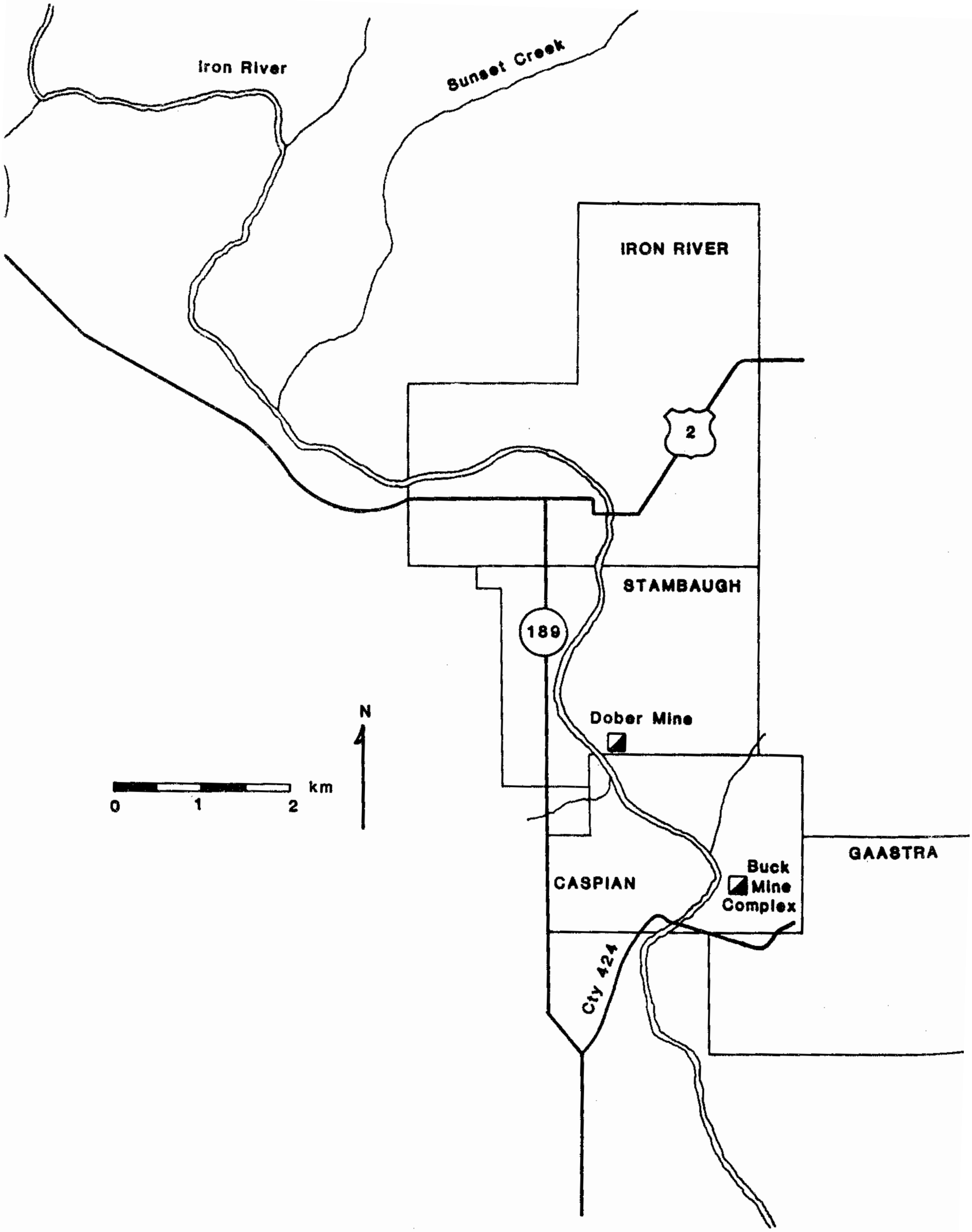

Figure 3. Location of Acid Drainage Sites in the Iron River District.

believed that one or more solutions to the acid drainage problem would evolve.

Flooding rate. Mine maps and production records were used to calculate the volume of mine openings. Work done by Cregger (1977) showed that the mine complex had a void volume of 7.96×10^6 m^3 from ore removed less a stope sand filling volume of 1.64×10^6 m^3 resulting in a total volume of 6.32×10^6 m^3. Mine pumping records showed that an average of 2890 m^3 of water was pumped daily from the mine. From this data the time to flood was calculated:

$$\text{Time to flood} = \frac{6.32 \times 10^6 \text{ m}^3 \text{ voids}}{2.89 \times 10^3 \text{m}^3 \text{ H}_2\text{O/day} \times 365 \text{ days/year}} = 6.0 \text{ years.}$$

It is interesting to note that the mine ceased operations in 1966 and was flooded six years later in 1972. Thus the rate of flooding could have been predicted. Of course, at that time no one thought about the possibility of acid water drainage so no effort had been made to determine the rate of flooding or to predict when the mine would be filled.

Mine water measurements. Measurement of water levels in the mine were restricted to the few available access points; i.e., at the Dober Mine open pit and at shafts and raises which came to the surface. Many of the former surface openings of the mine were inaccessible because of steps taken when the mine was closed. Some were backfilled with rock to the surface and others were sealed with thick concrete plugs and/or covered with steel-reinforced caps. In addition to the Dober Mine pit, concrete seals on 2 shafts and one raise were opened by diamond drilling so that water level measurements could be made and samples collected (see Figure 4).

Measurements from mine openings on the western side of the complex established that the free water surfaces were elevated as much as two meters above the level of water in the Dober Mine. It was initially considered that blockages on interconnecting deep drifts were responsible for the head differences.

Deep water sampling from the vertical No. 2 shaft (Figure 4) to 400 meters depth was undertaken with a Kemmerer sampler on a cable reel device. Analysis of these samples showed that a sharp boundry existed between lower acid waters and upper fresher waters at a depth of 160 meters. Density measurements of the water samples showed that the lower waters had a significantly higher specific gravity. This relationship is shown in Figure 5.

Calculations in which the product of the height of water in the No. 2 shaft and its average density was compared to the similar product in the Dober Mine Shaft, showed the two values to be equal. Thus, the head difference could be attributed to the presence of a shorter "column" of denser water in the Dober Mine shaft versus a taller "column" of less dense water in the No. 2 shaft. This relationship can be compared to a U-tube concept as shown in Figure 6.

Acid water flow model. Based upon these findings, it was concluded that the acid flowed from the shaft collared at a lower elevation in the river valley in response to recharging ground water entering the elevated workings in the western portion of the mine. Moreover, it was determined that the rate of flow was in direct response to the rate of recharge. High flow rates resulted from increased recharge following snow melt in the Spring and periods of high rainfall. Conversely, dry conditions caused a reduction in the flow rate. In fact, during the colder winter months, the flow from the

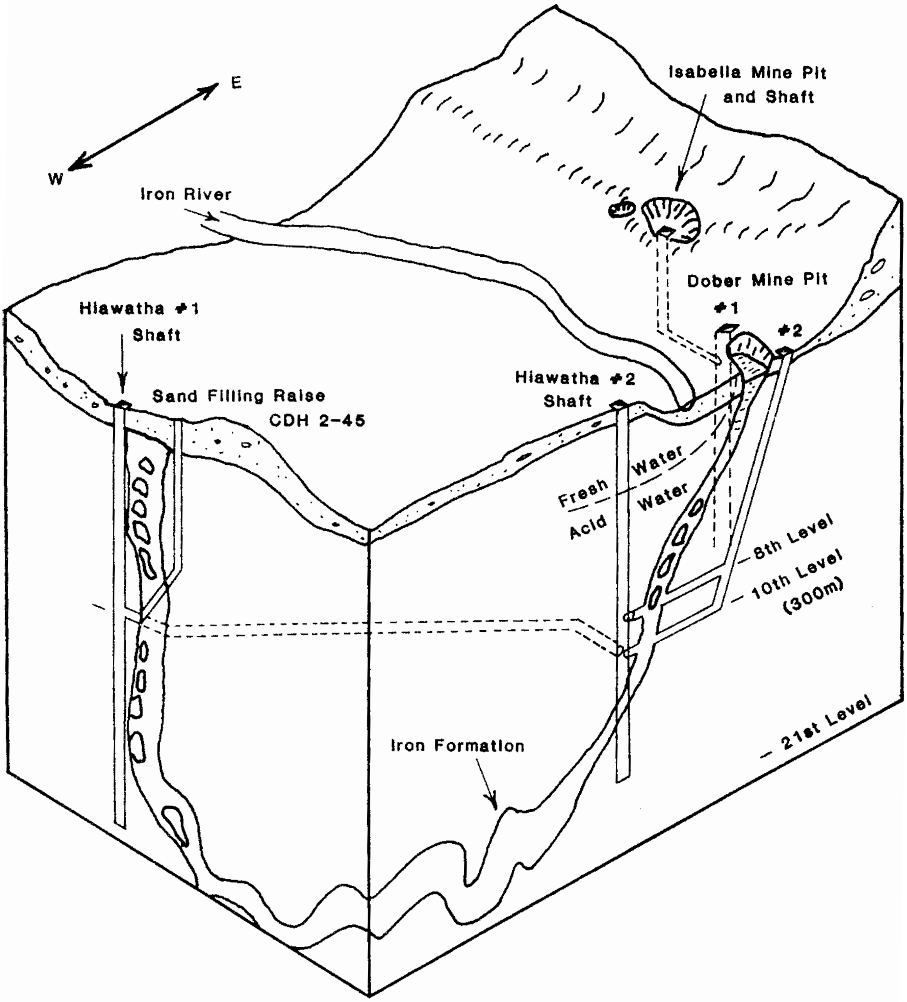

Figure 4. Isometric Sketch of the Dober Mine Complex (Modified from Dutton, 1969).

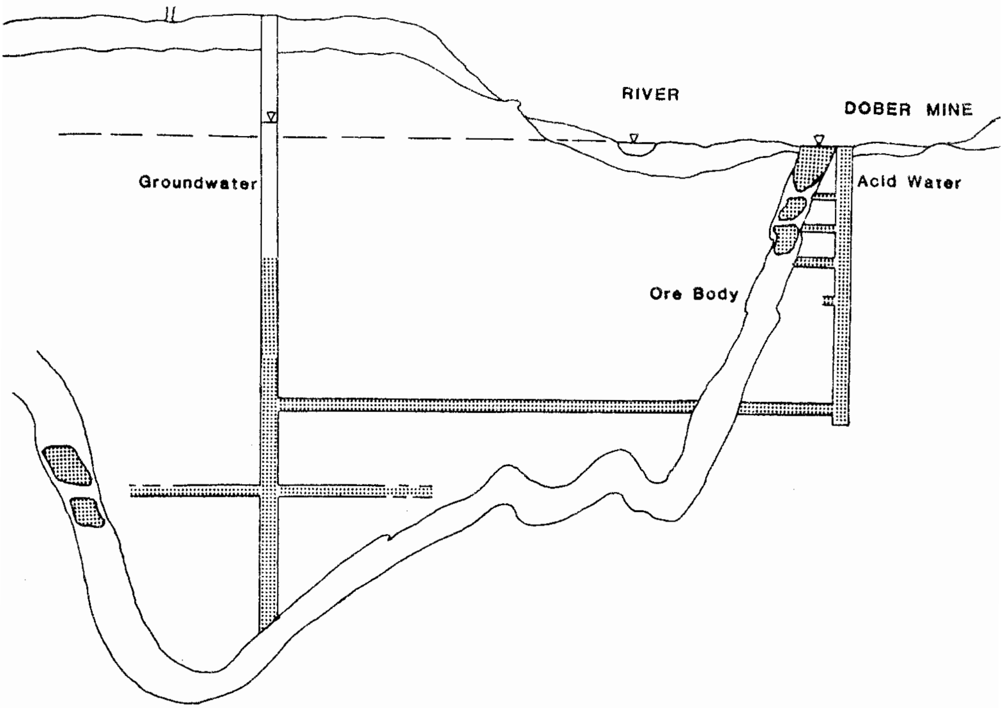

Figure 5. Schematic Representation of Acid Water and Groundwater Distribution in the Dober Mine Complex, Cross-Section Looking Northerly.

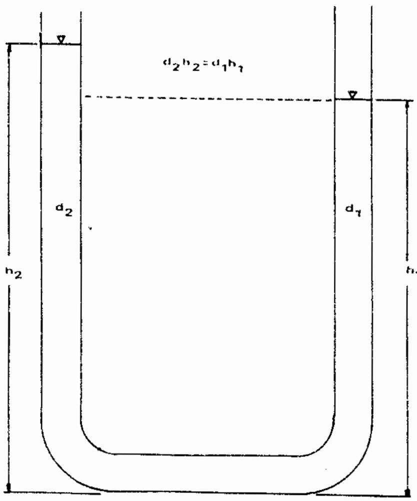

Figure 6. A "U-Tube" Concept to Illustrate Mine Water Elevation Variations as a Function of Water Density.

Dober Mine would sometimes stop. This was attributed to depletion of stored groundwater without recharge from the snow cover. It should be noted that the acid flow rate did not show an immediate response to precipitation because of the time lag required for the water to be transmitted through the glacial overburden and iron formation.

PUMPING AS A MEANS TO CONTROL ACID DRAINAGE

In the ongoing effort to learn more about the hydrology of the mine complex, a pumping test was planned. It was determined that the pumping should be done from the major groundwater recharge area in the western area of the mine complex. Pumping would lower the water level in the mine complex and allow the rate of recharge to be measured. The test would also confirm whether or not a blockage was present between the Hiawatha and Dober Mines.

Preparation. It was determined that a sand filling raise in the western area of the mine complex would be the most suitable location for pumping. Its location is shown in Figure 4. The concrete plug in the sand filling raise was opened by drilling a 30 cm diameter hole through 3 meters of concrete. A diesel-powered, 10-stage line shaft turbine pump was set 30 meters below the ground surface. Provisions were made to drain the pumped water to the nearby Iron River.

Pump test. The pumping was performed for a period of 13 hours at an average rate of 120 l/s. Water levels were taken continuously from the four shafts and the pumping site. The pumping caused water levels to drop as much as 1.02 meters in the recharging area of the mine to a low of 0.78 meters at the Dober Mine where acid water discharged. Thus, it was determined that no blockages were present which would affect free water movement between the mines of the complex.

The pumped waters were only slightly acid (pH = 6.0) and lightly mineralized with iron at 40 mg/l, manganese 8.5 mg/l and sulfate 900 mg/l. Ten days were required for the water levels in the mine complex to return to normal; an average recharge rate of 6.5 l/s. During this time no acid water flowed into the river.

Pumping to control AMD? The results of the pumping test indicated that it might be a feasible method to prevent acid drainage by controlling the water level in the mine. Consequently, a recommendation was made to install a pumping system to control the water level in the mine. It was proposed that the pumping rate be adjusted to remove water from the mine at the same rate it was being recharged by groundwater inflow. Thus, there would be no flow from the mine and the acid water would be held in balance.

Although the pumping system offered a plausible means to control the acid drainage problem, it was not implemented, largely because of lack of funds. This inaction was not acceptable to many Michigan and Wisconsin residents. Their concerns were translated into political pressure to do something to correct the pollution problem. At this time renewed efforts were made to implement the pumping plan to control the acid water. However, some additional problems with the pumping option arose. The iron and manganese levels in the pumped water exceeded lawful limits for discharge into surface waters. The system was also unsatisfactory in the sense that pumping would have to be done in perpetuity to keep the acid in the mine. Thus, the acid water problem would never be solved, just held in check. It was also possible that over the long term that the pumped water would become progressively more mineralized because not all of the groundwater entering the mine could be removed at a single pumping point.

Alternative solutions for AMD control. As it became apparent that pumping was not a viable solution to the acid drainage problem other solutions were sought. Mine sealing was considered but was also determined to be impractical because of difficulties in constructing effective seals at either the recharge or discharge points. In seeking a more acceptable method, it appeared that chemical treatment would have to be considered. It was realized that chemical treatment would be expensive. However, one possibility seemed to offer a simple and low cost solution. It would involve using river water to neutralize the acid. Neutralization could be accomplished by mixing the necessary volumes of river and acid water. Mixing could be done by diverting the required flor of river water into the Dober mine pit. Metal precipitation would take place in the pit and in a series of existing ponds situated downstream from the Dober Mine. In essence this system would duplicate the neutralization and metal precipitation that was occurring in the river but under controlled conditions. The acid would be neutralized and the metal precipitated in protected ponds. A much cleaner effluent would be returned to the river downstream. Although this plan seemed to be very appealing, work was needed to determine if it would be technically and economically feasible.

THE POND SYSTEM

To determine if the proposed pond system would work, a three-phased study was planned. Phase I would involve bench scale laboratory tests on the kinetics of acid neutralization and metal precipitation, a second phase would involve pilot scale tests in the field and the third phase would involve an analysis of the field conditions to see if balances existed between the critical elements; i.e., river and mine water flow and pond and sludge volumes.

Bench scale tests. River and acid water samples were used in the bench scale tests. The variables were to be mixing ratios (i.e., ratio of river water to acid water) temperature (2°C, 10°C) and time of reaction (2, 24, 72, and 144 hours). It was found from these tests that nearly complete precipitation of iron occurred at a mixing ratio of 27:1 in 3 days time at 2°C and in one day at 10°C. Under these conditions, the pH increased with time to between 7 and 8. Aluminum precipitation was nearly complete at lower mixing ratios (3:1 and 9:1), but at the 27:1 ratio, had a tendency to redissolve as the pH increased (due probably to oxidation and hydrolysis of iron). No significant precipitation of manganese, calcium or magnesium occurred under any of the test conditions.

Pilot scale tests. Based upon these results the tests were scaled up in the field near the Dober Mine. Four 9500 liter tanks were used to simulate the pond system. Adjustable positive displacement pumps were used to provide the desired ratios of acid and river water. The waters were pumped into the first tank where they mixed and flowed by gravity from tank to tank. The flow rate was adjusted to provide 5 days retention time in the tanks. In these tests mixing ratios and aeration were the two variables. The mixing ratios were run at 18:1 and 12.5:1, with and without aeration, for a total of four tests. The test results showed that over 90% of the iron and aluminum was removed at the 18:1 mixing ratio. With aeration, lower mixing ratios of river to acid water could be used to achieve similar results. Aeration was effective in precipitating aluminum.

Sludge volumes were also measured. From the data it was determined that approximately 9 m^3 of sludge would be produced each day in a full scale system. Field surveys of the Dober Mine open pit and the pond system, which were performed prior to the field pilot scale tests, showed that the pond system had sufficient volume for 5 days retention time at a 20:1 mixing ratio. This would allow sufficient time for the metal hydroxides to precipitate in the pond system. Based upon the field tests, it was determined that most of the sludge would be precipitated in the Dober Mine pit where mixing would first occur. Further calculations showed that this pit had sufficient volume to hold all of the sludge that would be produced from the acid water remaining in the upper 10 levels of the mine.

Based upon measured flow rates of acid water from the mine and observed reduction in iron content it was determined that the concentration of iron in the AMD was reduced by one half every five years. With the iron content presently at 500 mg/l the iron content would be reduced to less than 10 mg/l in 30 years.

Proposed pond system. The proposed system is shown in the map of Figure 7. Diversion of the river water is to be accomplished by a low head dam on the Iron River. About 6% of the average river flow will be required for the pond system to operate. The river water will be diverted into the Dober Mine pit where most of the neutralization and metal precipitation will occur. Retention time in the downstream ponds will promote additional settling. Weirs at the downstream end of each pond will maintain the desired elevations in this gravity system. No problems are expected in the operation during the warm part of the year. During the winter, ice cover on the ponds will hamper aeration. This may not be a serious problem as acid flow is greatly reduced in the winter. It appears that the pond system will provide a low cost means to reduce acid and metal pollution of the Iron River.

THE SYNERGETIC CONCEPT

In retrospect, it is apparent that the efforts to arrive at an acceptable solution to this acid drainage problem was a "trial and error" process which resulted in this synergetic concept. In this particular case history, a synergetic solution was easy to engineer, because few adjustments were required for it to work. For example, the flow of the Iron River was of sufficient magnitude so that only a small percentage of the flow volume is needed to neutralize the acid water. The location of the settling ponds downstream from the Dober Mine is fortuitous. Also, the combined volume of the mine pit and pond system allows five-day retention time for the mixed waters, which is the desired time required for settling based upon the laboratory tests. Furthermore the Dober Mine pit has sufficient volume to hold all of the sludge which would be produced from the acid calculated to remain in the mine water pool which will be flushed. Moreover, it is fortuitous that lower winter time flow rates will occur when ice cover will reduce the efficiency of metal precipitation.

The preceding analysis shows that it is quite remarkable that the set of conditions described above would all exist at this one location. Accordingly, it should not be expected that they will occur at other sites where acid drainage is a persistent problem. Therefore, synergetic solutions at other locations will likely require additional engineering design. For example, an essential element of the synergetic approach is to be able to match the acid flow with available neutralizing capacity so the

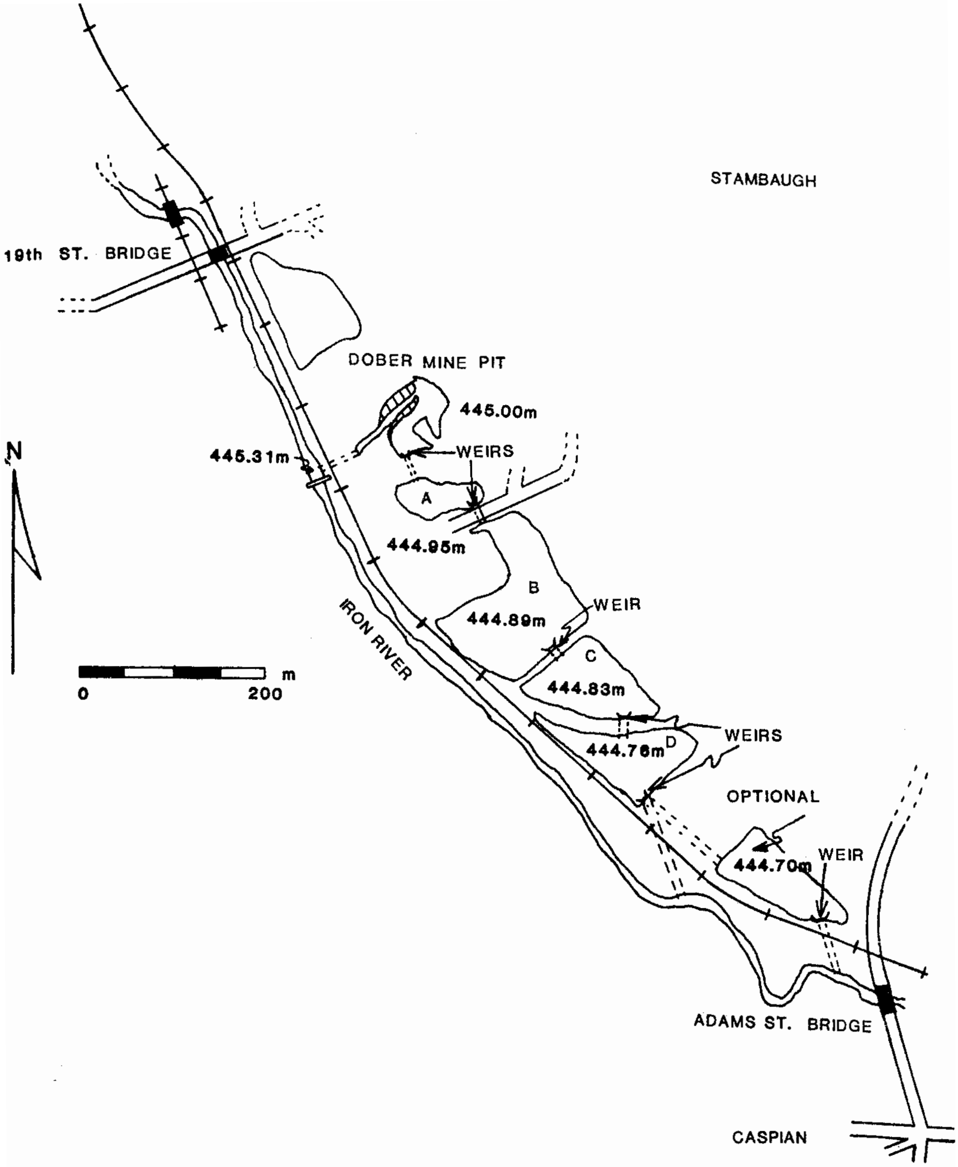

Figure 7. The Proposed Water Diversion/Pond System For Acid Water Treatment at the Dober Mine.

natural system is not overloaded. Another critical element, which may require adjustment, is a protected settling basin for the precipitated sludge. It must be capable of holding all of the sludge produced and must be safe from subsequent erosion. A third critical element is the need for gravity flow. The large volumes of waters involved in mixing systems would make pumping prohibitively expensive.

It will not always be possible to apply the synergetic approach to an acid drainage problem. However, by careful analysis, innovative engineering, and selective use of new technology, the application may be much broader than a first assessment may indicate. If the synergetic approach is given serious consideration, it is possible that many persistent sources of acid drainage could be effectively controlled at a reasonable cost. Even if the desired low levels of metal content in the effluent are not fully achieved, any significant reduction should be preferred over the alternative of no improvement at all.

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