm) and tap more-permeable zones in the Devonian and Mississippian shales, siltstones, and fine-grained sandstones. A few bedrock wells located along fracture traces and tapping thin sandstone aquifers pump maximum yields of approximately 100 gpm (Schiner and Gallaher, 1979).

The depth of the fresh-water circulation zone is not well defined, but appears to extend to a maximum of about 500 ft (164 m) below the land surface. On the other hand, in some upland areas where local relief is low and low-permeability shales underlie the surface, brackish water has been reported at depths of less than 100 ft (33 m) (Schiner and Gallaher, 1979), indicating that the bottom of the fresh-water circulation zone had been penetrated.

The model (Figure 8) combines several variables which affect the contamination hazard: lithology, magnitude of flow system (regional, intermediate, local), dominant component of shallow ground-water flow (upward, lateral, downward), and hydraulic gradient. Considering all of these variables, the overall hazard to ground water by gas wells located within the three major hydrogeologic zones is summarized in Table 1. Variations in the concentration of the introduced contaminant are not included in the model because their effects are obvious and because the purpose of the model is to predict the relative hazard associated with different hydrogeologic zones. Also, it is assumed that the density of the introduced contaminant is not so great that its flow path is different from that of the surrounding ground water.

Considering the hydrogeologic variables listed above, the highest overall hazard exists on the valley walls along the intermediate flow paths. A relatively high to moderate hydraulic gradient and the frequent presence of relatively permeable surficial sediments often result in rapid movement of contaminants downslope with only moderate dilution. Flow paths in this zone are often dominated by a lateral flow component, keeping contaminants relatively near the surface where they are apt to be intercepted by water wells.

The upland areas, on the other hand, have a low overall hazard assessment (Table 1). Ground-water flow beneath these areas is generally slow due to the low to moderate hydraulic gradient and the low permeability of the till. In most areas the underlying bedrock also has a relatively low permeability. There is usually a strong downward component beneath the upland recharge area, and high dilution occurs along the long flow paths. Exceptions would be local flow systems superimposed on the regional upland systems and areas near fracture traces. In both of these cases ground-water movement would be faster and a higher hazard would be locally present.

The valley-bottom zone generally is a low-hazard area due to the upward movement of ground water, the relatively small volume of the fresh-water zone potentially affected, and the low to moderate flow velocity. Important exceptions to this are areas near high-volume alluvial wells and recharge zones of local flow systems superimposed on the regional discharge system along the valley bottom (Table 1).

## EXAMPLES OF GROUND-WATER CONTAMINATION BY GAS WELLS

Three examples of ground-water contamination by gas wells are presented. All are from valley-wall locations. Two of the examples involve intermediate flow systems with flow paths of a few thousand feet. The third is a local flow system only a few hundred feet long superimposed on a valley-wall flow system.

### Case Number 1

A gas well located at the top edge of a valley-wall hydrogeologic zone has surface casing set to a depth of 270 ft (88.5 m), about 190 ft (62.3 m) into bedrock (Figure 9). Shortly after drilling and fracturing the gas well, household-water wells located at the base of the valley wall became turbid. Natural gas was being drawn into the alluvial wells and the "boiling" action that resulted, as gas bubbles floated up through the casing, dislodged sediment at the bottom of the well and from the casing, resulting in the turbidity.

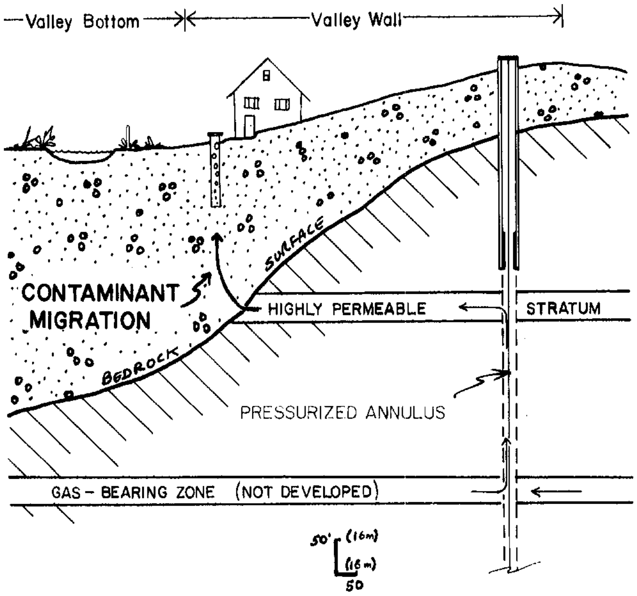


**Fig. 9. Water containing dissolved gas flows from pressurized annulus toward discharge area (major valley) via permeable stratum which intersects open annulus. Contaminated annular water is driven by pressure resulting from closed-in annulus.**

The gas appears to have travelled from a minor gas-bearing sandstone above the production zone. Gas from this upper zone either moved upward through the annulus and was incorporated into the regional flow under natural flow conditions or the contaminated annular water moved laterally toward the regional discharge zone very rapidly during a time when the annulus was sealed off and thus became pressurized. If this same well had been located away from the valley wall in an upland area, the problem would have been much less likely to have occurred because the surface casing would have extended below any water wells in the upland area and below the surrounding zone of fresh-water circulation. Because the well was located at an elevation 65 ft above an adjacent filled valley, however, the length of the surface casing used was insufficient. The problem might have been avoided if: (1) 650 ft (213 m) of surface casing had been used, (2) the annulus had not been allowed to pressure up beyond the normal hydrostatic pressure at the bottom of the surface casing, or (3) the annulus had been filled with cement.

### Case Number 2

This case involves a shallow, local flow system superimposed on an intermediate flow system in a valley-wall hydrogeologic zone. A gas well located in a local recharge zone 230 ft (75 m) from a 40-ft-deep (13.1 m) household well resulted in contamination several months after the gas well was drilled (Figure 10). The contamination, which resulted in hardness values in excess of 2,000 mg/l and chloride values of over 850 mg/l in the household well, was traced back to the slush pit adjacent to the gas well. Brine, formation cuttings, and fluids used during development of the well had been left in the pit for several months after the well was completed. During construction of the slush pit, a low-permeability shale was encountered at a depth of 6 ft (2 m). Excavation was continued to a depth of 8 ft (2.6 m). In the area of the water well and extending roughly half the distance to the water well, a layer of high-permeability sandy outwash occurs on top of the shale. Overlying the sandy layer is a low-permeability silty till and underlying it is the shale with extremely low primary permeability, though jointing and weathering provide some secondary permeability. Thus, the natural tendency for shallow ground-water migration from the slush pit to flow down the hydraulic gradient toward the household well was enhanced by the presence of relatively high-permeability sands. As was pointed out earlier, high-permeability sand and gravel deposits are common in the valley-wall hydrogeologic zone.

Contaminants bypassing the household well flow toward a small stream which is the discharge zone for the local flow system. Thus, only a small zone of fresh water is affected, as is characteristic of local flow systems (see Table 1). In this case, the contamination could have been avoided or minimized by: (1) not excavating the slush pit down to the shale bedrock, because the contact between the shale and the somewhat more permeable overlying sediments is a boundary along which shallow ground-water flow takes place; (2) not locating the gas well so close to the water well; (3) not locating the gas well in the recharge area of the local flow system which the water well taps; and (4) digging an exploratory backhoe pit between the proposed gas-well site and the existing water well to detect the high-permeability sandy layer. Even with the gas well where it is, the con-

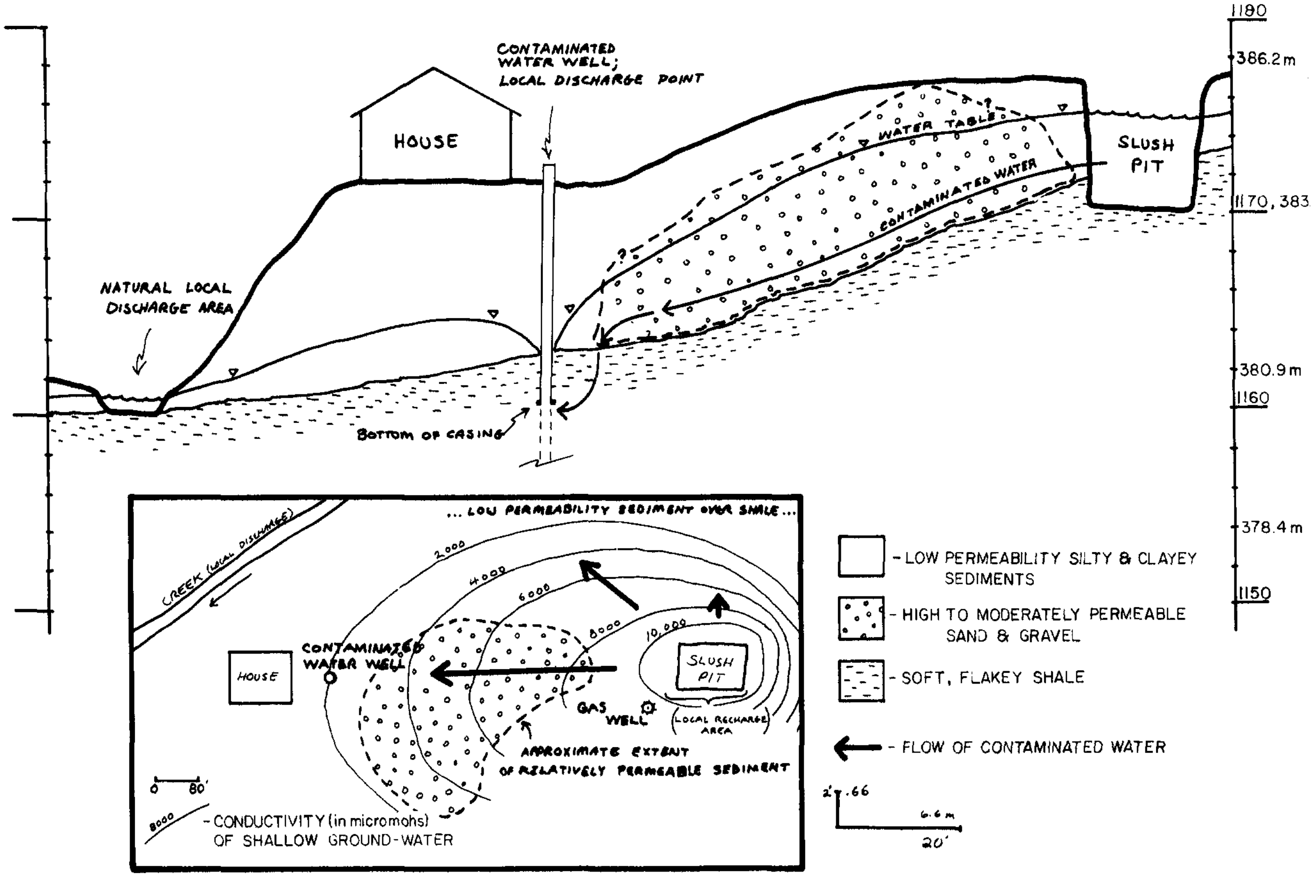


**Fig. 10. Contamination of a shallow water well by slush pit brines located in a local recharge area on a valley wall. Arrows on inset indicate relative velocity of flow of contaminants along shallow, local flow paths.**

tamination hazard would have been greatly reduced had the material in the slush pit been removed promptly instead of being left in the recharge zone for several months.

### Case Number 3

Several household-water wells became contaminated with natural gas several months after a nearby gas well was drilled and fractured. The bubbling of the natural gas in the water wells resulted in turbidity and the buildup of gas was sufficient that some homeowners reported hearing explosions from their pump houses. In one instance a pump house door was blown off and another homeowner demonstrated the presence of gas in her well by igniting the water as it discharged from her garden hose.

The affected water wells, which are located in a valley-wall hydrogeologic zone, range from 50 ft to 150 ft (16 to 49 m) deep and tap siltstone and sandstone zones within the predominantly shale bedrock (Figure 11). The gas well is located at the top of the valley wall about 3,000 ft (983 m) away from the affected area. Several water wells closer to the gas well were not affected.

Surface casing in the gas well extends about 550 ft (180 m) below the surface. Approximately 4,000 ft (1,312 m) of annulus is open between the surface casing and the cement seal above the producing horizon at the bottom of the hole. One or more of the formations open to the annulus contained natural gas which could be detected readily at the surface when the annulus was vented to the atmosphere. The problem is thought to have been caused when the annulus was closed off and thus became pressurized for a period of several months. Calculations show that with an annulus pressure of

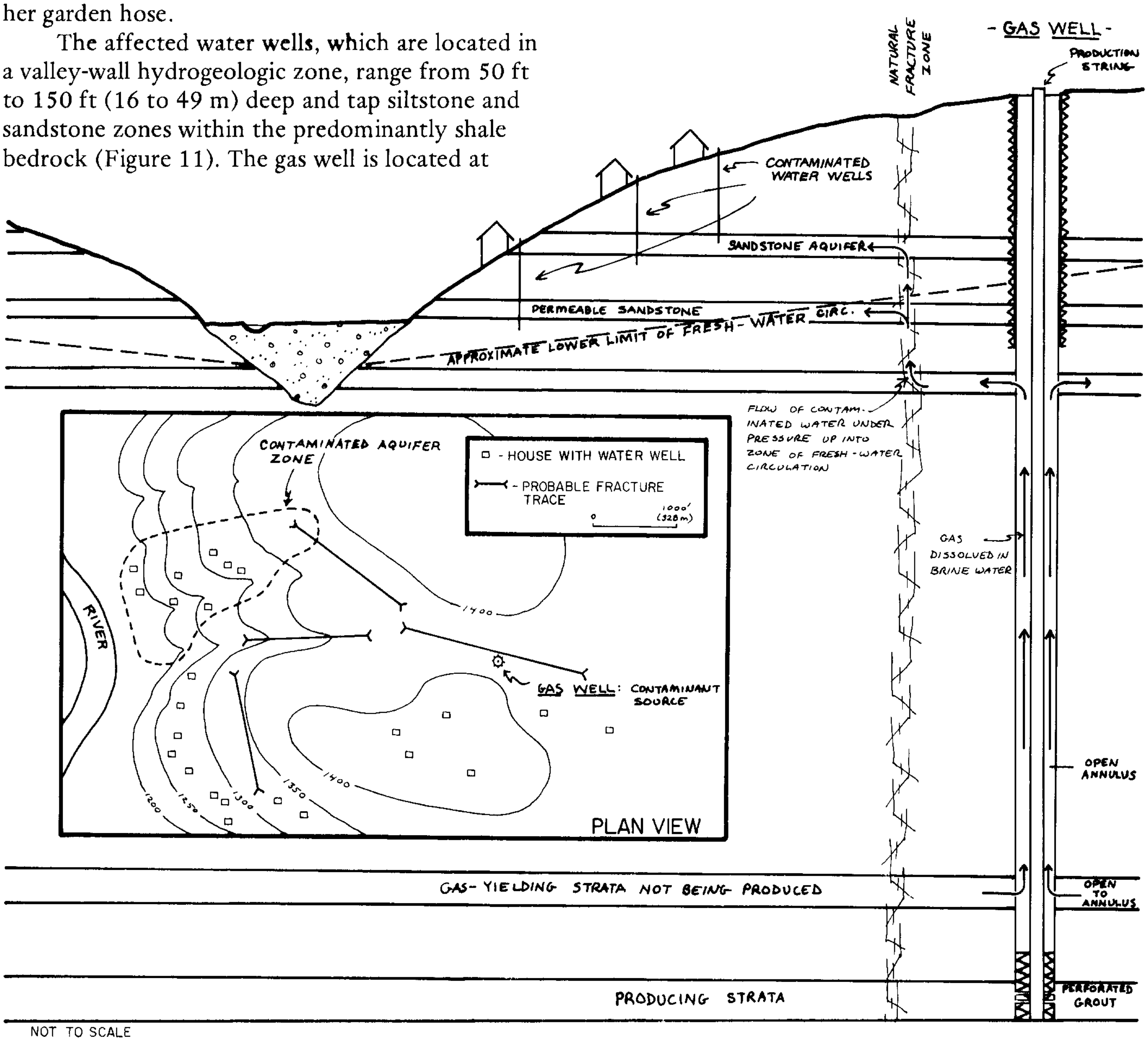


Fig. 11. Cross section showing contamination of water wells caused by rapid flow along fracture zones of brine and dissolved natural gas from a pressurized annulus. Inset shows plan view with locations of probable fracture traces relative to the gas well and the zone of contaminated aquifers.

**Table 2. Suggested Hazard Evaluation of Potential Gas-Well Sites**

| *Gas-well locations having high potential contamination hazard* | *Assessment of hazard* | *Possible actions to reduce hazard of aquifer contamination* |
|---|---|---|
| Valley wall and upland near valley wall. | Slope bordering major valley; located between upland and valley floor. | • Move site off valley wall onto valley floor or farther back onto upland if feasible.<br>• Extend surface casing *below* elevation of bottom of valley fill in adjacent major valley.<br>• Minimize or eliminate contact of brines and chemicals with ground.<br>• Never permit annulus to become pressurized[1] or better, fill entire annulus with cement. |
| High-permeability near-surface sediment. | Soils Conservation Service soils maps and glacial geology maps provide clues; use backhoe pits to test suspect sites. | • Move site onto lower-permeability surface sediment if possible.<br>• Minimize or eliminate contact of brines and chemicals with ground. |
| Near fracture trace(s). | Examination of air-photo stereo pairs by person skilled at fracture-trace detection. | • Avoid sites within a couple hundred feet of likely fracture traces.<br>• Never allow annulus to become pressurized or better, fill entire annulus with cement. |
| Near high-yield well on valley floor. | Inquire locally about location of high-yield wells (e.g., municipal, industrial). | • Avoid sites upgradient of these wells or within their cone of depression.<br>• If site used, minimize or eliminate contact of brines and chemicals with ground.<br>• Extend surface casing through valley-fill sediments into underlying bedrock into brackish-water zone.<br>• Never allow annulus to become pressurized or better, fill entire annulus with cement. |
| Recharge zone of local flow system. | Site topographically higher than adjacent nearby discharge area (e.g., stream). | • Move site if any water wells between site and discharge area.<br>• Move site if high-permeability sediment near surface and the adjacent discharge area is of high quality.<br>• Minimize or eliminate contact of brines and chemicals with ground. |

[1] Pressure should not exceed normal hydrostatic pressure at any given depth.

600 psi, contaminants in the annulus could travel at 15 times the normal flow rate in this area. Examination of aerial photos indicated that fracture zones occur near the gas well. These would not only provide avenues for rapid vertical migration of contaminants upward into the fresh-water zone (Figure 11), but also provide high-permeability zones of lateral ground-water movement. The orientation of these high-permeability fracture zones helps explain why some areas near the gas well were not affected whereas water wells more distant, but adjacent to the fractures, were.

In this case the contamination could probably have been avoided if: (1) the area had been examined for probable fracture traces before siting the well, and (2) the annulus had never been pressurized, or (3) the annulus had been filled with cement.

## SUGGESTED HAZARD EVALUATION OF SITES

The major hydrogeologic site hazards discussed in this paper are summarized in Table 2, along with suggestions for assessment of the hazards and suggested actions to reduce the hazard of contamination of fresh-water aquifers. Though each high-hazard factor is listed separately, two or more factors may exist at a given site. For instance, valley-wall areas are quite commonly veneered with high-permeability sediments (outwash deposits) and usually have steep hydraulic gradients, thus compounding the hazard of contaminating nearby fresh-water aquifers. A valley-wall location underlain by high-permeability sediments in a local recharge zone would be even more hazardous.

The suggestions for reducing potential hazards (Table 2) include moving the site in every instance. Although moving a site a few hundred feet may reduce the hazard at some sites, in other cases moving the site to one deemed less hazardous may not be feasible in terms of the gas-production objectives. If so, other choices would be to:
(1) abandon the site altogether, or (2) take whatever actions are feasible to reduce the hazard at that site. In many cases the suggestions include preventing contact of brines and chemicals with the ground. The plastic pit liners now used are probably of little value in isolating pit contents. Thus, either more substantial liners are called for or the development of a drilling process utilizing portable water-tight tanks instead of in-ground pits, if that is possible. It is common sense to minimize contact

time of brines and chemicals with the ground when it does occur, rather than leaving brine pits unemptied for several months or not removing their contents from the site when they are emptied. This is especially important in many of the high-hazard locations described in Table 2.

Although Table 2 focuses on well-site activities, it can also be helpful in assessing the hazard of offsite activities involving management of surface-origin contaminants. For example, brine is sometimes spread on roads for dust and ice control in the Glaciated Appalachian Plateau. Because brine spreading results in a less-concentrated application of a potential contaminant to the ground than a gas-well brine pit, not every potentially hazardous site for a gas well should necessarily be avoided in brine spreading. Generally speaking, the greatest hazard exists at sites where short ground-water flow paths lead to shallow-water wells. Thus, brine spreading on high-permeability sediment (outwash) directly upslope from water wells which border the road would be the greatest hazard. These areas would most likely be located where roads traverse outwash in local recharge areas on valley-wall and valley-bottom hydrogeologic zones. Using a soils map, many of these areas of relatively high-contamination potential could be identified (Figure 12). Obviously, the degree of hazard of contaminating flow paths varies directly with intensity and duration of brine spreading. Even regional flow paths could be adversely affected if surface applications of brines in the regional recharge area are of very high concentration or continued over a long period of time. And unfortunately, the longer the flow path the longer it takes for natural renovation once contamination has occurred.

The information summarized in this article does not describe every possible factor or situation that comprises a hazard of contamination of fresh-water aquifers by gas-well-drilling activities. In addition, it is possible that contamination may occur even if the suggested actions in Table 2 have been followed. Therefore, these hazards and the suggested actions have been presented to reduce the hazard of contamination.

## ACKNOWLEDGMENTS

Burt Waite of Moody and Associates and Robert Sterba, Pennsylvania Department of Environmental Resources, made several suggestions based on their extensive experience with gas and water wells in northwestern Pennsylvania. Suggestions for improving the manuscript were also made by Jay Lehr, National Water Well Association, and John Ifft, Division of Oil and Gas Regulation, Pennsylvania Topographic and Geologic Survey. Robert Schwartz, Marie Schwartz, and Alistair MacDonald, Allegheny College, provided data for one of the case studies, and Dan Williams, Allegheny College, prepared the illustrations.

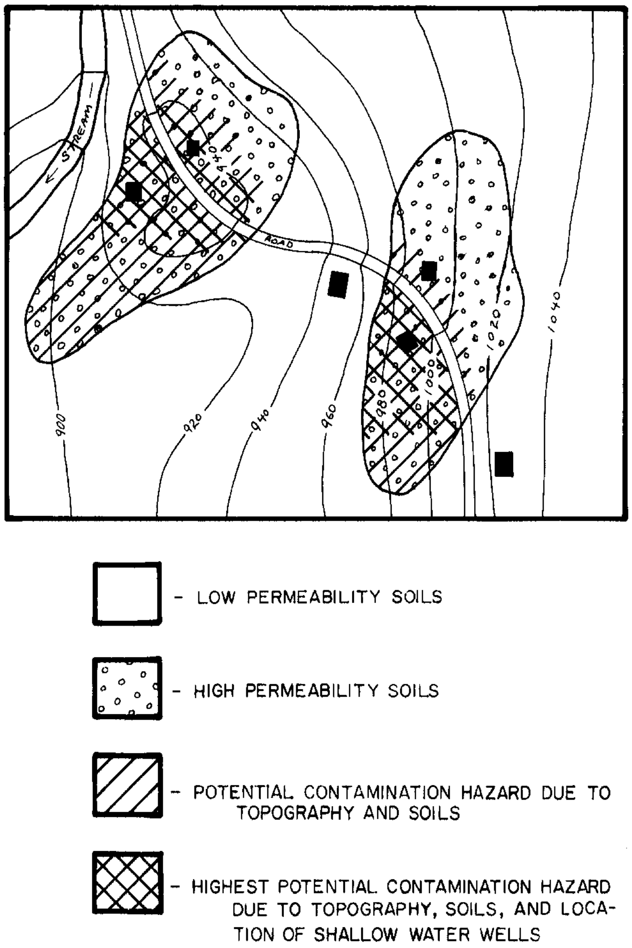


**Fig. 12. Use of information from soils maps and topographic maps to identify areas with a potential for contamination of fresh-water aquifers by brine spreading on roads.**

## REFERENCES CITED

Sharpe, William, and Richard Parizek. 1970. Water well location by fracture-trace mapping. Water Well Journal. Nov., pp. 38-41.

Schiner, George R., and John T. Gallaher. 1979. Geology and groundwater-resources of western Crawford County, Pennsylvania. PA Topographic and Geologic Survey, Water Resources Report 46. 103 pp., 3 PL.

* * * * *

*Samuel S. Harrison is a Professor of Geology and Chairperson of the Environmental Science Department at Allegheny College. A graduate of Allegheny, he earned his M.S. and Ph.D. degrees in Geology from the University of North Dakota. In addition to teaching hydrogeology, he is a private consultant, with most of his work focusing on ground water contaminated by landfills and gas-well-drilling activities.*