Environmental Geology (1993) 22: 314–320

R. A. DeStephen · C. P. Benson

Groundwater withdrawal impacts in a karst area

Received: 3 May 1993 / Accepted: 11 May 1993

Abstract During a 3000-gpm pump test on a groundwater supply well in Augusta County, Virginia, residential properties were impacted. The impacts included lowered farm pond water levels, development of a sinkhole, and water level decrease in residential wells. A study was performed to assess whether a lower design yield was possible with minimal impacts on adjacent property. This study included a 48-h 1500-gpm pump test that evaluated impacts due to: (1) sinkhole development and potential damage to homes, (2) loss of water in residential wells, and (3) water-quality degradation. Spring flows, residential well levels, survey monuments, and water quality were monitored. Groundwater and surface water testing included inorganic water-quality parameters and microbiological parameters. The latter included particulate analyses, *Giardia* cysts, and coliforms, which were used to evaluate the connection between groundwater and local surface waterbodies. Although results of the study indicated a low potential for structural damage due to future sinkhole activity, it showed that the water quality of some residential wells might be degraded. Because particulate analyses confirmed that groundwater into the supply well is under the direct influence of surface water, it was recommended that certain residents be placed on an alternate water supply prior to production pumping and that filtration be provided for the well in accordance with the Surface Water Treatment Rule. A mitigation plan was implemented. This plan included crack surveys, a long-term settlement station monitoring program, and limitation of the groundwater withdrawal rate to 1.0 million gallons per day (mgd) and maximum production rate to 1500 gpm.

Key words Karst areas — Sinkhole development — Groundwater quality

R. A. DeStephen (✉) · C. P. Benson
Schnabel Environmental Services, One W. Cary Street, Richmond, Virginia 23220-5609, USA

Introduction

Augusta County is in the northwestern part of Virginia. The county is flanked by the Blue Ridge Mountains to the southeast and is primarily in the Ridge and Valley Physiographic Province. Groundwater resources are plentiful in Augusta County, particularly along the toe of the Blue Ridge in what is known as the Lyndhurst-Grottoes alluvial corridor, immediately adjacent to the study area. To meet future water-use demand in the county, a groundwater supply well was developed and a 48-h pump test conducted at 3000 gpm.

Although groundwater reserves proved plentiful, a 45-cm (18-in.) deep sinkhole developed about 198 m (650 ft) from the well, farm ponds 457 m (1500 ft) away receded, and residential wells 244–610 m (800–2000 ft) away incurred reduced water levels. Residents feared a risk of damage to homes, loss of their water supply, and degradation of drinking water quality. A preliminary study presented at a public meeting indicated relatively low sinkhole potential under nonpumping conditions, but concluded that comprehensive direct data measurement during a second pump test at a reduced rate of 1500 gpm would be necessary to assess impacts. In an unusual, if not unprecedented effort, a cooperative study between the Augusta County Service Authority and the local citizens was initiated. This joint agreement included a major data compilation effort with citizen input, including submittal of residential well data and observation of residential well drawdowns during the pump test. The objective of this study was to assess potential negative impacts prior to production pumping and formulate a monitoring and mitigation plan.

Hydrogeologic setting

The central part of Augusta County contains principally Cambrian and Ordovician limestones, dolomites, shales, and thin sandstones, which are characterized by parallel, northeast trending anticlines and synclines. The production well site is underlain by the Cambrian age Elbrook formation. The Elbrook formation is divided into an Upper Member and a Lower Member. The Upper Member is present immediately beneath the site and primarily consists of fine- to medium-grained crystalline dolomite with phyllitic and slaty interbeds. Bedding trends strike to the northeast with dips of 60–74 degrees to the northwest (Gathright and others 1977).

The well site is located on uplands adjacent to the flood plain and low-level terrace deposits of the South River as indicated in Fig. 1. These terraces, which form the Lyndhurst-Grottoes alluvial corridor, overlie the Lower Member of the Elbrook formation.

For the Lower Member of the Elbrook formation, sinkhole activity is greater than in the adjacent Upper Member due to the granular alluvial soils that blanket the formation. This allows for significant infiltration and corresponding sinkhole development. Similarly, sinkholes are more prevalent in the Conococheague formation to the northwest. In this case, sinkhole occurrence is largely associated with sandy well-drained residual soils formed from sandstone interbeds. Figure 1 shows the sinkhole locations corresponding to the areas underlain by the various geologic formations.

Throughout Augusta County, very high yields are common where carbonate formations are overlain by the more granular alluvial and terrace deposits. Wells producing in excess of 100 gpm are typical where the alluvial overburden is present. Well yields for 83 wells in the carbonate rocks of Augusta County with alluvial cover average 294 gpm, while 92 wells in carbonates without alluvial cover average 37 (Hinkle and Sterrett 1978).

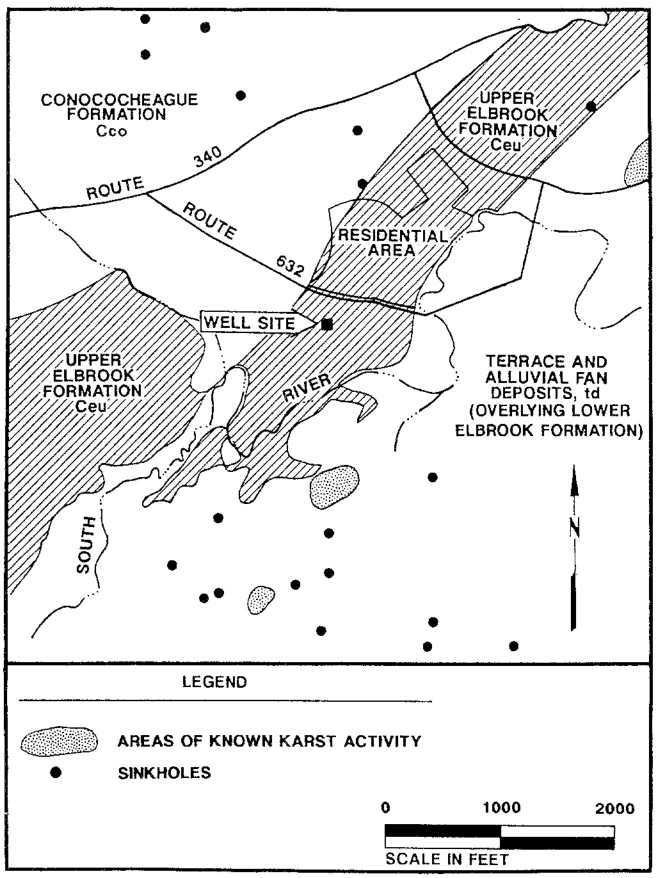

Fig. 1. Geologic formations and sinkhole occurrence

Within the study area as shown in Fig. 2, residential well yields reported on driller's logs varied from 2 to 60 gpm. No correlation could be drawn between well yield and site location. Reported yields are probably not accurate where flow rates were greater than needed for residential purposes. The residential well logs indicate well depths of 27.4–76.2 m (90–250 ft) with an average depth of 40 m (130 ft). Four wells are very deep, greater than 122 m (400 ft). All of the deep wells are low yielding at less than 10 gpm. Depths to rock in the residential wells vary from 3 to 18 m (10 to 60 ft) with shallowest depths occurring near Small Spring Branch and the South River and greater depths near the groundwater supply well. The rock data reveal that a ridge of high rock traverses the residential area in a northeasterly direction from the water supply well as depicted by the top of rock contours in Fig. 2.

An electromagnetic (terrain conductivity) survey was conducted at the site using a Geonics model EM 34-3XL Terrain Conductivity Meter. The instrument was operated in both the horizontal and vertical dipole alignment with a 20-m (66-ft) intercoil spacing to provide instrument response at a target depth of 0–30 m (0–100 ft). The horizontal dipole mode better measures conductivity variations in the near-surface zone, while the vertical dipole mode is more indicative of geological structural variations at a target depth of 9–30 m (30–100 ft).

Terrain conductivity readings were made at discrete stations along preselected survey lines. Isoconductivity contours were produced from values obtained from the survey. Readings taken in the vertical dipole alignment provided more meaningful data. Values resulting from the transmitter and receiver in the vertical dipole mode showed conductivities of 10–100 mmho/m for the areas shown in Fig. 2 as against background values of 2–6 mmho/m at all other locations. The higher conductivity readings in the areas described above are inferred to be due to water-bearing fractures and solution features in the rock. These data correlate fairly well with the location of the bedrock ridge shown in Fig. 2, which is under saturated conditions.

Fracture trace evaluations are frequently used to identify water-bearing structures. Aerial and infrared photographs are used to discern linear trends. Proliferation or intersection of linear trends is an indication of potential water-bearing features within underlying rock. Fracture traces near the site are predominantly in a northeast–southwest trend, similar to the strike of the major lithologic units. Small Spring Branch, whose course makes a right angle bend (DeStephen and Martin 1992), is considered one of the more significant fracture traces near the site.

In order to acquire supplemental hydrogeologic data and correlate the hydraulic effects of pumping on the ground and surface water, monitoring wells MW-1 and

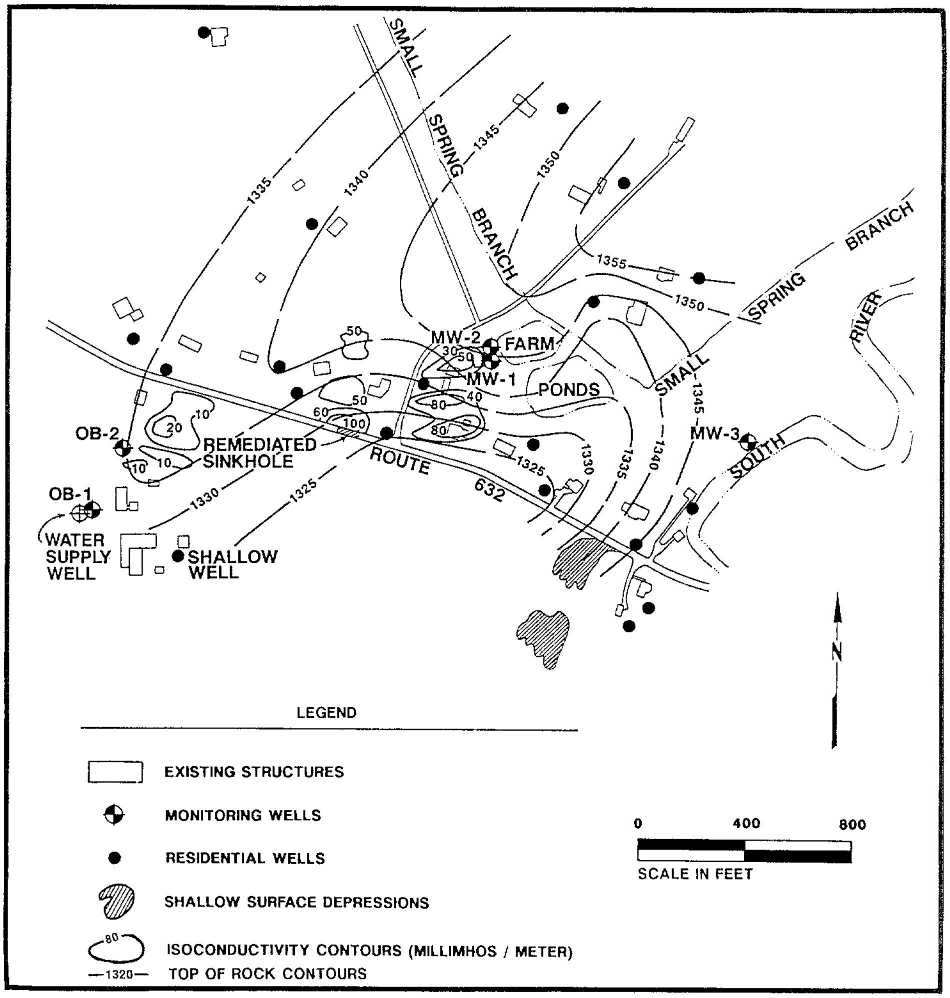

Fig. 2. Top of rock contours and terrain conductivity anomalies within study area

MW-2 were installed in the area of higher terrain conductivity and adjacent to the Small Spring Branch fracture trace (Fig. 2). These wells are immediately adjacent to the farm pond that receded during the 3000 gpm pump test. Well MW-1 is a 9.1-m (30-ft) deep well, screened in the upper weathered rock zone. Well MW-2 is 38 m (125 ft) deep, cased and grouted to 30.5 m (100 ft), and screened below this depth. The wells were drilled by air rotary methods and logged based on rock chips expelled during the drilling process. Observation of rock chips indicated highly weathered rock with clay seams in the upper 30 m (100 ft). This portion of the borehole caved continuously during drilling. A possible 0.6-m (2-ft) void was indicated at a depth of 20 m (66 ft). Rock was encountered at 3 m (10 ft), and overburden soils consisted of sandy lean clay.

Groundwater conditions were obtained prior to the pump test by taking water level readings on residential wells and new and previously installed monitoring wells. These data indicate the flow gradient at the site is very shallow at 0.7%. Groundwater flows south and southeasterly towards the South River.

Depths to groundwater, represented by water levels in the bedrock wells, vary from 1.5 to 18 m (5 to 60 ft) below ground surface. These water levels occur within the soil overburden. Shallowest depths occur in the topographically low portion of the site represented by Small Spring Branch. Flow in the bedrock aquifer appears to be in communication with shallow overburden groundwater since water levels in shallow and deep companion wells MW-1 and MW-2 were identical prior to the pump test.

Pump test program

A 48-h pump test was conducted on the groundwater supply well at a constant flow rate of 1500 gpm. This well is 104 m (341 ft) deep and screened over the lower 43 m (141 ft). Water levels in the pump test well, well OB-2, and wells MW-1 and MW-2 were recorded during the pump test and throughout the 24-h recovery period using data loggers. Wells OB-1, MW-3, 13 residential wells, the farm ponds, and Small Spring Branch were monitored using hand measurements.

Turbidity and ground surface subsidence was monitored during the pump test. Survey benchmarks were established near the previous sinkhole and within shallow surface depressions (Fig. 2). The turbidity data were acquired to assess whether the discharge water was transporting soil, which would indicate a mechanism for sinkhole development.

Water-quality sampling was performed on monitoring wells and residential wells prior to and at 48 h into the pump test. Background water-quality samples were also taken in various surface waterbodies, including the farm ponds, Small Spring Branch, and the South River. Field measurements were taken for temperature, pH, specific conductance, and turbidity. Water samples were obtained for inorganic and biological laboratory analyses. Inorganic analyses included pH, specific conductance, hardness, total dissolved solids, nitrates, and chloride.

Biological testing included total and fecal coliforms, particulate analysis, *Giardia lamblia*, and other pathogenic microorganisms. These parameters were tested to further evaluate potential surface and near-surface contaminant sources and the influence of production pumping.

Most coliform bacteria do not cause disease and are present in the intestines of all warm-blooded animals including humans. These nonfecal coliforms commonly occur in soil and vegetation and are not necessarily indicative of septic systems or animal wastes, which are sources of fecal coliforms and other health-related microorganisms. Fecal coliform contamination, particularly when associated with high nitrate or sulfate levels, usually indicates a septic system or other fecal pollution source.

Giardia lamblia is an intestinal parasite commonly found in surface water. This type of pathogen can cause giardiasis, a type of dysentery. Humans and certain animals can host *Giardia* and contaminate surface waters with cysts. Because *Giardia* cysts survive easily in water and are resistant to chlorine, safe removal of *Giardia* and viruses requires chemical pretreatment, filtration, and disinfection. *Giardia lamblia* is sampled by passing water through a filter at a given flow rate.

Particulate analysis is intended to identify organisms that only occur in surface waters as opposed to groundwaters and whose presence in groundwater would indicate partial mixing with surface water. The parameters tested in the particulate analysis included rotifers, live diatoms, blue-green algae, green algae, Coccidia, and insect parts. Diatoms, blue-green algae, and green algae require sunlight for their metabolism, and their recurring presence in groundwater would be evidence of direct surface water influence. Evidence of rotifers in groundwater indicates either surface water influence or that the groundwater contains organic matter sufficient to support the growth of rotifers. Thus, rotifer identification is not conclusive evidence of surface water influence. Insect parts and Coccidia (intracellular parasites that occur primarily in vertebrates) are good indicators of surface water influence.

Pump test results

No ground subsidences or damage to structures was observed or reported during or following the 1500-gpm pump test. No settlement changes were recorded at any of the settlement monitoring stations. Discharge water from the pump test was cloudy for the first few hours of the test and then became clear. Turbidity readings were taken and values decreased from 16.7 to 5.1 NTU over a 42-h period.

Forty-eight-hour drawdown in the residential wells varied from zero to 12.3 ft. Negligible values were recorded for wells about 640 m (2100 ft) from the pumping well in both northerly and easterly directions. Drawdown contours are indicated in Fig. 3, which shows 48-h readings. The drawdowns appear to be preferential, in a generally northeasterly direction. This preferential direction generally follows the rock ridge previously identified, and the higher conductivity area determined from the geophysical survey. The 48-h drawdown at the groundwater supply well was 18.27 ft.

Aquifer characteristics were estimated from the drawdown curves at both monitoring and residential well locations. Transmissivity and storage coefficients were computed using the time vs drawdown curves and modified nonequilibrium equations (Driscoll 1987). Transmissivity ranged from 53,660 to 111,900 gpd/ft with an average value of 79,600 gpd/ft. Transmissivity at MW-1, MW-2, and the residential well to the west ranged from 90,000 to 111,900 gpd/ft. These high transmissivity values correspond to wells along the bedrock ridge with anomalous terrain conductivity levels. This correlation supports the observed drawdown contours shown in Fig. 3. Storage coefficients ranged from 0.00023 to 0.0231, which indicates a partially confined aquifer condition (i.e., the clayey residual soils are less pervious than the bedrock aquifer).

Drawdown within the farm ponds was first noticed 4 h into the pump test. Maximum pond drawdown occurred at 72 h after the start of pumping (24 h into recovery) and was 254 mm (10 in.). Recovery of the ponds was slower than recovery of the adjacent wells. The slower drawdown and/or recovery of the ponds is due to the lower permeability of the overburden soils, which controls flow in the water-table aquifer. A similar effect was observed near the groundwater supply well when comparing drawdown data in a deep residential bedrock well (OB-2) and a shallow hand-dug overburden well at a similar distance from the supply well. The bedrock well was immediately affected, with drawdown of 5.3 m (17.4 ft) while the overburden well was not affected until 6 h into the pump test, with a maximum drawdown of 1.6 m (5.4 ft).

There was no change in flow measured in Small Spring Branch based on weir readings. Likewise, shallow monitoring wells adjacent to the South River showed no change in water level.

Water-quality samples were taken from monitoring and residential wells. In general, the surface water chemistry was not found to be distinguishable from the groundwater chemistry with regard to the chemical parameters tested. Thus organic and inorganic parameters were not conclusive in determining the influence of pumping on surface waterbodies.

Both the groundwater and surface water were considered hard to very hard, which is typical for carbonate rock

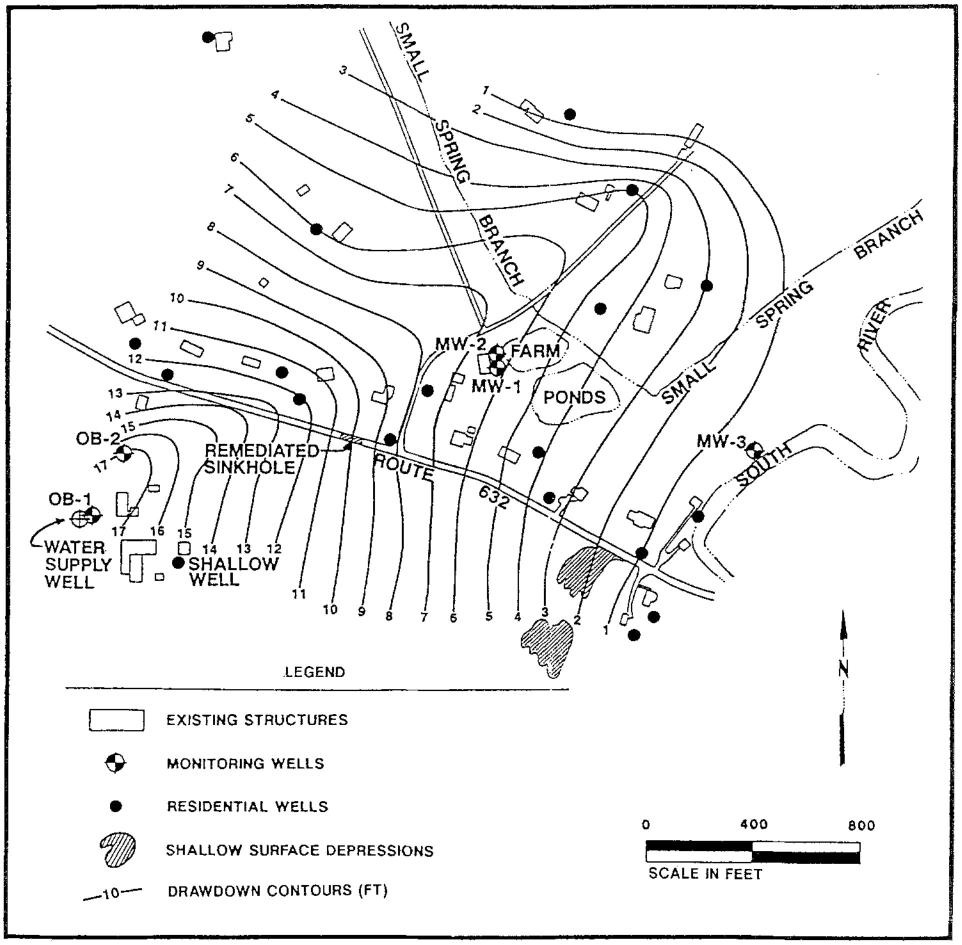

Fig. 3. Drawdown contours after pumping 48 h at 1500 gpm

aquifers. Nitrate nitrogen was generally less than 5 mg/l, similar to surface water, but higher values of 7.4 to 12.8 were obtained at MW-1, MW-2, and the two nearest residential wells southwest of the farm ponds. This is the lowest area of the study site, and this area constitutes the original farm site. The higher nitrate values suggest an influence from either septic drainfields or past farming practices. Agricultural activities including fertilizers and manure applied to crops, and feedlots and pastures are a major source of nonpoint pollution to carbonate aquifers (Berryhill 1989). All of the residential wells tested negative for total coliforms except two wells immediately downgradient (south) of the farm ponds. One of these wells also showed fecal coliforms. Total and fecal coliforms were prevalent in all of the surface waterbodies tested. *Giardia lamblia* was not detected in either surface water or groundwater. MW-2 and the same two wells that indicated coliform bacteria also indicated parameters of surface water influence from the particulate analysis. These particulate parameters included rotifers, live diatoms, blue-green algae, green algae, and Coccidia. Blue-green algae and green algae were identified in the pumping well at 46 h within a grab sample, and rotifers and diatoms at 48 h within a filter sample, suggesting that the pumping well, similar to wells MW-2 and the two downgradient residential wells, have been influenced by surface water.

Assessment of impacts

Impacts of groundwater withdrawal were evaluated with regard to sinkhole potential, water quantity loss, and water-quality degradation. Sinkhole potential was considered to be low under nonpumping conditions for the area based on regional factors such as geologic setting, sinkhole frequency, and estimated overburden depths. Pumping from the production well would increase the potential of triggering a subsidence sinkhole. This type of sinkhole is formed by erosion of soil into voids and solution openings in the underlying bedrock. This phenomenon can occur when soil, arching over an opening, collapses due to loss of buoyant force or due to strain softening as groundwater levels fluctuate up and down (DeStephen and Wargo 1992). Collapsing of soil into void space will occur until equilibrium is reached. If equilibrium is reached before displacements can reach the ground surface, a surface subsidence or sinkhole will not form. Where a sinkhole does occur, its location beneath a structure could cause settlement damage. This will depend on the size and relative location of the subsidence and the rigidity of the structure.

The potential for sinkhole development was considered to remain low under the recommended pumping conditions based on the following:

- Drawdowns would only be about 2.5 m (8.5 ft) at the nearest residences under maximum allowable pumping conditions.
- Water levels within the overburden do not decline below the rock surface upon pumping, limiting the mechanism of subsurface erosion (Newton 1987).
- Overburden depths are greater than 15 m (50 ft) where the highest drawdowns will occur. Therefore, arching of the soil mass would more likely preclude ground surface subsidence.
- The increase in effective stress on the underlying soil due to drawdown is a maximum of only about 24 kPa (500 psf), not considered high enough to cause punching failure or significant consolidation (Sowers 1975).
- Turbidity of the water from the groundwater supply well was low and no sediment removal was observed.

Production pumping from the groundwater supply well will not likely impact residential well quantity. Maximum drawdown at residential wells is estimated at 2.5 m (8.5 ft) and maximum fluctuations due to domestic pumping were about 1.5 m (5 ft). The water column for the residential wells in the area of concern is greater than 15 m (50 ft). Farm pond levels would be influenced by groundwater withdrawals. However, the effects of groundwater withdrawals together with seasonal effects could not be accurately forecast.

Residential well quality presently shows some signs of impact from surface water and near-surface activity. These impacts include elevated nitrate levels, most likely from previous farm activity and coliform bacteria. Coliform bacteria were associated with surface water since particulate parameters, also indicative of surface water, were identified in coliform-contaminated wells.

Residential wells near the farm ponds have the potential for continued impact by surface water with or without future production pumping. Effects of production pumping from the supply well will serve to change the groundwater flow directions. In doing so, water quality in wells already under surface water influence would continue to be affected. Impacts to wells could be positive or negative.

Identification of particulate parameters in the groundwater supply well suggests that some mixing of surface water with groundwater has occurred. Under the Surface Water Treatment Rule promulgated by EPA on 29 June 1989, public water systems using groundwater under the direct influence of surface water are required to disinfect and install filtration systems.

Recommendations for monitoring and mitigation

The following safeguards were recommended in order to minimize sinkhole potential and avert negative groundwater impacts:

1. Limit the groundwater withdrawal rate to 1.0 mgd and the maximum production pumping rate to 1500 gpm.
2. Establish settlement monitoring points on the seven nearest residential structures with at least semiannual readings taken for a period of two years from initiation of pumping.
3. Conduct a videotaped "crack survey" of the interior of the above residences prior to startup of production pumping.
4. Water levels on the farm ponds versus groundwater drawdowns should be measured during the first year of the well operation to evaluate the need for supplemental recharge to the ponds.
5. An alternate water supply system should be supplied to the residents between the farm ponds and the water supply well.
6. A filtration system should be installed on the water supply well in accordance with the Surface Water Treatment Rule for groundwater wells under the influence of surface water.

Conclusions

When developing substantial groundwater resources in carbonate formations, care must be given to potential impacts to surrounding development. Sinkholes and their consequent damage should be evaluated. The potential for water supply wells to go dry and for streams, ponds, and reservoirs to lose recharge must be evaluated. Furthermore, the effects of pumping on the quality of existing water supplies must also be considered. Treatment requirements for any municipal groundwater supply, particularly filtration, must be determined by evaluating whether the supply is under the direct influence of surface water.

This study demonstrates that cooperation with communities affected by proposed withdrawals can result in greatly enhanced data collection so crucial to reasonable characterization of subsurface conditions. Because karst geology is so complex, every type of information available should be gathered and used in a systematic approach to understanding how groundwater withdrawals will impact a site. Microbiological tests including total and fecal coliforms, *Giardia lamblia*, and particulate analyses can provide a valuable assessment of surface water and groundwater interaction.

Acknowledgments The writers would like to thank the Augusta County Service Authority for initiation of this study as well as their helpful cooperation and participation throughout the pump test.

References

Berryhill WS (1989) The impact of agricultural practices on water quality in karst regions. Third Multidisciplinary Conference on Sinkholes, St. Petersburg Beach, Florida. 6 pp

DeStephen RA and Martin RE (1992) Evaluation of water supply impacts on surrounding area, Route 632, Augusta County, Virginia. Richmond, Virginia: Schnabel Environmental Services

DeStephen RA and Wargo RH (1992) Foundation design in karst terrain. Bull Assoc Eng Geol 29(2): 165–173

Driscoll FG (1987) Groundwater and wells, (2nd ed). St. Paul: Johnson Division

Gathright TM, Henika WS and Sullivan JL (1977) Geology of the Waynesboro East and Waynesboro West quadrangles. Virginia Division of Mineral Resources, Publication 3, Charlottesville, Virginia

Hinkle KR and Sterrett RM (1978) Groundwater resources of Augusta County, Virginia. Planning Bulletin 310, Virginia State Water Control Board, 119 pp

Newton JG (1987) Development of sinkholes resulting from man's activities in the eastern United States. US Geological Survey Circular 968, 41 pp

Sowers GF (1975) Settlement in terrains of well-indurated limestones. Proceedings, analysis and design of building foundations. Bethlehem, Pennsylvania: Lehigh University, 701 pp