Chapter 4

IMPACTS OF MINE DRAINAGE ON AQUATIC LIFE, WATER USES, AND MAN-MADE STRUCTURES

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Introduction

"...The influx of untreated acid mine drainage into streams can severely degrade both habitat and water quality often producing an environment devoid of most aquatic life and unfit for desired uses. The severity and extent of damage depends upon a variety of factors including the frequency, volume, and chemistry of the drainage, and the size and buffering capacity of the receiving stream", (Kimmel, 1983).

Drainage from underground coal mines, surface mines, and coal refuse piles is the oldest and most chronic industrial pollution problem in the Appalachian Coal Region. In 1995, 2425 miles (3902 km) of stream in Pennsylvania did not meet EPA-mandated in-stream water quality standards due to over a century of mineral extraction (PA DEP, 1996). The unfavorable repercussions of coal mine drainage in the northern Appalachian Coal Region have been documented in the literature for over a century. It is believed that the first reference to what we now call acid mine drainage in North America was made by Gabriel Thomas, who in 1698 reported: "...And I have reason to believe that there are good coals, also, for I observed the runs of water which have the same colour as that which proceeds from the mines in Wales..."

Pyrite in coal and overlying strata, when exposed to air and water, oxidizes, producing iron and sulfuric acid (Chapter 1). Ferric iron, when discharged to surface water, hydrolizes to produce hydrated iron oxide and more acidity. The acid lowers the pH of the water, making it corrosive and unable to support many forms of aquatic life. Acid formation is most serious in areas of moderate rainfall where rapid oxidation and solution of exposed minerals can occur. Indeed, of the 19,308 km of United States streams reported degraded by acid mine drainage in 1970, 16,920 km or 88 percent were located east of the Mississippi River in the Appalachian coal fields of Pennsylvania, West Virginia, Ohio, eastern Kentucky, Tennessee, Maryland, and Alabama (Warner, 1970). Various impacts range in severity from isolated nuisance type problems to severe water quality impacts affecting large volumes of groundwater and miles of watercourse. Impacted uses include agricultural (irrigation and livestock), industrial, and potability of water supplies along with recreational uses, scenic resource appreciation, and aquatic organism habitat. The aggressive nature of mine drainage may also result in corrosion and incrustation problems with respect to such man-made structures as pipes, well screens, dams, bridges, water intakes, and pumps. The compromising of well casings (water supply or oil and gas wells) can be extremely troublesome because it can then allow the migration and co-mingling of water from one aquifer with another, often leading to inter- and intra- aquifer contamination (Merritt and Emrich, 1970). Acidic mine drainage in particular can also be toxic to vegetation when recharging to the shallow groundwater system and soil water zones.

Effects of Mine Drainage and Metals on Aquatic Macroinvertebrates and Fish

Mine drainage is a complex of elements that interact to cause a variety of effects on aquatic life that are difficult to separate into individual components. Toxicity is dependent on discharge volume, pH, total acidity, and concentration of dissolved metals. pH is the most critical component, since the lower the pH, the more severe the potential effects of mine drainage on aquatic life. The overall effect of mine drainage is also dependent on the flow (dilution rate), pH, and alkalinity or buffering capacity of the receiving stream. The higher the concentration of bicarbonate and carbonate ions in the receiving stream, the higher the buffering capacity and the greater the protection of aquatic life from adverse effects of acid mine drainage (Kimmel, 1983). Alkaline mine drainage with low concentrations of metals may have little discernible effect on receiving streams. Acid mine drainage with elevated metals concentrations discharging into headwater streams or lightly buffered streams can have a devastating effect on the aquatic life. Secondary effects such as increased carbon dioxide tensions, oxygen reduction by the oxidation of metals, increased osmotic pressure from high concentrations of mineral salts, and synergistic effects of metal ions also contribute to toxicity (Parsons, 1957). In addition to chemical effects of mine drainage, physical effects such as increased turbidity from soil erosion, accumulation of coal fines, and smothering of the stream substrate from precipitated metal compounds may also occur (Parsons, 1968; Warner, 1971).

Benthic (bottom-dwelling) macroinvertebrates are often used as indicators of water quality because of their limited mobility, relatively long residence times, and varying degrees of sensitivity to pollutants. Unaffected streams generally have a variety of species with representatives of all insect orders, including a high diversity of insects classed in the taxonomic orders of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (EPT taxa). Like many other potential pollutants, mine drainage can cause a reduction in the diversity and total numbers, or abundance, of macroinvertebrates and changes in community structure, such as a lower percentage of EPT taxa. Moderate pollution eliminates the more sensitive species (Weed and Rutschky, 1971). Severely degraded conditions are characterized by dominance of certain taxonomic representatives of pollution-tolerant organisms, such as earthworms (Tubificidae), midge larvae (Chironomidae), alderfly larvae (*Sialis*), fishfly larvae (*Nigronia*), cranefly larvae (*Tipula*), caddisfly larvae (*Ptilostomis*), and non-benthic insects like predaceous diving beetles (Dytiscidae) and water boatmen (Corixidae) (Nichols and Bulow, 1973; Roback and Richardson, 1969; Parsons, 1968). While these tolerant organisms may also be present in unpolluted streams, they dominate in impacted stream sections. Mayflies are generally sensitive to acid mine drainage; however, some stoneflies and caddisflies are tolerant of dilute acid mine drainage.

Fish are often used as indicators of pollution; however, they are not as useful as macroinvertebrates because of their greater mobility. Fish may temporarily swim through a non-lethal impacted area or away from a discharge of intermittent duration.

pH

Most organisms have a well defined range of pH tolerance. If the pH falls below the tolerance range, death will occur due to respiratory or osmoregulatory failure (Kimmel, 1983). Low pH causes a disturbance of the balance of sodium and chloride ions in the blood of aquatic animals. At low pH, hydrogen ions may be taken into cells and sodium ions expelled (Morris et al., 1989). Mayflies are one of the most sensitive groups of aquatic insects to low pH; stoneflies and caddisflies are generally less sensitive to low pH. Mayflies and stoneflies that normally live in neutral water experience a greater loss of sodium in their blood when exposed to low pH than do acid-tolerant species of stoneflies, such as *Leuctra* and *Amphinemura*, whose sodium uptake is only slightly reduced by low pH (Sutcliffe and Hildrew, 1989).

Acid waters typically have fewer species and a lower abundance and biomass of macroinvertebrates than near-neutral pH waters. Attempts have been made to specifically identify limiting factors, and two factors investigated are interruption of the food chain and direct effects of low pH levels on aquatic life. Macroinvertebrates are often grouped by their feeding habits, and assemblages of invertebrates in acidified waters appear to be related to food availability. The fauna of low pH streams is usually composed of shredders (organisms that eat leaves that fall into the stream), collectors (organisms that filter or gather particles of organic matter from the water), and predators. Low pH tends to eliminate species that feed on algae (scrapers or grazers). Low pH may inhibit growth of bacteria which help break down leaves to make them more easily digestible and which also serve as a food source. These observations led early investigators to theorize that low pH levels reduced the food sources for invertebrates, thereby indirectly reducing their numbers. This is partially true; however, more recent studies have shown that direct effects of low pH on aquatic life are more critical than indirect effects on food sources (Rosemond et al., 1992).

Cooper and Wagner (1973) studied the distribution of fish in Pennsylvania streams affected by acid mine drainage. They found fish species were severely impacted at pH 4.5 to 5.5; ten species showed some tolerance to pH 5.5 or less; 38 species were found at pH 5.6 to 6.4; and 68 species were found only at pH greater than 6.4 (Table 4.1). They found that a pH of 4.5 and total acidity of 15 mg/L accounted for complete loss of fish in 90% of streams studied. Although no concentrations of metals were taken into account, Cooper and Wagner indicated that the

Table 4.1 Order of appearance of 44 fish species in Pennsylvania streams with increasing pH levels. Sixty-eight additional species collected were never found at pH below 6.5 (Cooper and Wagner, 1973).

4.5	5.2	6.0	6.1
Ohio lamprey	Creek chub	Stoneroller	Cutlips minnow
		Silverjaw minnow	Fallfish
4.6	**5.5**	River chub	
Chain pickerel	Yellow perch	Common shiner	**6.2**
Golden shiner		Silver shiner	Redbreast sunfish
White sucker	**5.6**	Rosyface shiner	Rainbow darter
Brown bullhead	Bluntnose minnow	Mimic shiner	Variegate darter
Pumpkinseed	Blacknose dace	Northern hogsucker	Mottled sculpin
		Rock bass	
4.7	**5.9**	Smallmouth bass	**6.4**
Creek chubsucker	Brown trout	Greenside darter	Redside dace
Largemouth bass	Longnose dace	Fantail darter	Spotfin shiner
	Margined madtom	Johnny darter	Spottail shiner
5.0	Tessellated darter	Banded darter	Pearl dace
Brook trout	Slimy sculpin	Blackside darter	Green sunfish

absence of fish in acidified waters can be related to dissolved metals at certain pH levels. They also indicated that sulfates, a major constituent of acid mine drainage, did not become toxic to fish until concentrations exceeded the saturation level of several thousand mg/L.

The primary causes of fish death in acid waters is loss of sodium ions from the blood and loss of oxygen in the tissues (Brown and Sadler, 1989). Acid water also increases the permeability of fish gills to water, adversely affecting gill function. Ionic imbalance in fish may begin at a pH of 5.5 or higher, depending on the tolerance of the species; severe anoxia will occur below pH 4.2 (Potts and McWilliams, 1989). Low pH that is not directly lethal may adversely affect fish growth rates and reproduction (Kimmel, 1983).

Metals

Heavy metals can increase the toxicity of mine drainage and also act as metabolic poisons. Iron, aluminum, and manganese are the most common heavy metals which can compound the adverse effects of mine drainage. Heavy metals are generally less toxic at circumneutral pH. Trace metals such as zinc, cadmium, and copper, which may also be present in mine drainage, are toxic at extremely low concentrations and may act synergistically to suppress algal growth and affect fish and benthos (Hoehn and Sizemore, 1977). Some fish, such as brook trout, are tolerant of low pH, but addition of metals decreases that tolerance. In addition to dissolved metals, precipitated iron or aluminum hydroxide may form in streams receiving mine discharges with elevated metals concentrations. Ferric and aluminum hydroxides decrease oxygen availability as they form; the precipitate may coat gills and body surfaces, smother eggs, and cover the stream bottom, filling in crevices in rocks, and making the substrate unstable and unfit for habitation by benthic organisms (Hoehn and Sizemore, 1977). Scouring of iron flocculant increases turbidity and suspended solids and may inhibit fish feeding.

Aluminum rarely occurs naturally in water at concentrations greater than a few tenths of a milligram per liter; however, higher concentrations can occur as a result of drainage from coal mines, acid precipitation, and breakdown of clays (Hem, 1970). The chemistry of aluminum compounds in water is complex. Aluminum combines with organic and inorganic ions and can be present in several forms. Aluminum is least soluble at a pH between 5.7 and 6.2; above and below this range, aluminum tends to be in solution (Hem, 1970; Brown and Sadler, 1989).

Most information on the effects of low pH and aluminum on aquatic life is based on studies of acid precipitation, such as those summarized in Haines (1981), Morris et al. (1989), and Mason (1990). Of the three major metals present in mine drainage, aluminum has the most severe adverse effects on stream aquatic life. The addition of aluminum ions compounds the effect of low pH by interacting with hydrogen ions, further decreasing sodium uptake, and increasing sodium loss in blood and tissues. High calcium concentrations generally reduce mortality and sublethal effects of low pH and elevated aluminum by reducing the rate of influx of hydrogen ions into the blood. Streams most susceptible to degradation from elevated aluminum, however, normally have low concentrations of calcium.

Stream investigations by the author have indicated that a combination of pH less than 5.5 and dissolved aluminum concentration greater than 0.5 mg/L will generally eliminate all fish and many macroinvertebrates. Fishflies, alderflies, and several genera of stoneflies, caddisflies, and true flies (particularly within the family Chironomidae) are tolerant of low pH and high dissolved aluminum. Mayflies are the aquatic insects most affected by a combination of low pH and acidic water. Some exceptions do occur, for example, the mayflies *Ameletus* and *Ephemerella funeralis* are tolerant of slightly acidic water, especially at low aluminum concentrations (less than 0.2 mg/L). Aluminum is most toxic to fish at pH between 5.2 and 5.4 (Baker and Schofield, 1982).

Streams with precipitated aluminum usually have lower numbers and diversity of invertebrates than streams with low pH and high dissolved aluminum. Precipitated aluminum coats the stream substrate, causing slippery surfaces and difficulty for insects to maintain position in the current. Aluminum precipitate can also be directly toxic to macroinvertebrates and fish. Rosemond et al. (1992) stated that deposition of aluminum hydroxide particles on invertebrates blocks surfaces important for respiratory or osmoregulatory exchange. Aluminum precipitate also eliminates most of the filter feeders, such as Hydropsychid caddisflies, which normally comprise a major portion of total stream macroinvertebrates. Precipitated aluminum can also accumulate on fish gills and interfere with their breathing (Brown and Sadler, 1989).

Iron is a common component of mine drainage which can have a detrimental effect on aquatic life. Like aluminum, iron can be present in several forms and combines with a variety of other ions. The impact of mine drainage containing elevated iron on aquatic ecosystems is complex. Little animal life may be found in streams with the lowest pH (under 3.5) and elevated dissolved iron concentrations. Alderflies, fishflies, dipterans, and aquatic earthworms will be present if the pH rises slightly. With further increases in pH, a more diverse assemblage of macroinvertebrates may be present, although total numbers may be lower than in nondegraded streams (Table 4.2 and Figure 4.1). Wiederholm (1984), Letterman and Mitsch (1978), and Moon and Lucostic (1979) presented results of research on the effects of mine drainage and elevated iron on aquatic life.

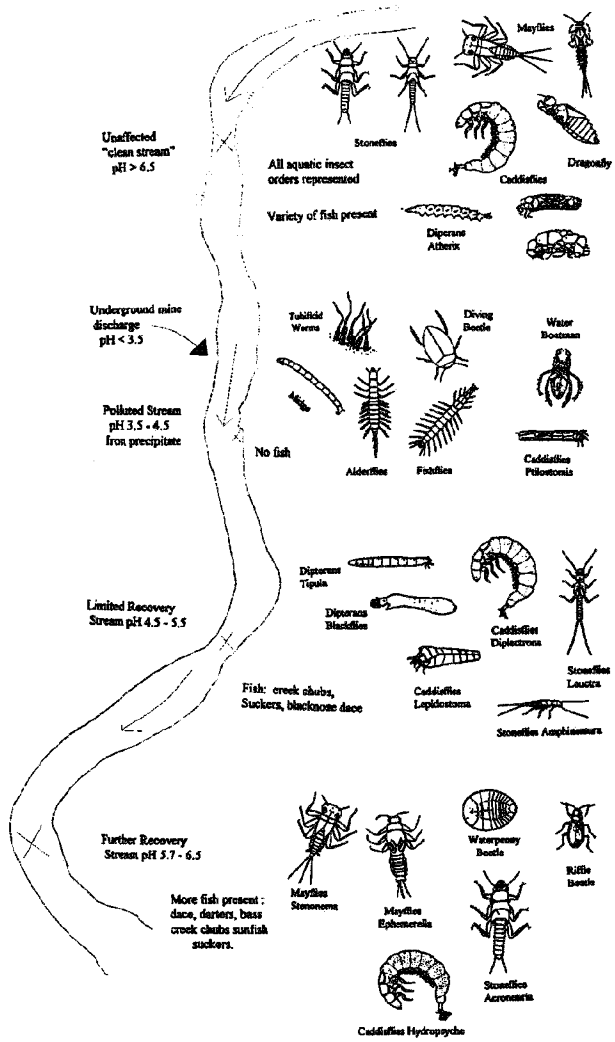

Figure 4.1 Macroinvertebrates and fish in polluted and recovery zones of a stream receiving acid mine drainage.

Iron precipitates at a pH greater than 3.5 and does not reenter solution at higher pH. Because iron can form precipitates at a lower pH than aluminum and can be present in streams with pH less than 4.5, separating the effect of iron from the effect of low pH is difficult. Precipitation of ferric hydroxide may result in a complete blanketing of the stream bottom, adversely affecting both macroinvertebrates and fish (Hoehn and Sizemore, 1977). The severity is dependent on stream pH and the thickness of the precipitate. Generally, the effect of precipitated iron is less severe in alkaline conditions. Many fish and macroinvertebrates are tolerant of iron precipitate in alkaline water; however, total numbers and diversity are usually lower than in unaffected streams. Koryak et al. (1972) found that ferric hydroxide greatly diminished total biomass of benthic organisms and limited fish populations in streams with survivable pH levels. The caddisfly genus *Hydropsyche*, which is generally sensitive to low pH, can live in alkaline streams with iron precipitate. The Hydropsychid caddisfly *Diplectrona*, however, is tolerant of iron precipitate and pH less than 5.0. Mayflies are generally more tolerant of alkaline mine drainage than acid mine drainage. Mayflies such as *Ephemerella*, *Baetis*, *Attenella*, and *Acentrella* may be found in alkaline streams with iron precipitate. *Acroneuria* and *Paragnetina* stoneflies are tolerant of alkaline water with iron precipitate but are intolerant of acid (Table 4.2). Since iron precipitate particles often cover the bodies of macroinvertebrates that otherwise appear healthy, the iron precipitate itself appears to be less toxic than aluminum precipitate. Smallmouth bass, rock bass, creek chub, johnny and rainbow darter, white sucker, common shiner, and river chub are some fish species that can be found in alkaline water with iron precipitate.

Table 4.2 Representatives of macroinvertebrate, fish, and algae communities in unaffected streams, streams impacted by acid mine drainage, stream recovery zones, and streams with alkaline mine drainage and iron precipitate.

UNAFFECTED STREAM UPSTREAM OF DISCHARGE	A diversity of aquatic insect orders Abundance of EPT taxa (mayflies, stoneflies, caddisflies) and other orders Variety of fish species, depending on habitat
ACID MINE DISCHARGE pH <3.5 high dissolved iron	
STREAM pH 3.5 - 4.5 IRON PRECIPITATE	Elimination of most EPT taxa Dominance by midges (Chironomidae) Also present: alderfly (*Sialis*), fishfly (*Nigronia*), diving beetles (Dytiscidae), water bugs (Corixidae) Algae: *Euglena, Ulothrix, Pinularia, Eunotia* No Fish
LIMITED RECOVERY STREAM pH 4.5 - 5.5	More insect orders represented Stoneflies: *Leuctra, Amphinemura* Caddisflies: *Diplectrona, Lepidostomis, Polycentropus*; Blackflies (Simuliidae), Craneflies (Tipulidae) At higher pH range: Mayfly: *Ameletus*; Fish: creek chub, white sucker, blacknose dace, brook trout
RECOVERY ZONE STREAM pH 5.7 - 6.0	Additional EPT taxa: *Acroneuria, Stenonema, Ephemerella funeralis*; Elmid Beetles Algae: Diatoms, Flagellates, Green algae, *Oscillatoria*
FURTHER RECOVERY STREAM pH > 6.0	Variety of EPT taxa: *Ephemerella, Baetis, Isonychia, Acentrella, Attenella, Hydropsyche* Variety of fish species
ALKALINE OR NEUTRALIZED MINE DRAINAGE STREAM pH > 6.0 IRON PRECIPITATE	Variety of EPT taxa may be present; But usually low abundance *Ephemerella, Baetis, Acentrella, Paragnetina, Acroneuria, Leuctra, Cheumatopsyche, Hydropsyche*, Elmid beetles, *Corydalus* Variety of fish species, reduced numbers: creek chub, river chub, white sucker, johnny darter, rainbow darter, rock bass, smallmouth bass, pumpkinseed

Sources: Roback and Richardson, 1969; Parsons, 1968; Warner, 1971; Kimmel, 1983; and stream investigations by author.

Manganese is another metal that is widely distributed in mine drainage. Manganese can be present in a variety of forms and compounds and complexes with organic compounds. Manganese is difficult to remove from discharges because the pH must be raised to above 10.0 before manganese will precipitate. Manganese, therefore, is persistent and can be carried for long distances downstream of a source of mine drainage. Less information is available on the effects of elevated manganese concentrations on aquatic life than the effects of iron and aluminum. Perhaps this is because manganese in mine drainage is usually associated with other metals which may have a more deleterious effect or mask the effect of the manganese. Manganese discharge limits have traditionally been based on the objectionable discoloration effects of manganese at concentrations as low as 0.2 mg/L in water supplies rather than effects on aquatic life.

Kleinmann and Watzlaf (1988) summarized the results of manganese toxicology tests on fish and invertebrates. They concluded that manganese tolerance limits for fish reported in the literature varied widely and that the lowest toxic concentrations were reported in watersheds with very low levels of hardness. They reported that several researchers found that hardness concentrations as low as 10 mg/L protected fish from adverse effects of manganese. Bioassay tests on invertebrates produced tolerance rates for manganese ranging from 15 to 50 mg/L, depending on the test organism.

The less common precipitated form of manganese may be more toxic than the dissolved form. Werner et al. (1982) noted the presence of precipitated manganese hydroxide which formed a black coating over the substrate of a Pennsylvania stream receiving mine drainage. They reported that the precipitate along with siltation significantly lowered macroinvertebrate species diversity and changed the stream community structure.

Summary

Mine drainage effects on aquatic life vary widely, from elimination of all but the few most tolerant algae, macroinvertebrates, and fish, to little or no effect. The most severe effects are caused by high volume, low pH discharges with high concentrations of dissolved metals that drain into lightly buffered streams and produce accumulations of precipitated iron or aluminum. Little or no effect may occur from low volume or alkaline discharges with relatively low concentrations of metals that drain into moderate or highly buffered streams.

Water Uses and Man-Made Structures

"Mine drainage can be considered to be an unstable aqueous system undergoing continuous change. The composition reflects not only its origin but also what it encounters along its flow path and forms the most important criteria for the selection and design of control systems and/or treatment facilities. Subject to the location of the sample collection with respect to point of pyrite solubilization, such a solution has; been diluted, dissolved additional mineral components, undergone internal reaction which may have deposited ferric oxyhydroxides in its stream bed and possibly been mixed with other pollution sources, domestic, industrial, or agricultural." (Lovell, 1976).

Chemical Impacts on Potable and Industrial Water Supplies

The following is a quote from a 1937 report on the detrimental aspects of mine drainage: "...the acid water caused excessive corrosion of the federal navigation locks and dams, ships and barges, bridges and culverts, pipelines and plumbing. The acid, iron sulfate, and iron oxide (red water) often destroyed all fish and aquatic life, interfered with nature's self-purification of the streams sometimes perhaps favorably, in other cases detrimentally, made water unfit for drinking or household purposes, and caused unsightly reddish brown spots on fabrics in laundries and textile factories and scum in washbowls, sinks and tubs. The water was destructive, scale forming, and unsuitable for use in locomotive and power plant boilers, in manufacturing industries, and in municipal waterworks..." (Hodge,1937).

In areas where surface and groundwaters have been contaminated by mine drainage, treatment of water supplies becomes more difficult, more time consuming, and more expensive. Listed below are constituents which are typically elevated in mine drainage or in groundwater recharged by mine drainage and their properties which can render a municipal or domestic water supply unusable without treatment, unpalatable, or aesthetically offensive.

Iron - The taste threshold of iron in water has been given as 0.1 and 0.2 mg/L of iron from ferrous sulfate and ferrous chloride respectfully. It has been reported that ferrous iron imparts a taste at 0.1 mg/L and ferric iron at 0.2 mg/L. Staining of plumbing fixtures occurs at 0.3 mg/L. Certain animals are sensitive to minor changes in iron concentration. Cows will not drink enough water (taste threshold 0.3 mg/L) if it is high in iron, and consequently, milk production is affected (Dairy Reference Manual, Third Edition, 1995).

pH - The hydrogen ion concentration can affect the taste of water. At a low pH water tastes sour. The bactericidal effect of chlorine is weakened as pH increases and it is advantageous to keep the pH close to 7. Water with a pH below 7.0 is corrosive to plumbing and can result in constituents such as copper, zinc, cadmium, and lead being dissolved in drinking water.

Sulfate - High sulfate levels in water may have laxative effects and cause taste and odor problems.

Total Dissolved Solids (TDS) - Excessive TDS in drinking water is objectionable because of possible physiological effects and unpalatable mineral tastes. Physiological effects related to TDS include laxative effects, effects on the cardiovascular system, and toxemia associated with pregnancy.

Manganese - Elevated manganese causes several specific problems when encountered in drinking water, such as unpleasant tastes, deposits on food, laundry staining, reduction in water main capacity, and discoloration of porcelain fixtures. Staining may occur at concentrations above 0.5 mg/L.

The major problem of most industrial water users is corrosion control. As discussed previously, increased acidity has been found to accelerate the corrosion of industrial water-using equipment, navigational equipment, buried transmission lines, and ordinary metal structures such as culverts, bridges, and pumps (Appalachian Regional Commission, 1969; and Skelly and Loy, 1973). Scale formation (incrustation) produced by increased water hardness reduces the heat exchange efficiency of boilers (Skelly and Loy, 1973). Elevated iron and manganese concentrations interfere with textile dyeing and metal plating (Appalachian Regional Commission, 1969).

Corrosion and Incrustation of Wells, Pipes, and Other Metal Structures

Damage to plumbing done by **corrosive** water represents a major expense to utilities and water users. The following is a list of indicators of corrosive water with respect to metal casings, screens, and other metal fixtures and conveyance devices: (Driscoll, 1986)

1. **Low pH.** pH below 7.0.
2. **Dissolved oxygen.** If dissolved oxygen in groundwater exceeds 2 ppm, corrosive water is indicated. Dissolved oxygen is likely to be found in shallow water table wells.
3. **Hydrogen sulfide.** Less than 1 ppm can cause severe corrosion and this amount can be detected by odor or taste. The presence of hydrogen sulfide can be detected readily from its characteristic rotten-egg odor.
4. **Total dissolved solids** Above 1000 ppm, the electrical conductivity of the water is great enough to cause serious electrolytic corrosion.
5. **Carbon dioxide** above 50 ppm.
6. **Chlorides** above 500 ppm.

As is evident by comparing the chemical signature of mine drainage with the list of corrosion indicators, the groundwater environment in areas affected by mine drainage (Chapter 1) has the potential to be highly corrosive. There are two recognized types of corrosion; chemical and electrochemical.

Chemical corrosion occurs when a particular constituent is present in water in sufficient concentration to cause rapid removal of material over broad areas. Chemical corrosion can cause severe damage regardless of the amount of total dissolved solids (Driscoll, 1986).

A second type of corrosion known as electrochemical corrosion is more prevalent. Two conditions are necessary for electrochemical corrosion to proceed; a difference in electrical potential on the surface of the metal(s), and water with enough dissolved solids content to act as a conductor. A difference in electrical potential can occur between two different metals or on the surface of the same metal in areas around joints, machine cuts, exposed threads, or breaks in surface coatings. (Driscoll, 1986)

Incrustation is a second major problem for wells, pumps and associated metal structures which is related to water quality. The kind and amount of dissolved minerals and gases in natural waters determine their tendency to deposit mineral matter as incrustation. The major forms of incrustation include; (1) incrustation from precipitation of calcium and magnesium carbonates or their sulfates; (2) incrustation from precipitation of iron and manganese compounds, primarily their hydroxides or hydrated oxides; and (3) plugging caused by slime-producing iron bacteria or other slime-forming organisms.

(Driscoll, 1986) Chemical incrustation usually results from the precipitation of carbonates, principally calcium, from groundwater in the proximity of the well screen. Other substances, such as aluminum silicates and iron compounds, may also be entrapped in the scalelike carbonates that cement sand grains together around the screen. The deposit fills the voids, and the flow of water into the well is reduced proportionally.

Iron and manganese incrustation is another common problem in pumping wells. During pumping, velocity-induced pressure changes can disturb the chemical equilibrium of the groundwater and result in the deposition of insoluble iron and manganese hydroxides. these hydroxides have the consistency of a gel, and may occupy relatively large volumes; over time, they harden into scale deposits.

Indicators of incrusting groundwater are:

1. **pH** - pH above 7.5
2. **Carbonate hardness-** If the carbonate hardness of the groundwater exceeds 300 ppm, incrustation due to deposition of calcium carbonate is likely
3. **Iron-** If the iron content of the water exceeds 2 ppm, incrustation due to precipitation of iron is likely.
4. **Manganese** - If the manganese content of the water exceeds 1 ppm, coupled with high pH, incrustation is extremely likely if oxygen is present (Driscoll, 1975).

Another common problem with well casings, screens, mains, and pipelines in the coal measures is the formation of **iron bacteria** in openings or adjacent areas due to elevated iron and/or manganese in the local groundwater. Crenothrix, Gallionella, and other iron bacteria utilize iron as a source of energy and store it in their microbial protoplasm. Problems are generally encountered at iron concentrations above 0.2 mg/L. These bacteria can become so numerous in the conveyance system that clogging can occur with resultant flow loss. Iron bacteria thrive best in the dark and are found most frequently in water containing little or no oxygen and a considerable amount of carbon dioxide along with dissolved iron. These bacteria obtain their energy by oxidizing ferrous ions to ferric ions. Precipitation of the iron and rapid growth of the bacteria create a voluminous material that quickly plugs any openings.

Durability of Concrete Structures

Two of the principal aggressive factors which affect the durability of concrete structures and are also a common by-product of mining in the eastern coal measures are sulfates and acidity. Problems resulting from **acid attack** to concrete are dependent on the following variables: (1) total acidity and pH of groundwater and (2) groundwater replenishment rate. When in contact with portland cement concrete, acid will attack the exposed surface and be neutralized by the alkalinity of the concrete. A given quantity of an acid will destroy a given mass of concrete, in proportion to the total alkalinity of the concrete. Without acid replenishment, the reaction stops. In static groundwater conditions acidity is the governing parameter, however the greater the anticipated movement of groundwater the greater is the replenishment rate of acid and the more important is the role of pH.

As a guideline, a pH of 5.0 and total acidity of 25 milligram equivalents per 100 grams of soil indicates a potentially aggressive groundwater situation. (Bealy, 1980). Such conditions would require a more comprehensive analysis of installation characteristics to determine if countermeasures are necessary to insure durability.

Sulfates in soil, groundwater, or mine effluents can be highly aggressive to portland cement concrete by combining chemically with certain constituents of the concrete, principally C_3A, to form calcium sulfoaluminate. This reaction is accompanied by expansion and eventual disruption of the concrete. If the concrete mass is dense, the action is superficial, such as rust on the surface of metal. If the concrete is porous, the action can be progressive through the mass. The stronger the sulfate concentration, the more active the corrosion (Table 4.3).

Table 4.3 Attack on Concrete by Waters Containing Various Sulfate Conc. (Bealy, 1980).

Relative Degree of SO_4 Attack	PPM Sulfate in Water Samples
Negligible	0 to 150
Positive	150 to 1500
Severe	1500 to 10000
Very Severe	10000 or more

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