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HYDROLOGY OF THE ABANDONED UNDERGROUND CORNING COAL MINE, PERRY COUNTY, OHIO[1]

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Abstract. The Corning mine complex, a suite of abandoned partially flooded room-and-pillar mines in Perry County, Ohio, contributes nearly 100% of the annual acidity load to upper Sunday Creek. Discharge, which issues from a single hole, averages 73 liters/s (2.6 cfs); acidity load averages 590 kg/day; and metal (Fe, Al and Mn) loads average 260, 2 and 13 kg/day respectively. The discharge is a high priority for remediation, but is not well suited for treatment by passive systems. Source-control strategies require knowing recharge sources, flow paths, underground pool interconnections, and mine residence times. This paper describes the development of both conceptual and quantitative models of the mine system, based on mine and soil water budgets, an equivalent-porous-medium numerical model, a barometric efficiency model, and a chemical mixing model. The models were based on monthly water sampling, continuous mine-pool and discharge hydrographs, borehole logs, meteorological data and mine maps.

The recharge rate is 20 cm/yr (13% of precipitation). Stream capture contributes 13% of the mine's annual recharge, with diffuse recharge accounting for 87%. During intense rainfall events, however, 50% of recharge can occur by stream capture. Mine storage varies seasonally, depending on recharge, which in turn depends on not just precipitation but also evapotranspirative demand and soil-moisture storage. Consequently, mine storage and discharge are highest in the late spring and lowest in the late summer and early fall. The mine aquifer is a gently dipping grid of rooms and tunnels that collectively provide hydraulic resistance to flow, and it does not form a single hydrostatic pool. Assuming that mines are fully interconnected and that water is well mixed yields a residence time of 5.1 years. However, barometric pressure response shows that the eastern 40% of the mine is separate and partially confined, with exceptionally poor water quality. The eastern portion accounts for only 10% of the flow, but contributes 50% of the chemical load. Excluding the weakly-connected eastern 40%, residence time is 3.9 years. Barometric responses of heads in various parts of the mine show unconfined behavior, confined behavior, or "displacement" behavior, in which heads increase with barometric pressure.

Additional Key Words: barometric efficiency, storativity, beach location

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Introduction

The Corning discharge (Fig. 1) is located along upper Sunday Creek near Corning, Ohio (Fig. 2), and was caused by drilling into an abandoned underground mine complex in the early 1970's to release water from the mine to facilitate up-dip surface mining. The hole is 15m deep, and currently 1m in diameter. The site drains a large underground room-and-pillar coal mine complex in the Middle Kittanning (No.6) Coal, mined 1903-1954, and then abandoned. The coal is 2-5m thick, and the coal sulfur content is 1.4 – 1.7% with 89 - 100% of the total sulfur in the form of pyrite (FeS_2) (Botoman and Stith, 1991). The discharge is one of the two major causes of acid-mine-drainage (AMD) degradation of Sunday Creek (McCament, 2004; Light, 2001), and is considered a high priority for remediation in order to restore the stream to warm-water habitat.

Figure 1. The Corning discharge is one of the two heaviest loaders of acidity and metals to Sunday Creek (in foreground).

Discharge varies by an order of magnitude, but because chemical concentrations are relatively uniform (Table 1), loadings are controlled by discharge and are high and variable (Table 2).

Table 1. Flow (n=19) and chemistry (n=21; n=5 for DO) of Corning discharge (12/00 – 8/03).

Flow regime	Discharge (liters/sec)	pH	Conductivity (uS/cm)	DO (mg/l)
High	150	5.6	1700	3.6
Low	25	4.3	1200	1.9
Average	75	5.3	1400	2.5
Median	66	5.4	1400	2.5

Table 2. Loadings of net acidity and metals into Sunday Creek (kg/day) (12/00 – 8/03; n=18).

Flow regime	Net acidity	Iron	Aluminum	Manganese	Total Metals
High	1300	490	6.5	29	520
Low	140	89	0.5	4.7	94
Average	590	260	1.9	14	280
Median	506	280	1.5	12	290

The purpose of this study was to investigate the hydrologic and geochemical behavior of the Corning mine and discharge in order to design effective remediation. This paper focuses on the hydrologic behavior, and the conclusions provide insight into behavior of other deep-mine discharges in the eastern coal region.

Previous Work

Abandoned underground coal mines degrade streams through acid mine drainage (AMD) loading, and alter the hydrology through collapse of overburden into the mine void and subsequent capture of surface drainage. Remediation is a challenge because every AMD site has unique local geologic and hydrologic conditions (Rose and Cravotta, 1998). Nevertheless, some patterns emerge. Recharge to mines can occur by diffuse flow through overlying strata, by fracture flow, or through surface capture (Moebs and Clar, 1990). When roof supports or coal pillars fail through time, overburden is fractured and may subside into the mine void. As subsidence propagates to the surface, sinkholes or fractures can capture streams and divert surface runoff into the mine as a new source of recharge (Reed and Rauch, 2001).

Abandoned mines that receive recharge from direct surface capture exhibit pseudo-karst behavior, or relatively rapid response to recharge (Pigati, 1997; Stachler, 1997; Light, 2001). Mines without known direct surface capture are recharged mainly by slow groundwater seepage, and discharge responds much more slowly to precipitation events (Shimala, 2000; López and Stoertz, 2001). Surface runoff and recharge are seasonal even with uniform rainfall, because of seasonal soil moisture storage and evapotranspirative demands. Most mines show seasonal variations in discharge, with the highest discharge occurring in the spring months and the lowest during summer when evapotranspiration is highest. Concentrations of acidity and metals vary in response to recharge, and tend to be highest in the spring when stored reaction products are flushed from the mine during high flows (López and Stoertz, 2001).

Most large AMD sources discharge from several underground mines, referred to collectively as a “mine complex” or “mine pool.” A mine pool is a cluster of mines that exhibit close hydraulic connection, such that no barriers, or only barriers with high hydraulic connectivity, exist between individual mines in the complex (Donovan *et al.*, 2000). Mine complexes with high-conductivity barriers have similar hydraulic heads while mine complexes with low-conductivity barriers have variable hydraulic heads (Donovan *et al.*, 2000; Aljoe, 1994).

Distinct acid-producing regions may exist in the pool, usually in the partially or seasonally flooded “beach” area (Greene, 1981; Hazen *et al.*, 2002). By identifying this acid-producing region, remediation may be possible by isolating the region from the atmosphere or the rest of the mine complex.

This paper extends these ideas through monitoring discharge, hydraulic head and water chemistry in a large deep-mine complex. We examine the relative roles of diffuse recharge and stream-capture recharge and the seasonality of these fluxes, the hydraulic connectivity and degree of confinement of different parts of the mine complex, and the relative contributions of different areas to the discharge.

Methods

To identify and quantify the key hydrologic characteristics of the Corning mine complex, we developed water budgets (including soil moisture), a conceptual flow model, a barometric efficiency model, and a chemical mixing model.

Water budgets were made for the year 2002 and for a single event. Inflows included stream capture (R_s) and diffuse recharge through overburden (R_d). Leakage from underlying strata or other mines was assumed negligible. Daily precipitation data were obtained from the Army Corps of Engineers at Tom Jenkins Dam, located approximately 5km to the south. Evapotranspiration (ET) and runoff values were calculated monthly and daily, using the Thornthwaite method (Thornthwaite and Mather, 1957). Temperature data for ET calculations were obtained from Scalia Laboratory at Ohio University. Soil type and moisture storage capacity were obtained from the Soil Survey of Perry County, Ohio (USDA, 1988). Stream captures (Fig. 2) were mapped by Sunday Creek Watershed Group. Areas of mines and captures were calculated using GIS. Recharge was assumed to be 100% of runoff in captured basins after soil moisture storage demands are met. Outflow was assumed to occur only via the Corning discharge (D_c). Diffuse recharge was calculated as a residual ($R_d = D_c - R_s$).

The unconfined or beach location in the mine pool (Fig. 3) was determined by comparing hydraulic heads from five monitoring wells to a 3-D GIS image of the mine. The mine image was developed from an underground mine map (ODNR, 1983) and a coal isopach map (Flint, 1951), which was digitized and converted to a raster grid. The southern extent of the complex is constrained by the Jumbo “fault” (Fig. 2), which is not a true fault in the geologic sense, having no displacement, but is an area where coarse-grained sandstone replaces the Middle Kittanning coal (Flint, 1951). Gridded coal thickness was added to gridded coal-floor elevations (Light, 2001) to develop a coal-seam ceiling. Querying both the coal-seam floor and the coal-seam ceiling layers for water elevations in the mine pool yields the beach extent. Residence time was calculated by dividing the flooded volume of the mine by the average discharge rate for specific time periods, assuming that the pool is completely mixed. The flooded volume of the mine was calculated using GIS, taking into account the average thickness of the coal seam (2.4 m) and a typical coal removal rate (60%).

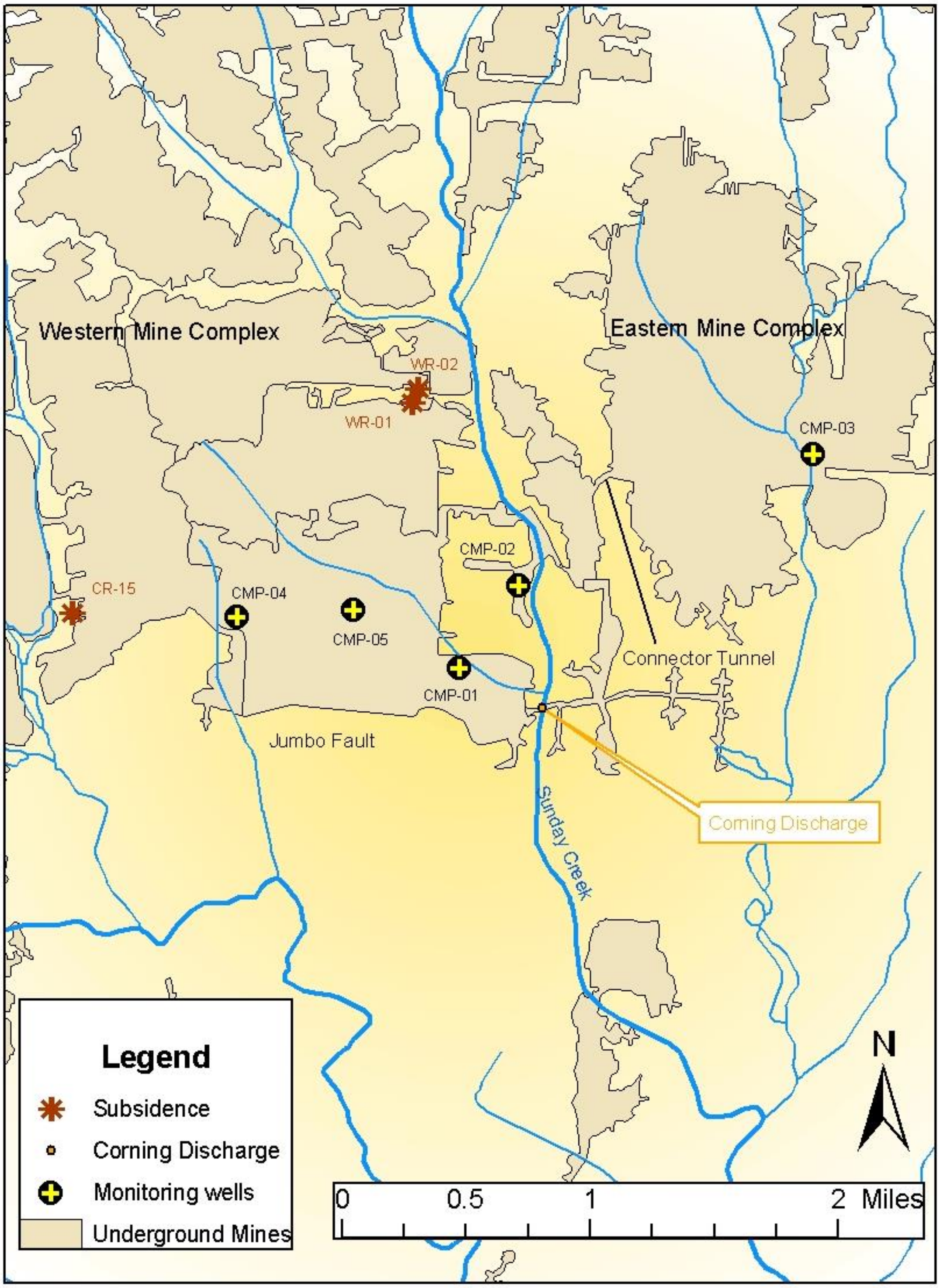

Figure 2. Map of mines (gray) in the Corning complex, showing locations of monitoring wells (yellow circles) and known subsidence captures (blue stars). Mine depth and well positions are projected onto cross section AA’ for Figure 4. (Distance scale is in miles. 1 mile = 1.6 km.)

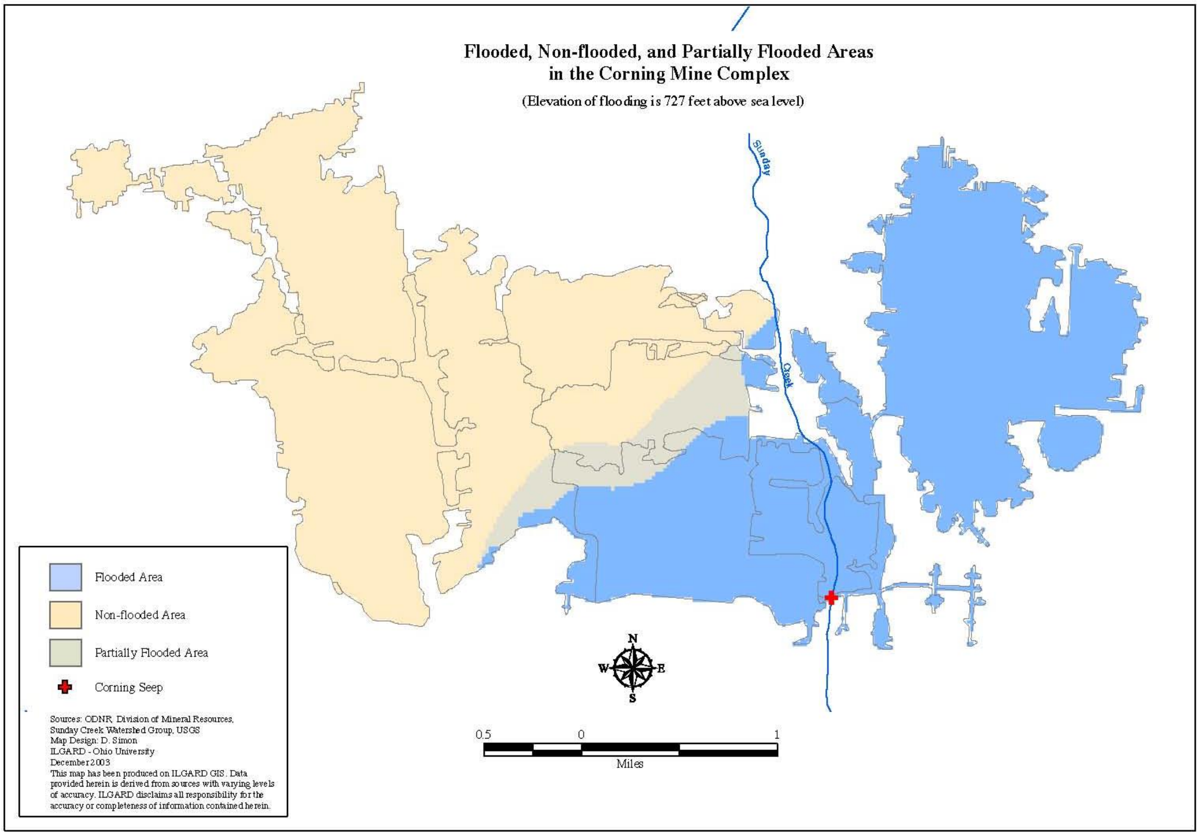

Figure 3. Extent of mine inundation (blue), showing the partially flooded beach (light gray).

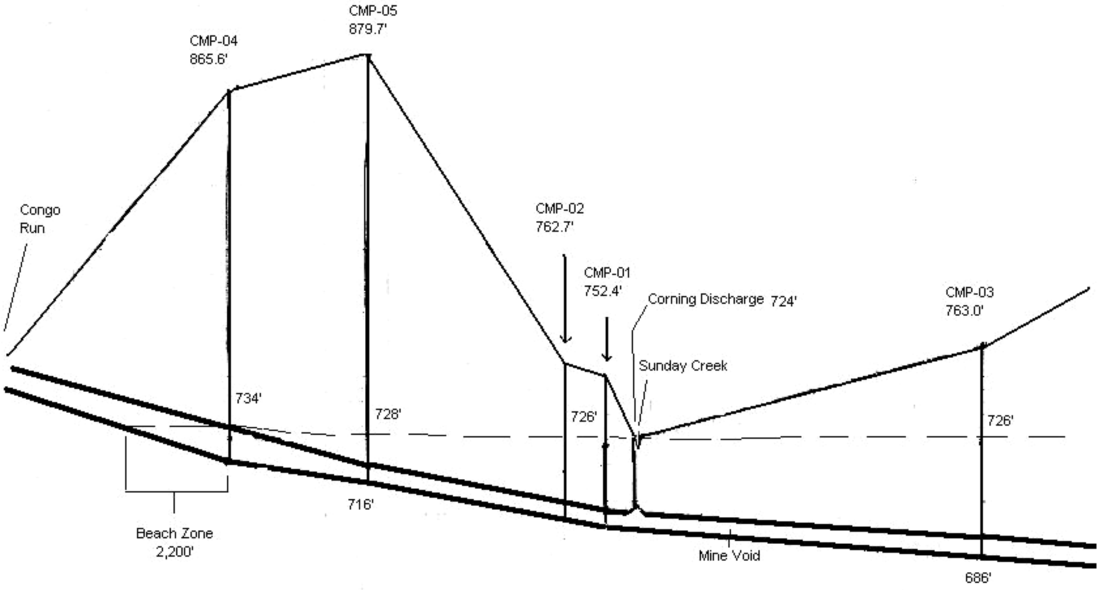

Figure 4. Cross section (AA’ in Figure 2) showing location and elevation of monitoring wells and the extent of the partially saturated, unconfined “beach” zone. (Elevations and distances are in feet. Conversion: 3.28 ft = 1 m.)

For the single-precipitation-event water budget, inflow was assumed equal to change in storage (ΔS) in the mine pool, where storage change was calculated only for the high-storativity unconfined beach area. $\Delta S = S$ (storativity) A (areal extent of beach) Δh (change in head at CMP-04, in the beach) (Fetter 1994). Assuming average coal removal is 50 –70%, a value of 60% was used for storativity. Storage of water in coal pores was considered negligible compared to storage in mine tunnels.

Sunday Creek discharge was measured upstream and downstream of the Corning site, calculating the mine discharge as the difference. Discharge was measured quarterly in 2001 and monthly in 2002 and 2003, using a spin-test calibrated Pygmy meter or Swoffer 2100 electronic flow meter (Rantz, 1982).

Five monitoring wells (Fig. 2) were installed into the flooded portion of the mine complex (Fig. 3). The Ohio Department of Natural Resources Division of Mineral Resources Management drilled and installed the monitoring wells using hollow-stem augers for the unconsolidated materials and air-rotary drilling to mine depth. When the mine void was reached, indicated by lack of resistance, the drill was pushed to resistance into the underclay and then removed. Monitoring wells consisting of 5-cm PVC pipe with a 3-m slotted PVC screen were installed into the mine void. Screens were end-capped to prevent entry of mine-floor materials. A rubber boot (filter pack) was placed just above the coal-mine ceiling. The hollow stem augers were removed, and Bentonite clay pellets were poured into the hole above the boot to create a watertight seal and prevent flow between the mine void and the overburden annular space. Grout was mixed and poured to fill the annular space from the Bentonite seal to the surface. The PVC pipe was cut off just below ground level, capped, and protected with a metal cover set in concrete. All wells were placed in voids except CMP-01, which may have been drilled into a collapsed room or fractured pillar (Table 3). Top-of-casing elevations were determined using a GPS Trimble XT. Over 100 data points were collected and averaged for each reading. All readings were 3D real time WAAS corrected. The GPS unit was checked on the day of the readings against a USGS benchmark and the precision was 0.18 m. The precision of top-of-casing elevations ranges from 0.43 to 0.82 m. For development, wells CMP 01 – 04 were pumped (CMP-05 was bailed) and sampled every 5 minutes until water cleared and was chemically stable with respect to conductivity, pH, and temperature.

Table 3. Monitoring well data.

ID	Drilled	Depth	Void hit
CMP 1	4-22-03	18.3 m	No; cracked pillar; flooded
CMP 2	4-21-03	21.3 m	Yes; flooded
CMP 3	4-23/24-03	25.5 m	Yes; flooded
CMP 4	4-28-03	44.5 m	Yes; partially flooded
CMP 5	4-29-03	51.5 m	Yes; flooded

Water samples were collected monthly at the Corning discharge from December 2000 to August 2003. Water samples were collected monthly at the monitoring wells monthly from May to October 2003. Water samples were initially collected from the monitoring wells using a 1-m PVC single-check-valve bailer (May 2003), purging one well volume. For the remaining samples a Solinst 1-m stainless steel point-source bailer was used. A minimum of one bailer volume was collected and discarded to prevent cross-contamination. Both filtered (0.35-micron) and non-filtered samples were collected from the wells for the first two sampling events. However, since the mine pool is a reduced environment and concentrations of dissolved and total constituents were found to be similar, only non-filtered samples were collected from July 2003 onward. All samples were preserved with 5 ml of HNO_3 except a ferrous/ferric iron sample that was preserved with 5 ml of HCl. A total of 4 samples were collected at each well: two 250-ml clear plastic bottles, one 1-liter cubitainer, and a 150-ml brown plastic bottle for ferrous and ferric iron determination. Sample collection at the Corning discharge varied only in that water was first obtained from the discharge point in a triple-rinsed bucket. Water samples were stored in ice-filled coolers and shipped to the ODNR – Cambridge Laboratory for analysis within 24 hours. Samples were analyzed for acidity, alkalinity, total and dissolved metals (Al, Mn, Fe^{+2}, Fe^{+3}), hardness, specific conductance, major ions (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Cl^{-}, $SO4^{2-}$), solids (TSS, TDS), and pH. Field chemical parameters were measured at the time of sampling, including pH, temperature, specific conductance, acidity, and dissolved oxygen. Measurements were made quickly to avoid oxidation. All instruments were calibrated the morning of use.

In-Situ Troll 4000, 8000, and 9000 stainless steel mini-Troll data-logging probes were installed in monitoring wells and at the Corning discharge, and programmed to collect continuous data at six-hour intervals. The only multi-parameter probe (8000) was at the Corning discharge where pH, temperature, water pressure, and specific conductivity were measured during certain time periods. Water-level measurements were also taken periodically with a Solinst water-level meter at monitoring wells to confirm probe readings.

Results and Discussion

Annual Water Budget

The discharge at Corning is the sole known mine discharge, with a median flow of 66 liters/sec (2.3 cfs; 1000 gpm) in 2002, or 2.1 million m^3 per year. Total drainage area for the three stream captures (CR-15, WR-01 and 02) is 126 ha (312 acres) or 1.3 million m^2. Annual 2002 precipitation was 857 mm and annual moisture surplus (precipitation – evapotranspiration, taking into account soil storage) was 220 mm. Multiplying the captured drainage area by the annual moisture surplus yields 0.3 million m^3 annual subsidence capture. Diffuse recharge, calculated as the residual of the Corning discharge volume minus the captured recharge volume, was 1.8 million m^3. Therefore, stream capture accounted for 16% of the total recharge in 2002, and diffuse flow through overburden accounted for the remaining 84%. By assuming that diffuse recharge is the difference between mine outflow and captured inflow, other inflow sources such as flow across peripheral barriers are assumed negligible. Calculated as an aquifer recharge rate for the entire mined area of 1150 ha (2800 acres), total recharge is equivalent to 19 cm/yr, somewhat less than regional mine recharge rates of 25-38 cm/yr (Stoertz *et al*., 2001).

Single-Event Water Budget

Recharge is assumed to be manifest as a rise in water level in areas of the mine showing unconfined behavior (as discussed later), including CMP-02, CMP-04 and bordering on CMP-05, which shows mixed behavior. In the beach area, storage is within the mine void; outside of the beach area, storage is in fractured overburden. Due to the 0.6-0.7% dip of the strata in this region, the length of the unconfined beach zone is about 700 m, and its area is 270 ha (2.7 million m^2). The storativity value is considered to be equal to a void (mine tunnel) space of 60%. The change in head for beach well CMP-04 after the large November 1-2 precipitation event was 7.3 cm, so storage change was 0.12 million m^3. Outside the mine void, porosity is likely to be extremely variable. Assuming an average porosity of 10% for fractured overburden, an unconfined area (excluding the beach) of 3 km^2, and a head change of 5.5 cm (average of CMP-02, -04 and -05), then the additional storage change is 0.02 million m^3. Total single-event storage change is therefore 0.14 million m^3. The precipitation total for the 2 days was 6.12 cm with a calculated moisture surplus of 4.9 cm. The subsidence-capture recharge from this single precipitation event was thus calculated as 0.06 million m^3 (40% of the total) by multiplying the subsidence capture area by the moisture surplus. The remainder is attributed to diffuse flow through overburden. Both annual and single-event water budgets confirm that subsidence flow is a significant contributor of recharge for the Corning mine. The contribution from subsidence varies seasonally, depending on soil-moisture deficits. In general, the highest instantaneous recharge rates will occur from subsidence captures during large runoff-generating precipitation events.

Residence Time

The flooded mine pool area is 8.2 million m^2 (817 ha), the coal seam averages 2.4 m in thickness, and 40% of the coal remains as pillars. Therefore, the mine water volume is equal to 11.8 million m^3. The annual flow from Corning (December 2001 to November 2002, one water year) was 2.3 million m^3. Assuming complete mixing of mine water, the residence time is calculated as 5.1 years. It is probable, as discussed below, that the entire mine volume is not equally replaced: Water following a preferential flow path will have a shorter residence time; water in relatively stagnant areas will have a longer residence time.

Seasonal recharge, storage and discharge

The Corning discharge hydrograph varies seasonally in response to precipitation and evapotranspiration (Fig. 5). In 2002, the highest flows occurred in late spring and lowest flows in the late fall and winter. Even though summer has ample rainfall, evapotranspiration and soil moisture replenishment result in low summer recharge. In general, the discharge is highest following periods when the ground is thawed, precipitation is high *and* evapotranspiration is low, as in spring 2002. Evapotranspirative demand creates a soil-moisture deficit, so its effects are not immediately reflected in low recharge rates.

Well hydrographs (Fig. 6) show variation in mean values due to frictional head loss as water flows from the higher-elevation beach area to the discharge, taking a tortuous pathway among pillars and rubble. However, seasonal trends in all wells are similar, reflecting mine recharge. Some hydrographs show superimposed diurnal cycles, attributed to barometric pressure changes (Fig. 7).

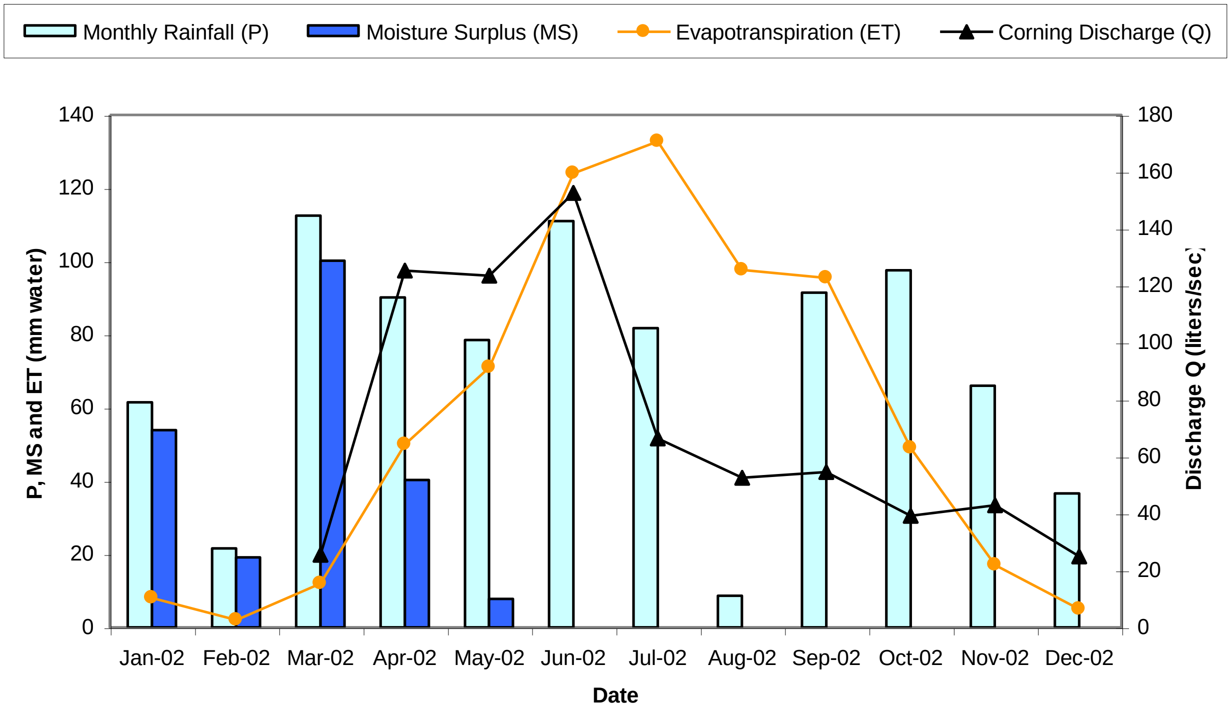

Figure 5. The Corning discharge is controlled by recharge, which depends on both precipitation and evapotranspiration. In summer 2002, the discharge decreases despite precipitation, because rainfall has to first meet soil moisture deficits.

Response to Barometric Pressure

Barometric pressure varies diurnally in response to daily temperature changes that affect air density. Barometric pressure changes affect confined aquifer wellbore levels more than those of unconfined aquifers, depending on the aquifer’s barometric efficiency (Spane, 2002), so the hydrograph sensitivity is a measure of the degree of confinement. (The transducers used in this study are pressure-compensated by an air-vent line, so barometric effects are due only to effects on the aquifer, not on the probe.) Both lateral and vertical bounding by pillars or collapsed roofs, and by distance from the beach zone can cause confinement in a mine aquifer. A negative correlation between water level change and barometric pressure change as observed at CMP-03 is characteristic of a confined aquifer (Freeze and Cherry, 1979) because the wellbore is subject to the full atmospheric pressure while the pressure on the aquifer is not fully transmitted by the overburden.

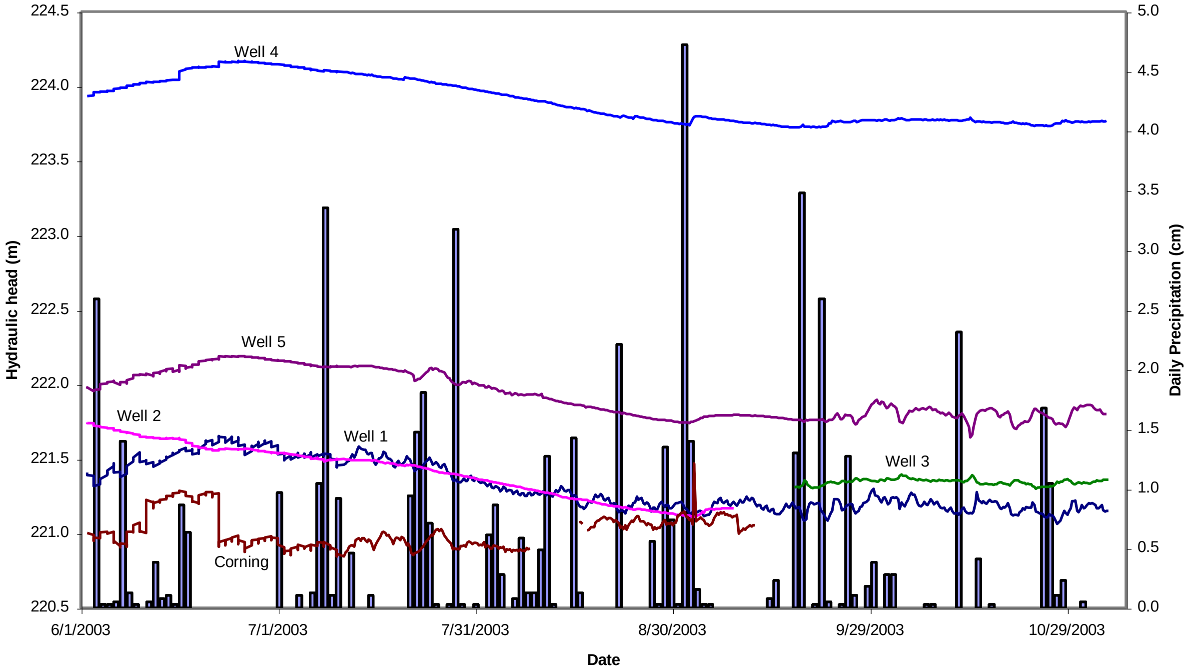

Figure 6. Mine-pool and Corning discharge hydrographs respond to seasonally variable recharge caused by seasonally variable evapotranspirative demand and soil moisture storage.

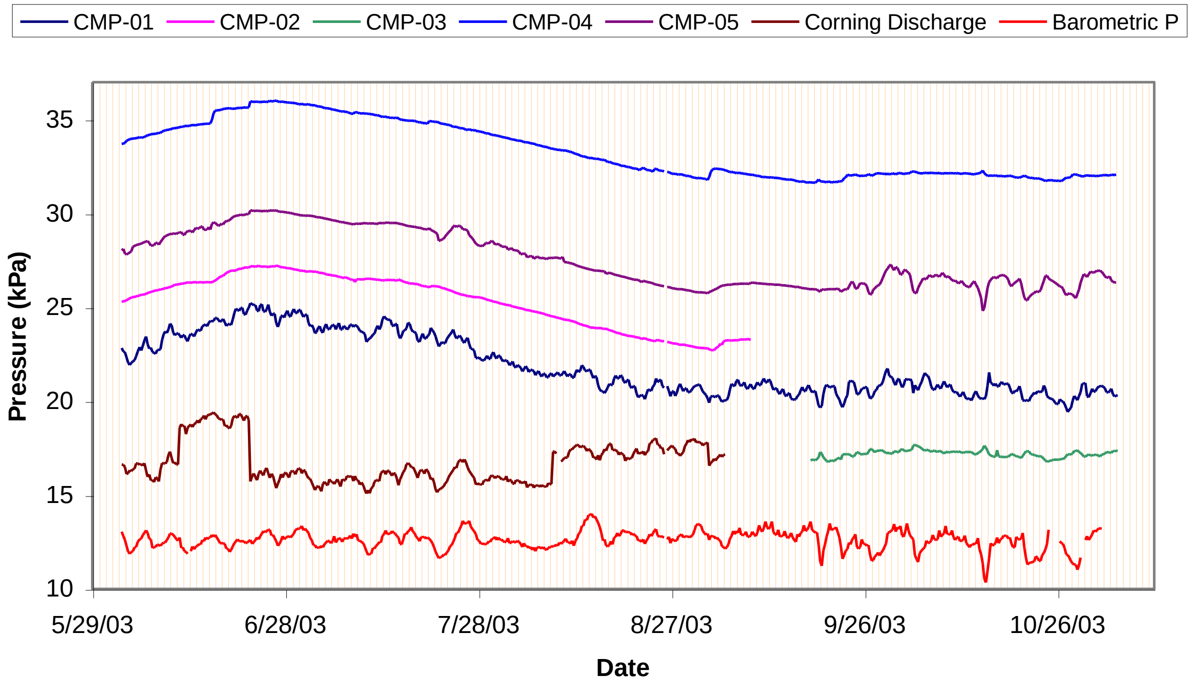

Figure 7. Diurnal variability is a result of barometric pressure. Vertical tan bars correspond to days. (Note! A different offset has been subtracted from each hydrograph for ease of comparison. For true values, see previous figure. Observations are correctly scaled.)

As a consequence, the borehole water level falls as the pressure increases. In unconfined cases, the water table and the wellbore are equally subject to the pressure increase, so the water levels are insensitive to barometric pressure, as seen in CMP-04, CMP-02, and to some extent CMP-05. The degree of confinement of CMP-03 can be quantified as the barometric efficiency BE (Jacob, 1940), which is the negative product of the specific weight of water and the slope of the graph. Well CMP-03 has BE = 0.09 (9%), which is quite low. This low BE could be interpreted either as partial confinement or as highly compressible overburden. However, BE for confined aquifers usually falls in the range 0.2-0.75 (Todd, 1959), suggesting partial confinement. Water may be displaced through the connector tunnel in response to increases in barometric pressure.

Well CMP-01 shows unusual positive correlation of wellbore levels with barometric pressure, which we interpret as “displacement” behavior: the “bottleneck” area where the mine narrows has increased heads due to water squeezed by barometric pressure from the much larger complex, including the eastern complex. The Corning discharge shows the same behavior, tending to support the mechanism of water being squeezed out by pressure applied to a large surface area. The bottleneck geometry is important because air pressure in the wellbore would normally be greater or equal to the pressure transmitted through the overburden to the mine aquifer, but in this case the geometry works as an amplifier. Well CMP-05 shows periodic changes in behavior from unconfined behavior to displacement behavior, for unknown reasons.

The mine complex, in summary, behaves like a groundwater reservoir that is recharged by diffuse flow through overburden and by stream capture (Fig. 8). The complex comprises the unconfined beach area, the weakly confined eastern complex, and the area near the discharge that acts as a bottleneck to flow and exhibits displacement behavior. Other areas display mixed behaviors (e.g., CMP-05; Fig. 7).

Hydraulic Connectivity

Understanding connectivity between mines within the complex is important for *in-situ* treatment that requires mixing nutrients or reagents with the mine-pool water. To determine if the mine pool behaves a single pool or as a series of interconnected pools separated by hydraulically resistive barriers, lag time and attenuation of head response to the 9/1/03 recharge pulse was examined for each well (Fig. 9). (Data are not available for that event for CMP-03.)

The pulse represents 40% quickflow (from subsidence capture) and 60% base flow (diffuse recharge). The hydraulic head at CMP-01 responds in part to water displacement by barometric pressure as discussed earlier. To eliminate that effect, a linear average trend line was used to filter out diurnal changes.

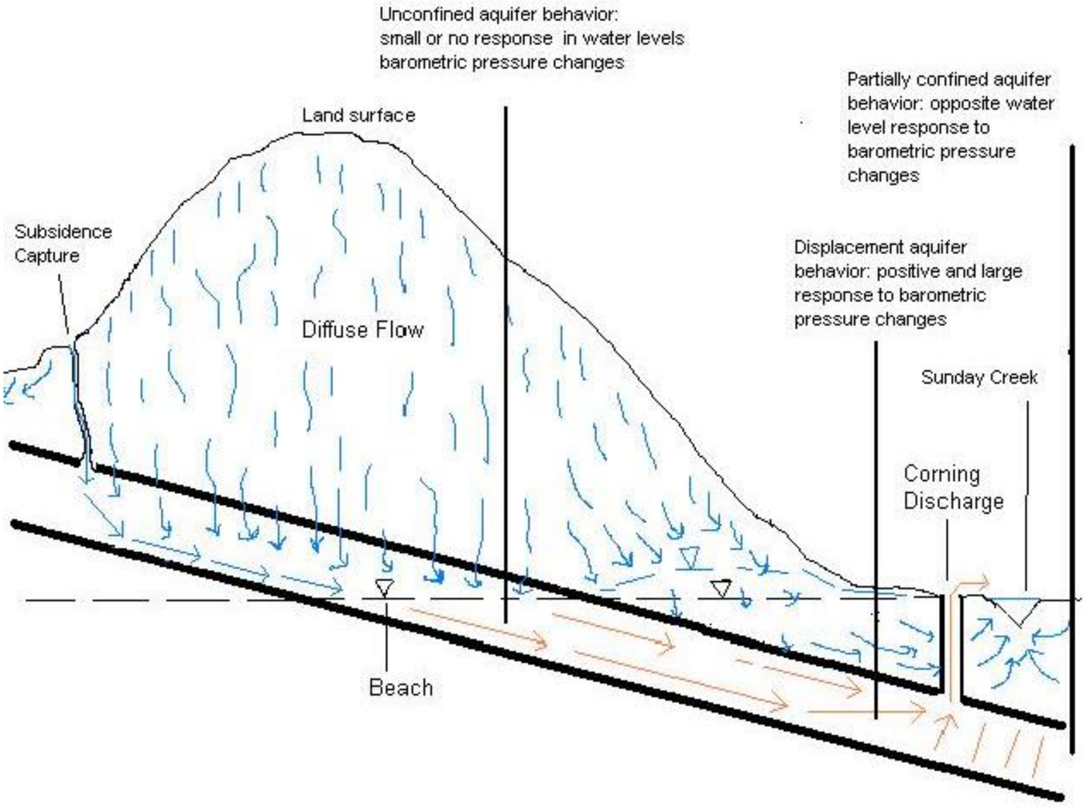

Figure 8. Conceptual model of recharge, discharge and mine-pool confinement.

The time to peak and the head increase show a linear trend that also correlates with proximity to the beach zone. Mine areas that respond rapidly to recharge (e.g., CMP-04) also show the least attenuation of the recharge pulse. Attenuation alone could be due to resaturation of the overlying rock, but the long lag time indicates presence of hydraulically resistive materials, and indicates that the mine complex does not behave as a well-connected pool.

The eastern mine complex, represented by CMP-03, is connected only by a single connector tunnel (Fig. 2) that is shown as sealed on abandoned underground mine maps. Sealing could create a separate inactive complex, but the seal may not be intact after 50(+) years since mining ceased. The water level at CMP-03 indicates inundation of the entire eastern mine complex. Water is suspected to exit the mine complex via the connector tunnel.

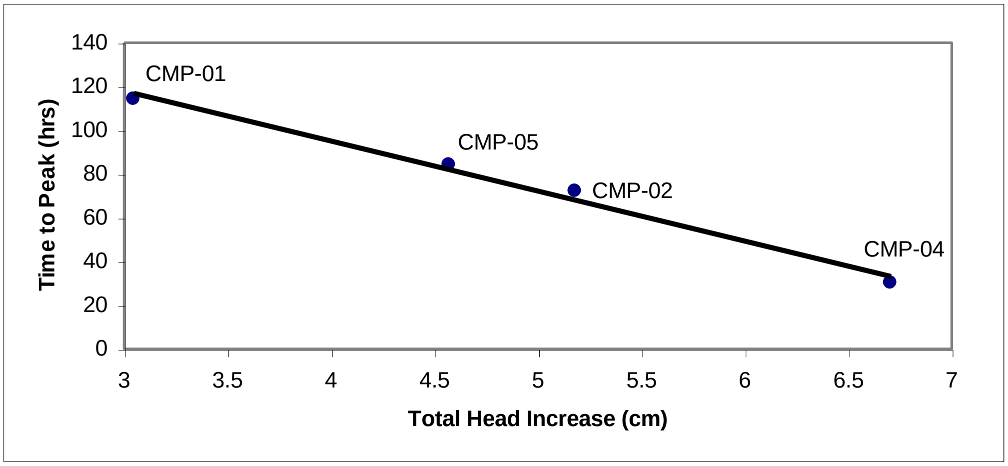

Figure 9. Lag time and attenuation of the 9/1/03 recharge pulse in different mine areas.

Geochemistry

Water quality in the mine discharge appears to be controlled in part by dilution; that is, high flows dilute dissolved substances (e.g., acidity, sulfate and iron), and low flows concentrate them (Fig. 10). Dilution is consistent with preferential flow paths and shorter residence times. In contrast, other mines in the region (López and Stoertz, 2001) exhibit relatively uniform discharge water quality, suggesting that the mine water equilibrates rapidly or that the pool is well mixed: Evidence of dilution is slight in these other mines.

Dissolved oxygen (DO) in wells (Table 4) indicates a reduced environment relative to surface waters: Average DO ranges from 0.6 to 2.8 mg/l (extremes 0.2 to 4.3), with the highest DO at CMP-04 in the beach area. The lowest DO was measured at CMP-01, which may be hydraulically isolated. Average AMD reaction product concentrations vary significantly among wells. The pH range is 5.4-6.6; the specific conductance range is 860 – 5,800 uS/cm. All wells except CMP-01 were net-acidic during most sampling events. CMP-01 was net-alkaline three out of four sampling events. The net-alkaline nature of CMP-01 may be due to microbial consumption of O_2 creating a reducing environment where iron and sulfur are being precipitated (Harrington, 2003). H_2S is an expected by-product of microbial activity, and high levels of H_2S gas at this well are apparent as a strong rotten-egg odor. CMP-01 also has the lowest sulfate concentrations. Further supporting the microbial activity hypothesis, a black amorphous mineral floc, possibly FeS, is seen in CMP-01 water. In contrast, CMP-03 water is severely degraded, with high concentrations of acidity, sulfate, and iron.

Table 4. Average water chemistry in the Corning Mine, May - Sept., 2003.

Site	pH	S.C.	DO	Acid.	Alk.	Net Acid.	Al	SO4	Fe tot	Fe+2	Mn	Ca	Mg	K	Na	Cl
		uS/cm	mg/l total					mg/l dissolved								
CMP-01	6.6	1000	0.6	48	249	-201	0.99	293	17	14	1.3	115	34	5.0	50	31
CMP-02	5.6	1400	2.3	138	43	95	1.01	749	46	41	18.2	98	85	5.3	34	13
CMP-03	5.8	5800	2	420	129	291	0.30	2517	257	252	3.0	324	119	20.4	857	142
CMP-04	5.5	860	2.8	59	25	34	0.88	354	0	0	1.0	69	23	3.5	25	27
CMP-05	5.4	1200	2.1	83	21	62	0.57	537	24	10	1.3	65	13	4.6	126	13
Discharge	5.2	1300	2.5	113	20	93	0.25	586	37	36	2.0	85	28	5.4	119	25

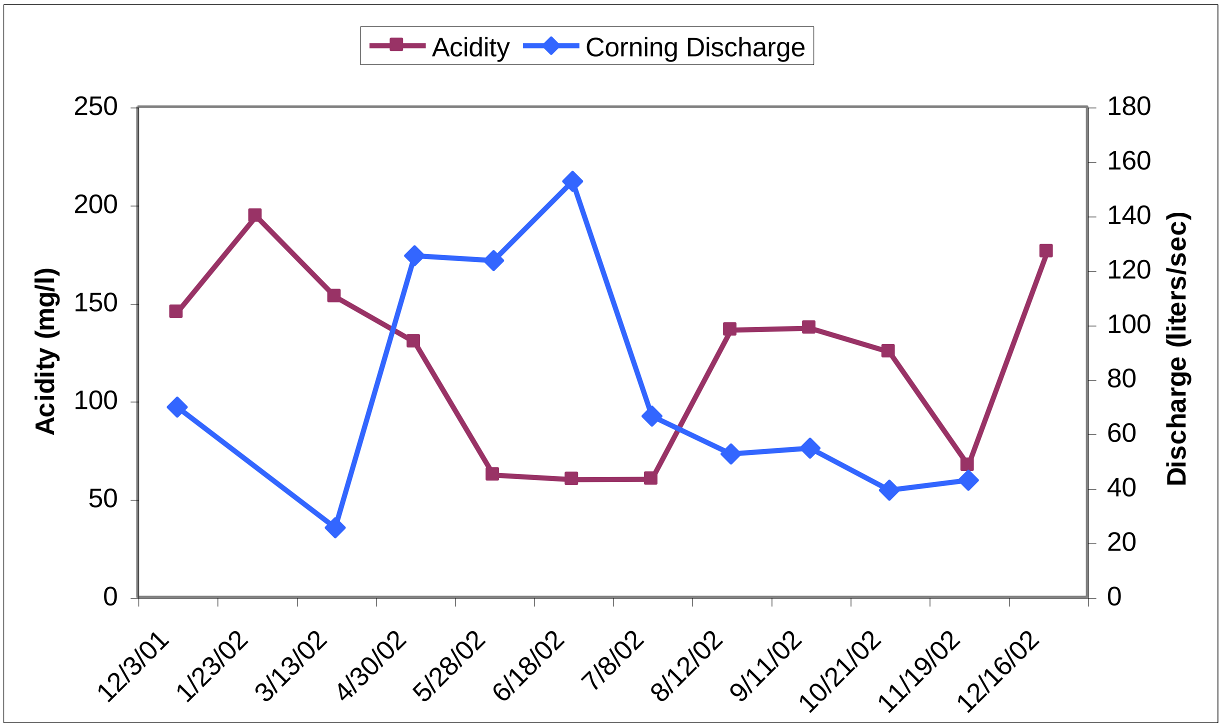

Figure 10. Chemical concentrations at the Corning discharge are mainly controlled by dilution: lower at high discharge and higher at low discharge.

Excluding CMP-01, which is alkaline and probably partly isolated, acidity and sulfate show an approximately linear gradient, consistent with mixing of waters from the eastern and western end members in the discharge (Fig. 11). If mixing of eastern and western waters occurs, a conservative solute can be used to quantify the relative contributions of the two areas to the discharge. Chloride was used in the following analysis. Cl^- concentrations averaged from 6/22/03, 7/20/03 and 8/24/03 were used in mass-conservation equations for water and for Cl^-, assuming that Corning discharge water ($[Cl^-]$ = 24.5 mg/l) is a mixture of CMP-03 water ($[Cl^-]$ = 143 mg/l) and main complex water represented by averaging water from CMP-02 and CMP-05 ($[Cl^-]$ = 13.5 mg/l). Accordingly, the eastern complex contributes 9% of the flow at Corning. The ratio of acidity load from the eastern complex (242 kg/day) to the load at Corning (725 kg/day), based on averaged acidity values measured 5/28, 6/22, 7/20, 8/24 and 9/23/03, is 0.33. The eastern complex contributes 9% of the flow but 33% of the load at Corning discharge.

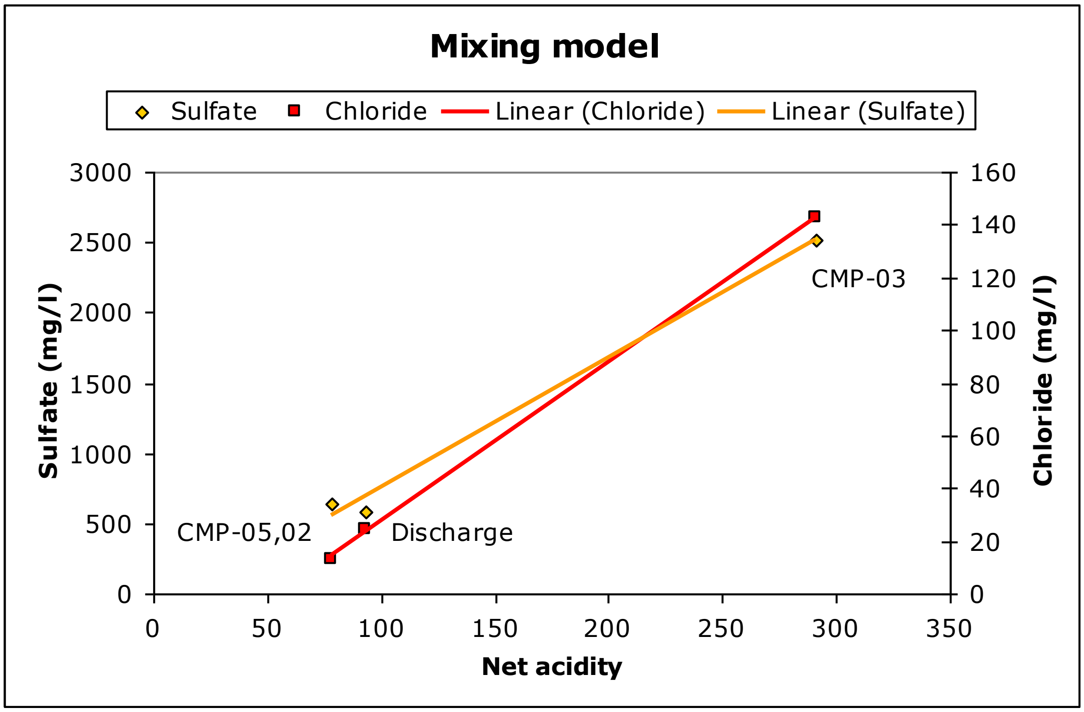

Figure 11. Concentrations of relatively conservative species (average of all sampling dates) show a linear relationship consistent with a mixing model. The western complex is represented by averaging CMP-02 and CMP-05 waters.

The observation that the eastern complex contributes only 9% of the Corning discharge (or 10% of the discharge attributed to diffuse recharge; that is, excluding stream capture), implies that the recharge rate to the eastern complex is lower, given that the area of the eastern complex is 35% of the total area. Calculated diffuse recharge rates are 11 cm/yr for the main complex and 3.1 cm/yr for the eastern complex. The lower recharge is consistent with thicker overburden in the eastern complex (Fig. 12).

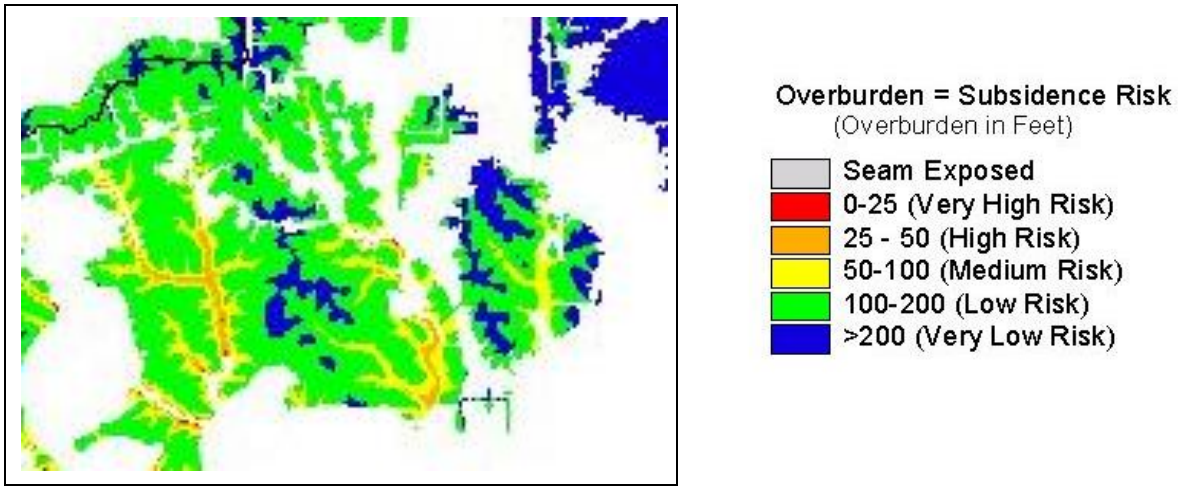

Figure 12. Average overburden thickness is greater in the eastern complex than the western complex, implying lower diffuse recharge rates to the eastern complex.

The high chemical loading from the eastern complex is interesting, because it is widely believed that complete inundation prevents acidity generation. Despite inundation, dissolved oxygen in the eastern mine complex appears sufficient to support pyrite oxidation (Table 4). Column studies found pyrite oxidation rates to be independent of oxygen partial pressures down to 1% of total pressure (Hammack and Watzlaf, 1990). At 12-17ºC (the temperature range measured in CMP-03), full oxygenation is ~10 mg/l, so pyrite oxidation can occur down to 1% of that, or at DO as low as 0.1 mg/l. A possible aeration mechanism is an old shaft located 300m south of CMP-03. This shaft was a large square opening with stairs in it, open until the 1980's when Sunday Creek Coal Co. filled it with earth for safety. Comparing mine areas with loads, the acidity load from the eastern complex is proportional to area: The load is 33% of the total and the area is 35% of the total, even though flows are not proportional to area. If this finding is not simply fortuitous, it suggests that chemical equilibrium is not the dominant mechanism as observed in other mines (López and Stoertz, 2001).

Conclusions

This paper summarizes of the study of a large, 1200-hectare deep mine complex that is one of two principal sources of acidity and metals loading to Sunday Creek, Ohio. Acidity loading rates are high, averaging 590 kg/day, so the discharge is a high priority for remediation. The findings provide insights into mine recharge and discharge mechanisms, transient behavior, and hydraulic interconnection among individual mines or areas within the large complex. These insights are needed for designing a remediation strategy.

Recharge occurs mainly by diffuse flow through the overburden (84% annually, assuming peripheral inflow is negligible), but also by capture of 126 ha of surface streams into subsided overburden (16% of annual recharge). During heavy rain, stream capture is more important: 40% of the mine recharge was derived from capture during one high-rainfall event.

Recharge is highly seasonal, even though precipitation is evenly distributed through the year. Recharge is highest in the late spring, following periods when the ground is thawed, precipitation is high *and* evapotranspiration is low. A lag time between evapotranspirative demand and decreased discharge is caused by creation of a soil-moisture deficit. Assuming complete mixing of the pool, residence time of mine water is about 5 years. However, residence times may be much shorter in some areas and much longer in others. Overall, however, flow in the western part of the mine moves southeast down-dip toward the discharge point, and frictional head loss occurs as the water takes a tortuous path among pillars and through mine rubble. Heads in the mine respond to recharge pulses with varying lag times and attenuation, consistent with the presence of hydraulically resistive barriers within the mine, and preferential flow paths. Areas nearest the beach respond more rapidly and with less attenuation. The mine pool is not well mixed, probably due to variability in recharge and in residence times (due to preferential flow paths), as well as mine geometry.

Water at the discharge point has a chemical composition that lies between compositions of water in the eastern and western areas, and a mixing model using chloride, assumed to be conservative, shows that the eastern area contributes 9% of the Corning discharge and the western area 91%. In terms of area, however, the eastern portion is 35% of the total area. Accordingly, the diffuse recharge rate in the western area must be higher, 11 cm/yr, while the eastern area has a lower recharge rate (3.1 cm/yr). The difference is consistent with thicker overburden in the eastern area. Water in the eastern area has a higher residence time, which may explain its very poor water quality. Although it contributes only 9% of the flow, the eastern area contributes 33% of the acidity load. On the other hand, the eastern area is believed to be fully flooded, so the generation of AMD is somewhat surprising. Dissolved oxygen concentrations averaged about 2 mg/l, levels that do not preclude pyrite oxidation. The source of the oxygen is unknown, but an old mine shaft in the vicinity may be a factor.

Calculations of barometric efficiency of the different parts of the mine provide insights into the confinement of the different parts. The partially flooded beach area and a large part of the flooded are behaves as an unconfined aquifer, showing little barometric sensitivity. The eastern complex behaves as a weakly confined aquifer, and the area near the discharge and the discharge itself acts as a bottleneck to flow and exhibits displacement behavior; that is, water levels rise with barometric pressure increases, possible in response to displacement or squeezing of water from up-dip areas or the eastern complex.

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