PERMEABILITY AND GROUND-WATER RECHARGE IN BLACK HILLS METAMORPHIC ROCKS

Perry H. Rahn
Department of Geology & Geological Engineering
South Dakota School of Mines & Technology
Rapid City, SD 57701
Corresponding author email: perry.rahn@sdsmt.edu

ABSTRACT

Daily precipitation data were collected from April to October, 2011, in an area underlain by Precambrian metamorphic rocks near Hill City, South Dakota. Ground water discharged from a nearby abandoned mine adit from May 20 to June 9 following two days of intense rain. The maximum discharge was 0.437 cfs (0.0124 m^3/s), and the total volume of water that discharged during the 21-day interval was 425,000 ft^3 (12,040 m^3). The onset of discharge lagged about 12 hours following 2.15 inches (5.46 cm) of rain on May 20.

The recharge area serving the mine adit is approximately 26.4 acres (10.7 ha). The precipitation during the 21-day interval affecting the mine discharge was 5.07 inches (12.9 cm). This is equivalent to a volume of water falling on the recharge area of 486,000 ft^3 (13,760 m^3), slightly more than the volume of water discharged from the mine adit during this period. Because nearly all the rain recharged the ground water, and because precipitation infiltrated the metamorphic rocks and recharged the water table within 12 hours, the metamorphic rocks demonstrate considerable permeability at shallow depths. This conclusion is supported by hydrogeologic studies of metamorphic rocks at other places in the Black Hills, such as a shallow ground-water contaminant plume at Nemo. The abundant base flow in streams draining metamorphic rocks also indicates shallow metamorphic rocks can store meteoric water for subsequent release to streams.

Data from this study site, supplemented by published permeability data, indicate the hydraulic conductivity of metamorphic rocks varies from approximately 1 m/d near the surface to 10^{-4} m/d at 1 km depth. A general formula relating this exponential decrease in hydraulic conductivity with depth was determined.

The permeable nature of the near-surface metamorphic rocks has practical ramifications. For instance, a water well that is open over the upper 100 ft (30.5 m) of saturated near-surface metamorphic rocks would probably have a greater specific capacity than if the well were drilled much deeper. The permeable nature of near-surface metamorphic rocks also helps explain the rapid transport of bacteria from onsite wastewater systems.

Keywords

Black Hills, ground water, permeability, recharge

INTRODUCTION

The water table in the Precambrian terrain in the Black Hills is generally shallow, rarely more than 100 ft (30.5 m) depth. Typically the water table is connected to perennial streams, and slopes gently upward under the surrounding hills.

The permeability of the Precambrian metamorphic rocks is low compared to aquifers in the sedimentary rocks such as the Madison Limestone, the Minnelusa Formation, and the Inyan Kara Group. [Note: while the permeability of metamorphic rocks depends to some degree on the rock type, for simplification this paper considers the metamorphic rocks a single unit.] Well yields in Precambrian rocks for 561 wells were found to have a median yield of 10 gpm (37.9 l/min) (Carter et al. 2002), much lower than median values for major aquifers. Assuming a 100 ft saturated thickness for these wells, I estimate that the median specific capacity would be at least 0.1 gpm/ft (1.82 m^3/d per m). From a conversion table (from USBR, 1995) the median transmissivity would be approximately 30 ft^2/day (2.8 m^2/d), and the hydraulic conductivity would be approximately 0.3 ft/d (0.091 m/d).

Few values of the hydraulic conductivity of metamorphic rocks in the Black Hills have been published. A pumping test of a 423 ft (129 m) well in slate northwest of Hill City yielded a specific capacity of 0.0086 gpm/ft (0.154 m^3/d per m) (Rahn 1994). The USBR (1995) conversion table yields a transmissivity of 2.5 ft^2/day (0.25 m^2/d) and a hydraulic conductivity of 0.025 ft/day (0.008 m/d). The specific capacity data for ten shallow water wells in metamorphic rocks were studied near Silver City (Aurand, pers. comm. 2011). She found an average transmissivity of 75 ft^2/day (7.0 m^2/d). With an aquifer thickness of 50 ft (15.2 m), the hydraulic conductivity would be approximately 1.5 ft/day (0.45 m/d).

The permeability of metamorphic rocks generally decreases with depth (Davis and DeWeist 1966). Murdoch et al. (2011) studied the permeability of Black Hills metamorphic rocks in the former Homestake Mine area. Here the Precambrian rocks are predominantly phyllite and schist. Homestake Mine is considered a "dry" mine, and the overall low permeability of the rocks is demonstrated by Whitewood Creek, which crosses over the mine workings yet loses very little water despite the fact that the mine was dewatered to approximately 2.4 km depth during years 1980 to the present, although some mine flooding occurred when the dewatering pumps were turned off from years 2003 to 2008. The overall hydraulic conductivity is low, and is largely dependent on fractures. The rocks are increasingly less permeable with depth due to increasing lithostatic stress. The hydraulic conductivity values utilized by Murdoch et al. (2011) range from approximately 10^{-7} m/sec (8.6 X 10^{-3} m/d) near the surface, decreasing to 10^{-8} m/sec (8.6 X 10^{-4} m/d) at 100 m depth, further decreasing to 1.8 X 10^{-9} m/sec (1.6 X 10^{-4} m/d) at 1 km depth, and ultimately decreasing to 1.5 X 10^{-9} m/sec (1.3 X 10^{-4} m/d) at 2 km depth.

Rahn and Gries (1973) noted that major streams such as Spring Creek and Boxelder Creek are perennial in the low permeability Precambrian core of the Black Hills but normally lose all their flow upon encountering the permeable sedimentary rocks surrounding the Precambrian core. Interestingly, despite the overall low permeability of the Precambrian rocks, large streams draining this terrain typically have a fairly high base flow. For example, Carter and Driscoll (2001, Table 2) reported the base flow for streams in crystalline core basins, including Boxelder, Elk, and Bear Butte creeks, averages approximately 0.339 cfs per square mile (0.0037 m^3/s per km^2), equivalent to an annual runoff from base flow of 4.59 inches (11.7 cm) over the entire basin. To some degree, surficial deposits in these basins undoubtedly contribute to this base flow; for example, a large spring supplying Mt. Rushmore National Memorial occurs where surficial deposits (talus) and weathered schist overlie granite (Rahn 1990). The high discharge of base flow in the crystalline core basins indicates that abundant ground-water recharge occurs in the metamorphic rocks despite their overall low permeability.

Precambrian metamorphic rocks at Nemo were found to readily transmit contaminants (Rahn and Johnson 2002). A surface disposal pit containing ethylene dibromide at Nemo generated a contaminant plume that migrated along the foliation approximately 1 km during 20 years. A major transmissivity tensor was found to be 0.73 m^2/d; therefore, if the saturated thickness is 10 m, the hydraulic conductivity would be 0.073 m/d.

From the above discussion, there seems to be conflicting data concerning the permeability of metamorphic rocks. They have very low permeability at depths. Yet they have high permeability at shallow depths, and hence they are able to transmit contaminants and supply abundant base flow to streams.

HYDROGEOLOGIC SETTING

At this study area, there is an opportunity to determine the permeability of near-surface metamorphic rocks by examining the precipitation, infiltration, ground-water recharge, and the response time of ground water discharging from an abandoned gold mine adit. Despite many abandoned mine adits throughout the Precambrian terrain, most are dry and the hydrogeology of those that occasionally discharge water have rarely been studied.

The study area is 7 miles (11 km) northwest of Hill City, on land owned by the author. Figure 1 shows part of Section 32, T 1 N, R 4 E. The bedrock in Section 32 is primarily phyllite, interpreted as a metamorphosed tuff (Redden and DeWitt 2008).

Figure 1 shows that the topography above the mine adit is a gently sloping hill, with approximately 200 ft (61 m) local relief. The mine adit probably does not extend more than 100 ft (30.5 m). No water wells are within this part of Section 32; nevertheless, the water table is presumably close to the mine adit entrance and slopes gently under the hill to the southwest. The surrounding hills are forest covered, with about 10% of the area consisting of outcrops and 90% of the area covered by colluvium, duff, and pine needles.

Precipitation at Mt. Rushmore is assumed to be typical of the study area. The data (www.wrcc.dri.edu) indicate the average annual precipitation is 21.68 inches (55.07 cm). The years 2001 through 2008 were below normal, and the years 2009 through 2011 were above normal. No discharge from the mine adit was observed from 2001 through 2008, but discharge occurred in years 2009 through 2011.

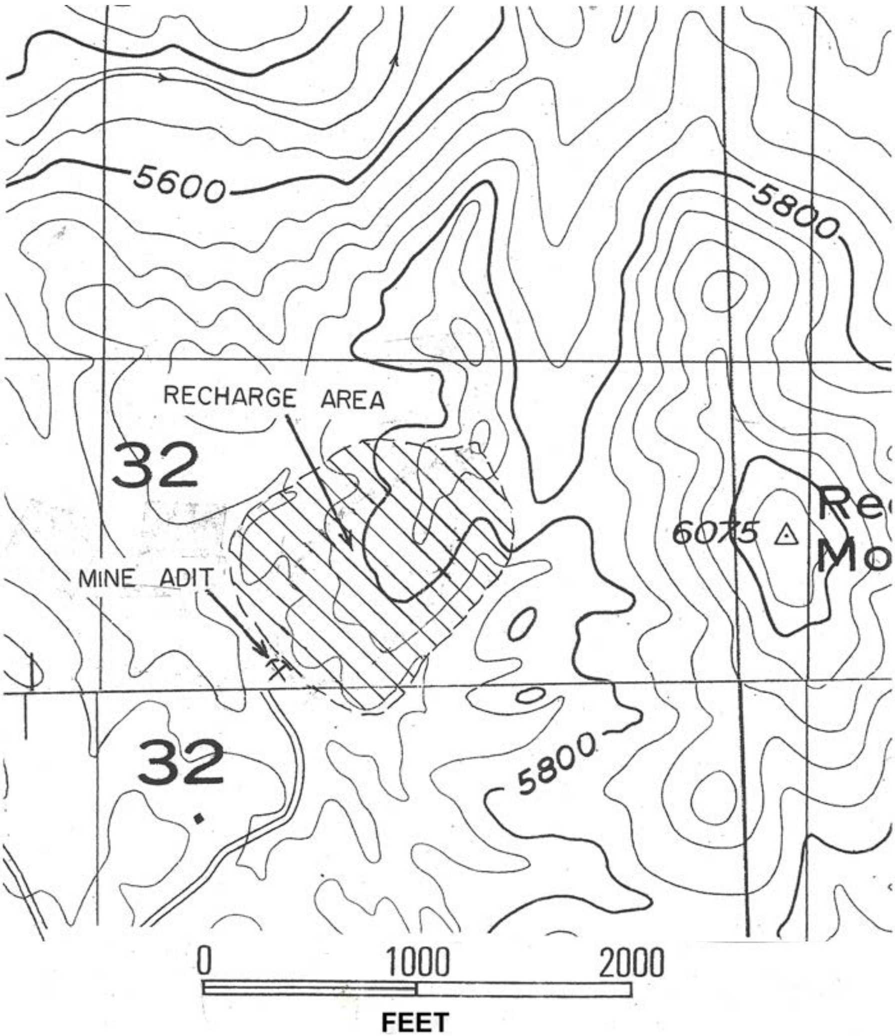

Figure 1. Part of the USGS Rochford 7.5 minute topographic quadrangle map showing mine adit location and approximate recharge area. Contour interval 40 ft.

PRECIPITATION AND MINE DISCHARGE DATA

Precipitation was measured from April through October, 2011, at a location about 0.5 miles (0.8 km) north of the mine adit. Figure 2 is a histogram of the daily precipitation during the time when discharge occurred at the mine adit.

Figure 1 shows the recharge area believed to supply water to the mine. Typically there is no water discharging from the mine. In fact, no discharge was observed from the mine or in any of the adjacent gullies within 0.5 miles (0.8 km) of the mine adit during 7 years of below normal precipitation (2003-2007).

In early May, 2011, a 90-degree V-notch weir was constructed at the mine adit. The discharge was determined from the depth of water in the weir (Figure 3). Water discharged from the mine adit from May 20 to June 9 following two days of intense rain. The onset of discharge lagged only about 12 hours following 2.15 inches (5.46 cm) of rain on May 20. This is a remarkably short response time. The maximum discharge (11 days later) was 0.437 cfs (0.0124 m^3/s), and the total volume of water that discharged during the 21-day interval was 425,000 ft^3 (12,040 m^3).

The recharge area serving the mine adit is approximately 26.4 acres (10.7 ha). The total precipitation during the 21-day interval when there was mine discharge was 5.07 inches (12.88 cm). This is equivalent to a volume of water falling on the recharge area of approximately 486,000 ft^3(13,760 m^3), slightly above the total volume of mine adit discharge during this period.

Figure 4 is a conceptual model showing infiltration and ground water recharge at the study area. From Figure 2, the short response time between the heavy rain event on May 20 and the onset of discharge from the mine is apparent. It is possible that the water discharging from the mine adit is the same water that had just fallen as rain. But more likely the infiltrating rain increased the elevation of the water table in the recharge area and the resulting increased hydrostatic pressure forced the (normally near-stagnant) ground water within the rock fractures into the mine adit. This study shows that rain infiltrates from the land surface to the water table in approximately 12 hours, although some infiltrating rain may traverse the entire zone of aeration and continue to the mine adit discharge point in approximately 12 hours.

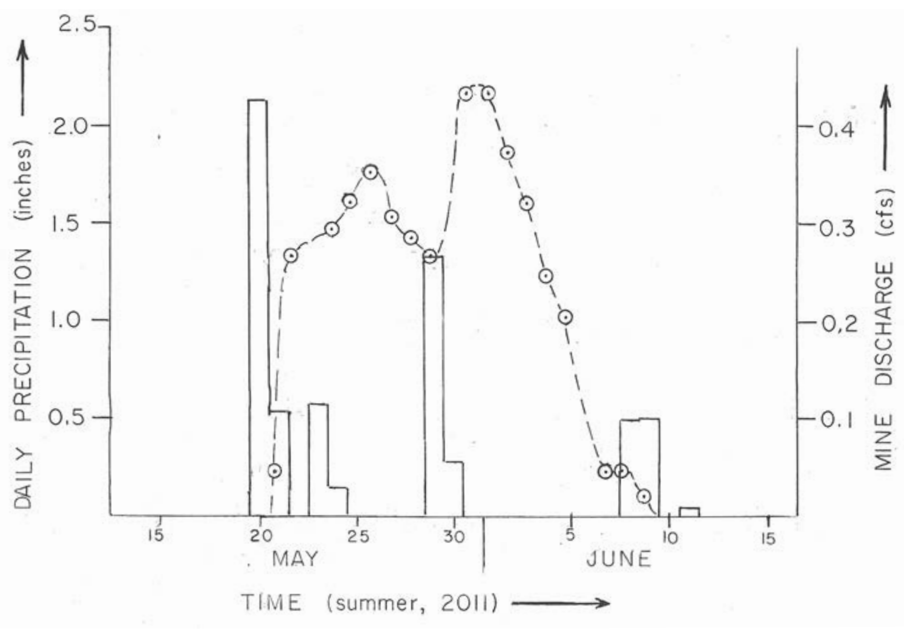

Figure 2. Histogram showing daily precipitation from May 13 to June 16 and mine adit discharge (circles) from May 20 to June 9, 2011.

Figure 3. Photograph of weir used to measure mine adit discharge. The discharge at this time (June 2, 2011) was 0.37 cfs (0.0105 m^3/s).

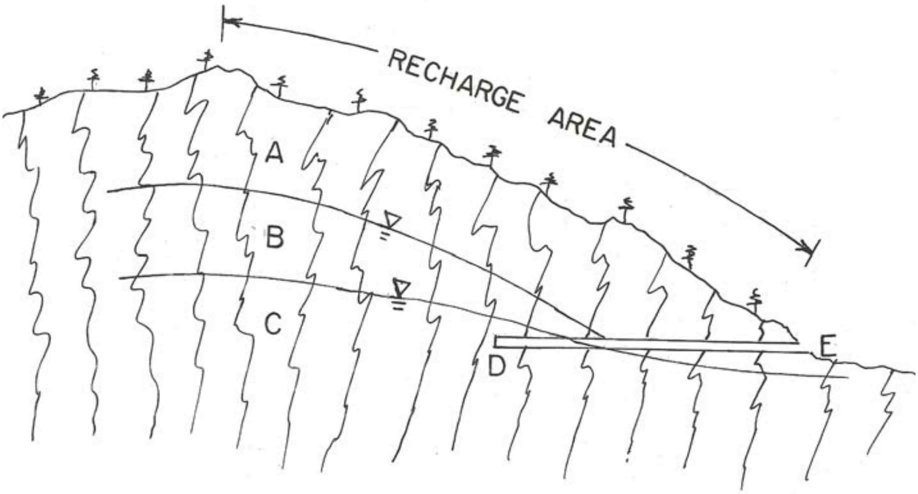

Figure 4. Conceptual model showing response of mine adit discharge to precipitation:
A = Zone of aeration ("vadose zone"). Infiltration of heavy precipitation causes increased water in the vadose zone, resulting in a rise of the water table under the recharge area.
B = Zone of seasonal water table fluctuation.
C = Zone of saturation ("phreatic zone"). Recharge to ground water increases the elevation of the water table, resulting in increased pressure within the phreatic zone.
D = Ground water conditions during low water table showing nearly stagnant pool of ground water in back end of mine adit.
E = Discharge from mine adit occurs during high water table conditions.

PERMEABILITY FORMULA

An estimate of the hydraulic conductivity at this study site can be made from the travel time (12 hours) that it takes the infiltrating rain water to reach the water table at approximately 50 m depth. The velocity of water moving downward in the vadose zone is 100 m/d. The Darcy velocity, aka "specific discharge" (Freeze and Cherry 1979), is the true water velocity multiplied by the effective porosity, here estimated at 1%. The hydraulic conductivity (K) is the Darcy velocity divided by the hydraulic gradient (in this case, 50 m head loss over 50 m travel distance). Thus the hydraulic conductivity is approximately 1 m/d.

From the earlier discussion in this paper, the hydraulic conductivity of Black Hills metamorphic rocks decreases with depth over approximately four orders of magnitude. Data from the study site and the references described above (Rahn 1994; Aurand 2012; Murdoch et al. 2011, Rahn and Johnson 2002) yield the following general formula for hydraulic conductivity (K, meters per day) as related to depth (D, meters):

$$K = 500\ D^{-2.3}.$$

PRACTICAL CONSIDERATIONS

Hydrogeologic information learned in this study is useful in other practical considerations. For example, water wells drilled in the metamorphic terrain produce most water from cracks. If saturated rock is encountered and the well can only produce a marginal yield for a domestic supply, well drillers, once set up for drilling, tend to continue drilling deeper hoping to hit a very productive crack. Due to the exponential decrease in permeability with depth, however, if a driller encounters only a marginal yield of ground water (~1 gpm (5.45 m^3/d)) in the first 100 ft (30.5 m) of the phreatic zone, it would be wiser to move to a different location and drill another 100 ft (30.5 m) well rather than continue drilling where initially set up.

Another practical consideration involves onsite wastewater systems. The drain field for a septic tank, located within a few feet of the surface, relies on gravity to disperse the wastewater. In the metamorphic terrain, bedrock would most likely exist just below the drain field. The rapid infiltration and recharge in near-surface metamorphic rocks as shown in this study helps explain the rapid movement of wastewater and why sickness from onsite wastewater systems has been documented only in the metamorphic terrain in the Black Hills (Rahn 2011).

CONCLUSION

This study shows that there is a rapid infiltration of rain and flow of water through the unsaturated zone down to the water table, resulting in abundant discharge from the mine adit. Practically all the precipitation from May 20 to June 9 recharged ground water.

This rapid transmission of water seems to contradict the overall low hydraulic conductivity of metamorphic rocks. A most likely explanation for this apparent contradiction is because of the weathered nature of the metamorphic rocks near the surface. This area was never glaciated, and the residual soils and outcrops of weathered phyllite have abundant open fractures that easily accept all the precipitation, even in a moderate downpour. The water moves quickly through the zone of aeration, and, once the infiltrating water reaches the phreatic zone, the water table rises dramatically. The additional hydrostatic pressure in this phreatic zone then forces ground water through the weathered rocks.

The high permeability near the surface explains the rapid movement of contaminants in near-surface metamorphic rocks, and why streams in the metamorphic terrain have a relatively high base flow.

At depths greater than approximately 100 m, the metamorphic rocks are practically unweathered. Any fracture would be nearly squeezed shut due to the great lithostatic stress, and therefore metamorphic rocks below this depth would barely transmit ground water at all.

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