# PREDICTED VERSUS ACTUAL WATER QUALITY AT HARDROCK MINE SITES: EFFECT OF INHERENT GEOCHEMICAL AND HYDROLOGIC CHARACTERISTICS[1]

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**Abstract.** The Environmental Impact Statements (EISs) for 70 large modern-era hardrock mines in the United States were reviewed to determine their predicted impacts to water resources. EIS predictions were then compared to actual water quality conditions for 24 of the 70 mines (case studies), and the effects of geochemical characteristics and hydrologic conditions on operational water quality were evaluated. Nearly all case study mines with close proximity to water resources and moderate to high potential for acid drainage or contaminant leaching had operational water quality impacts ranging from increases over baseline concentrations to exceedence of water quality standards, with most having exceedences of standards. EIS water quality predictions made after considering the effects of mitigations largely underestimated actual impacts to groundwater, seeps, and surface water. EIS water quality predictions made before the ameliorating effects of mitigations were considered were more accurate at predicting operational water quality. Of the case study mines with these inherent geochemical and hydrologic characteristics, at least three-quarters underestimated operational water quality impacts in their pre-mining EIS predictions.

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## Introduction

This study is part of a larger study on the reliability of water quality predictions in Environmental Impact Statements (Kuipers et al., 2005). The larger study compares predictions about operational water quality with predictions made about operational water quality in EISs. Such a comprehensive comparison has never before been completed for hardrock mines. Regulatory agencies, the pubic, and the mining community need to know the reliability of water quality predictions in order to set adequate bond amounts and to reduce future liability associated with hardrock mining. The public accessibility of documents under the National Environmental Policy Act (NEPA) made the collection of EISs for this study possible.

## Methods and Approach

After identifying 182 major hardrock mines and 136 major mines eligible for National Environmental Policy Act (NEPA), the Environmental Impacts Statements or Assessments were reviewed for 70 NEPA-eligible mines. Two levels of study were undertaken for this project: reviewing all available EISs for information relevant to water quality predictions; and a more in-depth study of a more limited number of mines for a comparison of predicted and actual water quality. The primary goal of the in-depth studies is to gain insights into the methods and approaches used to predict water quality and to determine whether these tools were successful.

For the 70 NEPA-eligible mines with reviewed EISs, the information gathered from the NEPA documents was scored numerically for entry into an Excel database. The scoring allowed statistics to be performed on the information in the NEPA documents. The information collected consisted of the following elements: geology/mineralization; climate; hydrology; field and lab tests performed; constituents of concern identified; predictive models used; water quality impact potential; mitigations; predicted water quality impacts; and discharge information. For each element and sub-element, a score was derived to characterize the element (e.g., geology/mineralization used six scores, including one for no information provided). Scores generally included zero (no information available), 1 for low (acid generation potential, far from water resources, low potential to impact water resources, etc.), 2 for moderate, and 3 for high or closer proximity to water resources. For mines with multiple EISs, the highest score was used (i.e., score for the EIS that predicted the highest acid generation potential or closest proximity to water resources, etc.) when discussing the mine as a whole. However, the scores for the individual EIS were also maintained in the database. The details of the scoring are contained in Kuipers et al. (2005), and specific scoring details for this paper will be provided when the results are presented in later sections.

Each case study includes a brief description of the information contained in the NEPA documents for each mine, along with information on water quality impacts either included in the NEPA documents, or contained in other documents as referenced. A summary of information on the water quality impacts and their causes is then provided for each mine in the larger study (Kuipers et al., 2005).

The availability of water quality information after mining began was one of the primary factors in selecting a mine for in-depth study. For example, a number of operating or recently closed open-pit mines in Nevada and other states have no or very limited information on pit water quality because the mines have not stopped dewatering operations. These mines may have water quality information on groundwater or leachates, but no information is currently available that can be used to compare pit-lake water quality predictions in the EIS to actual water quality. In addition to the availability of water quality information, the selected mines are also intended to represent a cross-section of commodities, mining types, and climates. In making the final selection of mines for in-depth study, the following priorities were identified: mines with long histories and NEPA documentation from new project through reclamation and closure; mines with different proximities to water resources; mines that conducted some geochemical testing, and if possible, some water quality modeling; and mines with different potentials to generate acid and leach contaminants to water resources.

There are two types of "predictions" made in EISs: "potential" water quality (a prediction that does not take mitigations into account) and "predicted" water quality (a prediction that does take mitigations into account). Nearly all the EISs reviewed reported that they expected acceptable water quality (concentrations lower than relevant standards) after mitigations were taken into account. Indeed, if this prediction was not made in the EIS, the regulatory agency would not be able to approve the mine (with certain exceptions, such as pit water quality, in states where pit water is not considered a water of the state). For the 70 mines with EISs reviewed (including the case study mines), we recorded both "potential" and "predicted" water quality from information in the NEPA documents. For the case study mines, comparisons were made between potential, predicted, and actual water quality conditions.

The list of mines that meet these criteria and had publicly available operational water quality information is limited. In some cases, later EISs include an evaluation of operational water quality conditions. These cases provide the most readily accessible, although not only, opportunities for insight into the accuracy of water quality predictions made in EISs. In addition to data from NEPA documents, operational water quality data were obtained from State agencies or consultant or agency report for mines in Arizona, Nevada, California, and Wisconsin.

## Selected Case Study Mines

In all, 22 different mines with complete NEPA documents and additional water quality information were selected for a comparison of water quality predictions (made in EISs) and actual water quality conditions after mining began. In addition, two mines presently being constructed (Safford, AZ and Pogo, AK) were selected to compare NEPA information and mining practices at new mines with mines that have been operating for various time periods. Table 1 shows the complete list of 24 mines selected for case studies.

## General Characteristics of Case Study Mines

The general characteristics of the case study mines, including location (state), commodity, extraction and processing methods, and operational status, are similar to those of the larger set of NEPA mines with reviewed EISs (Table 2). The mines studied in detail include two from Alaska, three from Arizona, three from California, two from Idaho, six from Montana, seven from Nevada, and one from Wisconsin. Sixteen primary gold and/or silver mines were selected for study in detail. Three of the mines selected are primary Cu or Cu/Mo mines. Three mines selected are polymetallic mines (Au, Ag, Cu, Pb, Zn). One Pt group metals mine and one primary Mo mine were also selected.

Table 1. Case Study Mines.

| Mine | State |
|---|---|
| Greens Creek | AK |
| Pogo | AK |
| Bagdad | AZ |
| Ray | AZ |
| Safford | AZ |
| Jamestown | CA |
| McLaughlin | CA |
| Royal Mountain King | CA |
| Grouse Creek | ID |
| Thompson Creek | ID |
| Beal Mountain | MT |
| Black Pine | MT |
| Golden Sunlight | MT |
| Mineral Hill | MT |
| Stillwater | MT |
| Zortman and Landusky | MT |
| Florida Canyon | NV |
| Jerritt Canyon | NV |
| Lone Tree | NV |
| Rochester | NV |
| Round Mountain | NV |
| Ruby Hill | NV |
| Twin Creeks | NV |
| Flambeau | WI |

Five of the mines selected for study are underground mines, 17 are open pit mining operations, and two are combined open pit and underground mining operations. For ore processing, six of the mines use flotation (and in some cases gravity), two use both flotation and dump leach solvent extraction electrowinning (SX/EW), one uses dump leach SX/EW processing, one uses flotation with vat leaching, and 14 use either heap leaching, vat leaching, or a combination of both processes.

## EIS Information for Case Study Mines

Table 3 contains a summary of the information obtained from the NEPA documents for the case study mines, including: geology and mineralization; geochemical characterization (including constituent of concern) and modeling performed; water quality impact potential (including acid drainage and contaminant leaching potential and groundwater, surface water, and pit water impact potential); predicted water quality impacts (for surface water, groundwater, and pit water); and discharges (zero discharge, surface water discharge, or groundwater discharge). The results and discussion in the following sections refer to information presented in Table 3.

Table 2. Comparison of General Characteristics for NEPA Mines with Reviewed EISs and Case Study Mines.

| **Characteristic** | **Feature** | **NEPA-Eligible Mines with Reviewed EIS's (% of Total)** | **Case Study Mines (% of Total)** |
|---|---|---|---|
| State | Alaska | 10% | 8% |
| | Arizona | 11% | 13% |
| | California | 11% | 13% |
| | Colorado | 0% | 0% |
| | Idaho | 8.6% | 8.3% |
| | Michigan | 0% | 0% |
| | Montana | 19% | 25% |
| | Nevada | 33% | 29% |
| | New Mexico | 2.9% | 0% |
| | South Carolina | 0% | 0% |
| | South Dakota | 1.4% | 0% |
| | Utah | 1.4% | 0% |
| | Washington | 0% | 0% |
| | Wisconsin | 1.4% | 4.2% |
| Commodity | Primary Gold | 20% | 17% |
| | Primary Silver | 7.1% | 4.2% |
| | Gold and Silver | 54% | 54% |
| | Primary Copper | 20% | 8.3% |
| | Copper and Molybdenum | 1.4% | 4.2% |
| | Molybdenum | 1.4% | 4.2% |
| | Lead and Zinc | 5.7% | 4.2% |
| | Platinum Group | 2.9% | 4.2% |
| Extraction and Processing Methods | Underground | 19% | 21% |
| | Open Pit | 71% | 71% |
| | Underground and Open Pit | 10% | 8.3% |
| | Heap or Vat Leach | 61% | 63% |
| | Flotation and/or Gravity | 27% | 33% |
| | Dump Leach (SX/EW) | 11% | 13% |
| | Heap Leach only | 26% | 21% |
| | Vat Leach only | 14% | 13% |
| | Heap Leach and Vat Leach | 21% | 21% |
| | Smelter | 1.4% | 4.2% |
| Operational Status | Operating | 49% | 54% |
| | Closed | 37% | 38% |
| | In Construction | 1.4% | 4.2% |
| | Permitting | 7.1% | 4.2% |
| | Withdrawn | 5.7% | 0% |
| Total Number | | **70** | **24** |

Table 3. EIS Information for Case Study Mines.

| NEPA EIS Water Quality Category | | Greens Creek | Pogo | Bagdad | Ray | Safford | Jamestown | McLaughlin | Royal Mountain King | Grouse Creek | Thompson Creek | Beal Mountain | Black Pine |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AK** | **AK** | **AZ** | **AZ** | **AZ** | **CA** | **CA** | **CA** | **ID** | **ID** | **MT** | **MT** |
| Geology and Mineralization | | Sulfides present, carbonate or mod/high NP rock present | No/insufficient information available | Sulfides present, no carbonates/ carbonates not mentioned or associated with ore body. | No/insufficient information available | Sulfides present, no carbonates/ carbonates not mentioned or associated with ore body. | No/insufficient information available | No/insufficient information available | No/insufficient information available | Sulfides present, no carbonates/ carbonates not mentioned or associated with ore body | Sulfides present, carbonate or mod- high NP rock present | Sulfides present, no carbonates/ carbonates not mentioned or associated with ore body. | Sulfides present, no carbonates/ carbonates not mentioned or associated with ore body. |
| Geochemical Characterization and Modeling | Testing Methods | Static, short-term leach, kinetic | Static and kinetic | Static | None/unknown | Static and short-term leach | Short-term leach | Static and short-term leach | Static | Static and short-term leach | Static, short-term leach, kinetic | Static, short-term leach, kinetic | No information |
| | Constituents of Concern | zinc | No information available | arsenic, fluoride, lead, metals, sulfate | copper, beryllium, zinc, turbidity, pH | Pit: aluminum, copper, iron, manganese, nickel, zinc, thallium, sulfate | Tailings leachate: barium, arsenic, chromium | copper | No information | lead, arsenic, cyanide, ammonia, nitrate | cadmium, copper, iron, lead, zinc, selenium, sulfate | arsenic, cadmium, lead, nitrate, sulfate, cyanide, TDS | sulfate, copper, zinc, iron, cadmium, low pH |
| | Predictive Models | Water quality and quantity | Water quality and quantity | None | None | Water quality and quantity | None | None | None | Water quantity | Water quality and quantity | None | None |
| Water Quality Impact Potential | Acid Drainage Potential | Moderate | Low | Low | No information | Low | Low | Low | Low | Moderate | Moderate | Moderate | High |
| | Contaminant Leaching Potential | Low | Moderate | No information | No information | Low | Low | Moderate | No information | Low | Low | Low | Moderate |
| | Groundwater Impact Potential | Moderate | High | Low | No information | No information | Moderate | High | Moderate | Moderate | Moderate | Moderate | No information |
| | Surface Water Impact Potential | Moderate | Low | Low | No information | No information | Moderate | Moderate | No information | Moderate | Moderate | Moderate | No information |
| | Pit Water Impact Potential | No pit lake expected to form | No pit lake expected to form | Low | No information | High | Moderate | High | No information | Moderate | Moderate | No information | No pit lake expected to form |
| Predicted Water Quality Impacts | Groundwater | Low | High | Low | No information | Low | Low | High | No information | Low | Moderate | Low | Low |
| | Surface Water | Low | Moderate | Low | No information | Low | Low | Moderate | No information | Low | Moderate | Low | Low |
| | Pit Water | No pit lake expected to form | No pit lake expected to form | No information | No information | Low | Moderate | High | No information | Low | Low | Low | No pit lake expected to form |
| Discharges | Zero Discharge | | | | | | Yes | | No information | Yes | | Yes | Yes |
| | Surface Discharge | Yes | Yes | Yes | Yes | Yes | | Yes | No information | | Yes | | |
| | Groundwater Discharge | | | | | | | | No information | | | | |

# Table 3. EIS Information for Case Study Mines.

| NEPA EIS Water Quality Category | | Golden Sunlight | Mineral Hill | Stillwater | Zortman and Landusky | Florida Canyon | Jerritt Canyon | Lone Tree | Rochester | Round Mountain | Ruby Hill | Twin Creeks | Flambeau |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **MT** | **MT** | **MT** | **MT** | **NV** | **NV** | **NV** | **NV** | **NV** | **NV** | **NV** | **WI** |
| Geology and Mineralization | | High sulfide content, carbonates low/not present | Sulfides present, no carbonates/carbonates not mentioned or associated with ore body. | Sulfides present, carbonate or mod- high NP rock present | Sulfides present, no carbonates/carbonates not mentioned or associated with ore body. | Sulfides present, carbonate or mod- high NP rock present | Low sulfide content, carbonate present or hosted in carbonate | Sulfides present, carbonate or mod- high NP rock present | Low sulfide content, carbonate present or hosted in carbonate | Sulfides present, carbonate or mod- high NP rock present | Sulfides present, carbonate or mod- high NP rock present | Sulfides present, carbonate or mod- high NP rock present | Sulfides present, no carbonates/carbonates not mentioned or associated with ore body. |
| Geochemical Characterization and Modeling | Testing Methods | Static, short-term leach, kinetic | Short-term leach and kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic | Static, short-term leach, kinetic |
| | Constituents of Concern | aluminum, arsenic, cadmium, copper, zinc, pH, sulfate, chromium, iron, lead, manganese, nickel, selenium, nitrate | arsenic, cyanide, manganese, nitrate | nitrate | aluminum, cadmium, iron, copper, fluoride, zinc, cyanide, metallocyanide complexes, low pH, sulfate, nitrate, arsenic | aluminum, antimony, arsenic, cadmium, iron, lead, mercury, thallium, TDS, cyanide | arsenic, selenium, nitrate, sulfate | arsenic, iron, cyanide, antimony, cadmium, nickel, fluoride, sulfate, TDS | iron, aluminum, copper, lead, cadmium, zinc, pH | aluminum, arsenic, fluoride, nickel, zinc, antimony, selenium, iron, mercury, lead, manganese, nitrate, sulfate, TDS | arsenic, aluminum, antimony, TDS, pH | pH, TDS, zinc, beryllium, cadmium, selenium, aluminum, antimony, arsenic, iron, manganese, mercury, nickel, thallium, sulfate | iron, manganese, sulfate |
| | Predictive Models | Water quality and quantity | Water quantity | Water quality and quantity | Water quantity | Water quantity | None | Water quality and quantity | None | Water quality and quantity | Water quality and quantity | Water quality and quantity | Water quality |
| Water Quality Impact Potential | Acid Drainage Potential | High | Low | Low | High | Low | Moderate | Moderate | Moderate | Low | Low | Moderate | No information available |
| | Contaminant Leaching Potential | High | Moderate | Moderate | Moderate | High | Moderate | High | Moderate | High | Moderate | High | Moderate |
| | Groundwater Impact Potential | High | Moderate | Low | Moderate | High | Moderate | Low | Moderate | High | Low | Moderate | Moderate |
| | Surface Water Impact Potential | Low | Low | Low | High | No information available | Moderate | Moderate | Moderate | Moderate | Low | High | Moderate |
| | Pit Water Impact Potential | High | No pit lake expected to form | No pit lake expected to form | No information available | No information available | No pit lake expected to form | High | No pit lake expected to form | Moderate | No pit lake expected to form | High | High |
| Predicted Water Quality Impacts | Groundwater | High | Low | Low | High | Low | Low | Low | Low | Low | Low | Low | Low |
| | Surface Water | Low | Low | Low | High | Low | Low | Low | Low | Low | Low | Low | Low |
| | Pit Water | High | No pit lake expected to form | No pit lake expected to form | High | No pit lake expected to form | No pit lake expected to form | High | No pit lake expected to form | Moderate | No pit lake expected to form | High | High |
| Discharges | Zero Discharge | No information | | | | Yes | No information | | No information | Yes | Yes | | |
| | Surface Discharge | No information | Yes | Yes | Yes | | No information | Yes | No information | | | Yes | Yes |
| | Groundwater Discharge | No information | | Yes | | | No information | | No information | | | Yes | |

## Inherent Factors Affecting Water Quality at Mine Sites

One of the goals of the larger study (Kuipers et al., 2005) was to determine if there are certain factors that make a mine more or less likely to cause water quality problems. Some of the characteristics that may influence the environmental behavior of a mine include:

- Ore type and association (e.g., commodity, sulfide vs. oxide ore, vein vs. disseminated)
- Climate (e.g., amount and timing of precipitation, evaporation, temperature)
- Proximity to water resources (distance to surface water resources, depth to groundwater resources, presence of springs)
- Pre-existing water quality (baseline groundwater and surface water quality conditions)
- Processing chemicals used
- Type of operation (e.g., vat leach and tailings vs. heap leach facility; underground vs. surface mine)
- Constituents of concern
- Acid generation and neutralization potentials (and timing of their release)
- Contaminant leaching potential

Of these, the ore type and association, climate, proximity to water resources, constituents of concern, acid generation potential, and contaminant leaching potential are considered inherent factors that are a function only of the mine’s geochemical characteristics and physical location. The acid generation and contaminant leaching potential refer to the potential of the mined material before mitigations are put in place. While these potentials can have different environmental effects depending on mitigation, their pre-mitigation potentials are considered inherent in this study. For this study, the proximity to water resources was considered to be a function of climatic conditions (as shown in Kuipers et al., 2005); therefore, climate will not be discussed separately. Similarly, the constituents of concern will be reflected in the contaminant leaching potential and will not be discussed separately. The characteristics listed above that are not considered inherent factors are the type of processing chemicals used, the type of operation, and the pre-existing water quality. These characteristics are instead more dependent on economics or site history (which in turn is a function of both inherent and non-inherent factors) than on geochemical and geographic factors.

The following sections examine the influence of inherent factors on operational water quality for the 24 case study mines. Information from the EISs was used to identify the inherent factors listed above, and operational water quality was used to determine if water quality impacts were present after mining began. The inherent factors evaluated below include: geology and mineralization, proximity to water resources, and geochemical characteristics of mined materials, such as acid drainage and contaminant leaching potential.

### Geology and Mineralization

For five of the 24 case study mines, little or no information was available on rock type or mineralization, as shown in Table 3. Geologic and mineralogic information available in the EISs was generally insufficient to make even general predictions about contaminant leaching potential or acid generation potential based on mineralogy (e.g., identification of arsenic-containing minerals).

The identification of geology and mineralization, as currently conducted in EISs, is generally a blunt tool for predicting water quality impacts. Geologic and mineralogic information is usually focused on the ore body rather than on all mined materials that could potentially impact water resources. We found relatively weak relationships between geology and mineralization or ore association and identified acid drainage potential. For example, nine of the case study mines indicated that either sulfides were present or there was a high sulfide content and that there was no carbonate material present. However, five of these identified low to moderate acid drainage potential.

The reasons for the low acid drainage potential scores may be related to different rocks being evaluated for mineralization and acid drainage potential or to other factors that were considered by the mine in determining the potential for acid drainage. However, the discrepancy or lack of good agreement between identified mineralization and acid drainage potential highlights the importance of coordinating mineralogic and acid drainage potential evaluations in the NEPA process. As noted in Maest et al. (2005), the same geochemical test units should be used for testing of all parameters used to predict water quality impacts. In addition, more extensive information on mineralogy and mineralization should be included in EISs.

### Geochemical Characteristics of Mined Materials

This section discusses changes in geochemical characterization approaches over time, as reflected in the reviewed EISs. It also discusses combinations of geochemical characteristics and proximity to water resources, and examines linkages between these combinations of inherent factors and operational water quality.

Changes in Geochemical Characterization Testing over Time. The use of geochemical characterization testing in EISs has changed somewhat over the years. Mines with EISs or Environmental Impact Reviews (EIR's), are expected to have more geochemical characterization information than mines with EAs. The EISs reviewed in detail spanned a period from 1978 to 2004. The first EISs (for Troy Mine in Montana in 1987 and Zortman and Landusky Mine in Montana in 1979) did not provide any information on geochemical characterization. Starting in 1980, mines began to provide basic information on geochemical characterization, such as static and short-term leach testing.

The first kinetic tests performed at the group of 70 mines with reviewed EISs were five-day "weathering" tests conducted in 1981 at the Stibnite Mine in Idaho. Kinetic testing was combined with other types of geochemical characterization testing (static and/or short-term leach tests) beginning in 1986 at the Mineral Hill Mine in Montana. After 1990, many of the mines were conducting combinations of kinetic testing and static or short-term leach testing. However, a number of mines still used only static testing to help predict acid drainage potential. The availability of geochemical characterization data affects our ability to determine the potential for mines to release contaminants to water resources.

Identified Acid Drainage and Contaminant Leaching Potential. Two of the case study mines had no information on acid drainage potential (Ray, AZ and Flambeau, WI) in their NEPA documents (see Table 3). Eleven of the 24 case study mines (46%) identified low acid drainage potential, eight (33%) identified moderate acid drainage potential, and only three (Black Pine, Golden Sunlight, and Zortman Landusky – all in Montana) identified high acid drainage potential. Generally the potential for acid generation was presented verbally in the text of the NEPA document, even though the basis may have been extensive acid-base accounting (ABA) and/or kinetic testing. In a number of cases the ABA testing results suggested that the mined material could be acid generating, but kinetic testing produced neutral leachate and the material was considered to have low acid generation potential.

The potential for contaminant leaching was generally based on information from short-term leach tests or kinetic testing. The geochemical testing results presented in the NEPA documents were used to score the mine as having low potential for contaminant leaching if leachate from the tests did not exceed water quality standards, moderate potential if the leachate exceeded water quality standards by one to ten times, and high potential if the leachate exceeded water quality standards by over 10 times. The verbal summaries, as discussed above for acid generation potential, were used if no quantitative information was available in the NEPA documents. Three mines (Bagdad and Ray, AZ and Royal Mountain King, CA) had no information on contaminant leaching potential in their NEPA documents. Royal Mountain King had information on contaminant leaching potential in its Report of Waste Discharge, but this information was not transferred to the EIR and was therefore not readily available to the public. Six mines (25%) identified a low potential for contaminant leaching; 11 (46%) identified a moderate potential; and four (17% - Golden Sunlight, MT; Lone Tree, Round Mountain, and Twin Creeks, NV) identified a high potential for contaminant leaching.

## Relationships between Inherent Factors and Operational Water Quality at Case Study Mines

This section examines the relationships between multiple inherent factors (proximity to water resources and geochemical characteristics) and operational water quality. For this evaluation, a water quality impact is defined as increases in water quality parameters as a result of mining operations, whether or not an exceedence of water quality standards or permit levels has occurred. Information on whether groundwater, seep, or surface water quality exceeded standards is also included. For this section, EIS predictions and information are compared to operational water quality; therefore, the Pogo Mine in Alaska and the Safford Mine in Arizona are excluded because they have not yet become operational. Mines with close proximity to water resources and moderate to high acid drainage or contaminant leaching potential are examined together to determine if this combination of inherent factors results in a higher risk of adverse water quality impacts. Results for case study mines with this combination of factors are included in Tables 4a (surface water) and b (groundwater and seeps). Table 4 lists the following information: acid drainage and contaminant leaching potential; whether or not there was a surface water or groundwater impact; whether or not acid drainage has developed on the site; whether or not standards have been exceeded in surface water, groundwater or seeps; which constituents have seen increases over baseline conditions or exceed standards; and whether there are perennial streams on site or there is a discharge to surface water, or both. The discharges to surface water are usually permitted National Pollution Discharge Elimination System (NPDES) discharges under the Clean Water Act. Table 4 also includes information from the EISs on predictions. The last two columns list the highest potential (pre-mitigation) impact to surface water, groundwater and seeps, and the highest predicted (post-mitigation) impact to these resources. More information on mines with other types of inherent characteristics and conditions is provided in Kuipers et al. (2005).

Mines with Perennial Streams on Site or Direct Surface Water Discharges and Moderate to High Acid Drainage or Contaminant Leaching Potential

This section addresses mines with close proximity to surface water that also have moderate to high potential for developing acid drainage or contaminant leaching. The next section addresses mines with close proximity to surface water that have the same geochemical characteristics.

Mines with Moderate to High Acid Drainage Potential. The following case study mines have perennial streams on site or discharge directly to surface water and have a moderate to high acid drainage potential:

- Greens Creek, Alaska
- Grouse Creek, Idaho
- Thompson Creek, Idaho
- Beal Mountain, Montana
- Black Pine, Montana
- Zortman and Landusky, Montana
- Jerritt Canyon, Nevada
- Lone Tree, Nevada
- Twin Creeks, Nevada

Of these nine mines, all had some impact to surface water quality (Table 4a). Of the nine mines with identified moderate to high acid drainage potential and close proximity to surface water resources, four have currently developed acid drainage on site. Impacts to surface water from the other five mines resulted from CN, $NO_3^-$, $SO_4^{-2}$, metalloids, ammonia, or other anions.

At the Greens Creek Mine, elevated concentrations of $SO_4^{-2}$ and Zn and lower pH values have been measured in smaller streams, most likely as a result of leaching of high sulfide material (tailings or waste rock) lying outside of the tailings pile capture area. At the Grouse Creek Mine, tailings impoundment leakage into groundwater resulted in Cn in surface water. At the Thompson Creek Mine, creeks downgradient of the waste rock dumps had increasing concentrations of $SO_4^{-2}$ (to values in excess of water quality standards) over a six-year period. At the Beal Mountain Mine, $NO_3^-$, TDS, and $SO_4^{-2}$ concentrations in streams have increased relative to baseline conditions, and CN exceeded aquatic life standards. At the Black Pine Mine, springs impacted by waste rock flow into Smart Creek and have elevated concentrations of $SO_4^{-2}$, Cu, Zn, Fe, and Cd, and low pH values. At the Zortman and Landusky Mine, streams have been impacted by acid drainage from waste rock and the heap leach pad. The Lone Tree Mine has been in general compliance with overall permit requirements for discharge of its dewatering water to the Humboldt River, but there have been some exceedences of permit limits, and Newmont has been fined for these exceedences. Although no information was obtained on stream water quality at the Twin Creeks Mine, dewatering water discharged to Rabbit Creek has shown exceedences of TDS and arsenic standards by up to ten times.

These results, although not comprehensive, suggest that the combination of proximity to surface water resources (including direct discharges to surface water) and moderate to high potential for acid drainage does increase the risk of water quality impacts. All of these nine mines predicted a low impact to surface water after mitigations were in place in at least one or all of the EISs. For the Thompson Creek and Zortman Landusky mines, later EISs predicted a

Table 4a. EIS and Operational Water Quality Information on Case Study Mines with Moderate to High Acid Generation or Contaminant Potential and Perennial Streams on Site or Discharge to Surface Water.

| Site | State | Acid Drainage Potential | Contaminant Leaching Potential | SW Impact? | Acid Drainage Developed on Site? | Standards Exceeded? | Constituents Increasing or Exceeding | Perennial or Discharge? | Highest Potential Impact to SW | Highest Predicted Impact to SW |
|---|---|---|---|---|---|---|---|---|---|---|
| Greens Creek | AK | 2 | 1 | Yes | Yes | Yes | low pH, Cd, Cu, Hg, Zn, $SO_4$ | Both | 2 | 1 |
| McLaughlin | CA | 1 | 2 | Yes | Yes | Yes | $SO_4$, As, Cr, Cu, Pb, Mn, Ni, Hg, Fe, Zn | Discharge | 2 | 2 |
| Grouse Creek | ID | 2 | 1 | Yes | No | Yes | CN exceeded in surface water | Perennial | 2 | 1 |
| Thompson Creek | ID | 2 | 1 | Yes | Yes | Yes | Cd, Cu, Pb, Zn, $SO_4$ | Both | 2 (1) | 2 (1) |
| Beal Mountain | MT | 2 | 1 | Yes | No | Yes | $NO_3$, TDS, $SO_4$, CN | Both | 2 | 1 |
| Black Pine | MT | 3 | 2 | Yes | Yes | Yes | $SO_4$, Cu, Zn, Fe, Cd, low pH | Perennial | 0 | 1 |
| Mineral Hill | MT | 1 | 2 | Yes | No | Yes | CN, $NO_3$, Mn, $SO_4$, As, TDS | Discharge | 1 | 1 |
| Stillwater | MT | 1 | 2 | Yes | No | No | $NO_3$ | Discharge | 1 | 1 |
| Zortman and Landusky | MT | 3 | 2 | Yes | Yes | Yes | metals, metalloids, $NO_3$, low pH, CN | Both | 3 | 3 (1) |
| Jerritt Canyon | NV | 2 | 2 | Yes | No | Yes | TDS, $SO_4$ | Perennial | 2 | 1 |
| Twin Creeks | NV | 2 | 3 | Yes | No | Yes | TDS, As | Both | 3 | 1 |
| Lone Tree | NV | 2 | 3 | Yes | No | Yes | pH, TDS, F, B, $NH_4$ | Discharge | 2 | 1 |
| Flambeau | WI | 0 | 2 | No | Yes | No | $SO_4$, Mn, low pH, Fe | Discharge | 2 | 1 |

1=low; 2=moderate; 3=high. SW=surface water; GW=groundwater.

Table 4b. EIS and Operational Water Quality Information on Case Study Mines with Moderate to High Acid Generation or Contaminant Potential and Shallow Depth to Groundwater on Site or Discharge to Groundwater.

| Site | State | Acid Drainage Potential | Contaminant Leaching Potential | GW or Seeps Impacted? | Acid Drainage Developed on Site? | Standards Exceeded? | Constituents Increasing or Exceeding in GW or Seeps | Shallow GW or GW Discharge? | Highest (Lowest) GW Impact Potential | Highest (Lowest) Predicted GW Impact |
|---|---|---|---|---|---|---|---|---|---|---|
| Greens Creek | AK | 2 | 1 | Yes | Yes | Yes - seeps | GW: $SO_4$; seeps: $SO_4$, Zn, pH, Cu, Pb, Se | Shallow GW | 2 | 1 |
| McLaughlin | CA | 1 | 2 | Yes | Yes | Yes - GW | TDS, Cl, $NO_3$, $SO_4$, Cu, Fe, Mn, B, Zn | Shallow GW | 3 | 3 |
| Grouse Creek | ID | 2 | 1 | Yes | No | Yes - GW | CN; Al, Cu, As, Se, Ag, Zn, CN in tail pore water | Shallow GW | 2 (1) | 1 |
| Thompson Creek | ID | 2 | 1 | Yes | Yes | Yes - seeps | Seeps: Fe, Zn, $SO_4$, Se; GW: no info | Shallow GW | 2 (0) | 2 (1) |
| Beal Mountain | MT | 2 | 1 | Yes | No | Yes - GW and seeps | GW: $NO_3$, Fe, CN; TDS. Seeps: CN, Se, $SO_4$, $NO_3$ | Shallow GW | 2 | 1 |
| Black Pine | MT | 3 | 2 | Yes | Yes | Yes - Seeps; NA - GW | Seeps: low pH, $SO_4$, Cu, Zn, Fe, Cd; GW: no info | Shallow GW | 0 | 1 |
| Golden Sunlight | MT | 3 | 3 | Yes | Yes | Yes - GW and seeps | CN, Cu, low pH | Shallow GW | 3 (2) | 3 (1) |
| Stillwater | MT | 1 | 2 | No - GW; Yes - adit | No | No - GW; Yes - adit | Adit: Cd, Cu, Pb, Mn, Zn, $NO_3$. GW: Cr, Fe, $SO_4$, Cl, $PO_4$, Cd, Zn | Both | 1 | 1 |
| Zortman Landusky | MT | 3 | 2 | Yes | Yes | Yes - GW and seeps | low pH, As, metals, $NO_3$, CN | Shallow GW | 2 (1) | 3 (1) |
| Florida Canyon | NV | 1 | 2 | Yes | No | Yes | CN, Hg, $NO_3$, Cl, TDS | Shallow GW | 3 | 1 |
| Jerritt Canyon | NV | 2 | 2 | Yes | No | Yes - GW | CN, Cl, TDS, $SO_4$ | Shallow GW | 2 (1) | 1 |
| Lone Tree | NV | 2 | 3 | No? | No | Yes (baseline?) | F, Fe, Mn, TDS, Al, B, $NH_4$, pH | Shallow GW | 1 | 1 |
| Rochester | NV | 2 | 2 | Yes | No | Yes - GW | CN, Hg, Cd, $NO_3$, As | Shallow GW | 2 | 1 |
| Twin Creeks | NV | 2 | 3 | Yes | No | Yes - perched GW | TDS, $SO_4$, Cl , CN, Al, Sb, As, Mg, Fe, Hg, Mn | GW Discharge | 2 | 1 |
| Flambeau | WI | 0 | 2 | Yes | Yes | Yes | Fe, Mn, pH, $SO_4$, TDS | Shallow GW | 2 | 1 |

higher potential impact to surface water, but in both cases the initial EIS, on which the mitigations were based, predicted a low impact to surface water resources. These results suggest that even though mines may identify a moderate to high acid drainage potential, they predict that surface water resources will not be impacted after mitigations are implemented. In all cases examined, these predictions underestimated the eventual impact to surface water resources.

<u>Mines with Moderate to High Contaminant Leaching Potential</u> The following mines have perennial streams on site or discharge directly to surface water and identified a moderate to high potential for contaminant leaching in their EISs:

- McLaughlin, California
- Black Pine, Montana
- Mineral Hill, Montana
- Stillwater, Montana
- Zortman and Landusky, Montana
- Jerritt Canyon, Nevada
- Lone Tree, Nevada
- Twin Creeks, Nevada
- Flambeau, Wisconsin

Of these nine mines, five also have moderate to high acid drainage potential and proximity to surface water resources, as discussed above. All of these have had some impact to surface water quality from mining operations, as shown in Table 4a. Of the remaining four mines, the McLaughlin Mine has had some impact to surface water quality, including high concentrations of $SO_4^{-2}$ (showing steady increases since mining has begun) and nickel. Downstream surface monitoring locations show exceedences of $SO_4^{-2}$, and occasionally large exceedences of As, Cr, Cu, Pb, Mn, Hg, Fe, and Zn. Apparently no violations of surface water quality have been recorded for the McLaughlin Mine. At the Mineral Hill Mine, tailings leachate containing CN, $NO_3^-$, Mn, $SO_4^{-2}$, As, and TDS has escaped the liner system and caused exceedences in surface water. The Stillwater Mine does not have perennial streams on site, but it does have a NPDES permit for discharge of mine water to surface water. However, this permit has never been used. Nitrate concentrations in the Stillwater River have increased to as high as 0.7 mg/l (limit is 1.0 mg/l) as a result of mining activity, but no standards or limits have been exceeded. At the Flambeau Mine, there have been no observable changes in surface water quality, but there is some concern that surface water sample locations may not capture all releases from mine. The Flambeau Mine has had groundwater impacts from the backfilled pit. More monitoring of additional locations and over a longer time period is required before we will know if observed poor groundwater quality will adversely affect downgradient surface water.

Therefore, for nine mines with proximity to surface water resources and moderate to high contaminant leaching potential, eight have shown some impact to surface water quality. Seven of the nine mines have had exceedences of standards in surface water. These results, although not comprehensive, suggest that the combination of proximity to surface water resources (including direct discharges to surface water) and moderate to high potential for contaminant leaching does increase the risk of water quality impacts. In terms of EIS predictions, six of the nine mines identified a moderate to high potential for surface water impacts without mitigations, but eight of the nine predicted a low impact to surface water after mitigations were in place (as noted above, the Zortman Landusky Mine initially predicted a low impact to surface water resources). To date, predictions for surface water impacts at the McLaughlin, Stillwater, and Flambeau mines have been accurate, but the remaining six mines underestimated the actual impact to surface water in their EISs.

Overall, for the 13 mines with close proximity to surface water and high acid drainage or contaminant leaching potential (see Table 4a), 12 (92%) have had some impact to surface water as a result of mining activity. Eleven of the 13 (85%) have had exceedences of standards or permit limits in surface water as a result of mining activity. Of the 11 with exceedences, ten (91%) predicted that surface water standards would not be exceeded. Considering the two mines that accurately predicted no surface water exceedences (Stillwater and Flambeau), and the one that accurately predicted exceedences (McLaughlin), 77% of mines with close proximity to surface water or direct discharges to surface water and moderate to high acid drainage or contaminant leaching potential under predicted actual impacts to surface water. EIS water quality predictions made before the ameliorating effects of mitigations were considered ("potential" water quality impacts) were more accurate at predicting operational water quality than predictions based on assumed improvements from mitigations. Mines with these inherent factors are the most likely to require perpetual treatment to reduce or eliminate the long-term adverse impacts to surface water resources.

### Mines with Shallow Depth to Groundwater or Discharges to Groundwater and with Moderate to High Acid Drainage or Contaminant Leaching Potential

Mines with close proximity to groundwater resources are often close to surface water as well. Therefore, a number of mines evaluated above will also appear in this section. Mines that discharge to groundwater usually do so through infiltration basins or some other kind of land application. Although this is not a direct discharge to groundwater, it does increase the likelihood that the discharge water and any associated contaminants will reach groundwater.

Mines with Moderate to High Acid Drainage Potential. The following mines have a relatively shallow depth to groundwater (0 to 50 feet), have springs on site, or discharge to groundwater – and have a moderate to high acid drainage potential:

- Greens Creek, Alaska
- Grouse Creek, Idaho
- Thompson Creek, Idaho
- Beal Mountain, Montana
- Black Pine, Montana
- Golden Sunlight, Montana
- Zortman and Landusky, Montana
- Jerritt Canyon, Nevada
- Lone Tree, Nevada
- Rochester, Nevada
- Twin Creeks, Nevada

Of these 11 mines, we obtained some groundwater quality information for all but two (Thompson Creek, Idaho and Black Pine, Montana). However, there is information about seepage water quality from both of these facilities. Of the nine mines with shallow depths to groundwater, springs on site, or that discharge to groundwater and that have moderate to high acid drainage potential, all have had some impact to groundwater quality from mining operations (see Table 4b).

The Greens Creek Mine in Alaska has a depth to groundwater that ranges from the ground surface up to 50 feet deep. Seepage/runoff from the waste rock piles has an average Zn concentration of 1.65 mg/l, and tailings seepage water (including underdrain water) has had pH values as low as 5.8, with elevated $SO_4^{-2}$ (up to 2,400 mg/l), Zn (up to 3.6 mg/l), Cu, Pb, and Se concentrations. Anomalously high $SO_4^{-2}$ concentrations have been observed in groundwater monitoring wells, but metal concentrations have not increased as of 2000.

No groundwater data were obtained for the Thompson Creek Mine, which has flowing artesian wells, alluvial groundwater that is connected to streams, and some groundwater in bedrock fractures. However, tailings seepage water quality has shown increases in Fe and Zn, and $SO_4^{-2}$ and Se concentrations in waste rock seepage have been increasing since 1991, with selenium concentrations in excess of water quality standards.

At the Beal Mountain Mine in Montana, there is limited information on groundwater depth, but there are springs on site, and groundwater depth below the pit is 25 to 50 ft. Groundwater in the land application area exceeded standards for $NO_3^-$, Fe, and CN and has elevated total dissolved solids. Springs below the land application area also show appreciable increases in CN and Se. Concentrations of Se, $SO_4^{-2}$, $NO_3^-$, and total dissolved solids are elevated in springs sampled at the toe of the waste rock dump. At the Black Pine Mine in Montana, groundwater depths are approximately 45 feet in the impoundment area, and there are 30 springs in project area. Although we have no direct information on groundwater quality, seeps downgradient of waste rock and the soils barren areas are acidic (pH 2.6-4.7) and have elevated concentrations of $SO_4^{-2}$, Cu, Zn, Fe, and Cr. The Golden Sunlight Mine has alluvial groundwater at 50 to 60 feet deep and numerous springs on site. Tailings effluent has contaminated downgradient wells with CN and Cu (up to 65 mg/l Cu). Acid drainage is being produced from the waste rock dumps, ore stockpiles, tailings, and adits. The Zortman and Landusky Mine in Montana has perched groundwater at 150 to 150 feet, an overall depth to groundwater of <200 ft, and springs and seeps on site. Karst features control groundwater flow in some areas. Acid drainage has been generated from waste rock dumps (as low as pH 3.9), the ore heap retaining dikes, pit walls and floors, and leach pads and pad foundations. Sulfate concentrations have increased in alluvial groundwater downgradient of the heap retaining dikes.

The Jerritt Canyon Mine has perched groundwater at 8 to 70 feet deep, and 23 springs and 8 seeps on site. The regional groundwater depth is approximately 700 feet. Groundwater has been impacted by seepage from the tailings impoundment, and a CN plume exists on site. Groundwater in the vicinity of the tailings area also has exceedences of $Cl^-$ (up to 12,000 mg/l), TDS (up to 30,000 mg/l), and $SO_4^{-2}$. Groundwater at the Lone Tree Mine ranges from 10 to >200 feet deep. Pre-mining groundwater levels have scored the mine as being close to groundwater resources, but the large dewatering rate for this mine has lowered groundwater levels considerably. The Lone Tree Mine in Nevada has had exceedences of primary and secondary drinking water standards in groundwater, but it is not clear if the cause is baseline conditions or seepage from mine facilities. Depth to groundwater at the Rochester Mine ranges from <1 to 20 feet in the alluvial aquifer and from the ground surface to approximately 400 feet in the bedrock aquifer. There are springs on site. Leaks from the heap leach pad and the barren solution pond have caused numerous exceedences of WAD CN, Hg, Cd, $NO_3^-$, and As in groundwater. The Twin Creeks Mine, which has a large dewatering operation, has a groundwater depth of over 100 feet over most of the mine site, and the pit floor is approximately 400 feet below pre-mining groundwater levels. However, the mine discharges to groundwater through infiltration basins. Degradation of groundwater (perched water) with CN and other constituents has occurred as a result of seepage from the tailings impoundment. The vadose zone monitoring wells that were added during 2003 to monitor seepage from the tailings impoundment have shown multiple exceedences of total dissolved solids, $SO_4^{-2}$, $Cl^-$, CN, Al, Sb, As, Fe, Hg, and Mn.

Therefore, for the 11 case study mines with close proximity to groundwater resources or that discharge to groundwater and that have moderate to high acid drainage potential, eight (73%) have shown some adverse impact to groundwater quality from mining activity. Of the remaining three mines in this category, two have contaminated seeps flowing from tailings and/or waste rock storage areas (Thompson Creek and Black Pine mines), but no groundwater quality data were obtained. Therefore, a total of 10 mines (91%) have had mining-related impacts to groundwater or seeps. One mine in this category, the Lone Tree Mine, has had no groundwater impacts. However, the groundwater table at the Lone Tree Mine has been lowered considerably from dewatering operations, and it is unlikely that groundwater impacts would be evident at this time. These results, although not comprehensive, suggest that the combination of proximity to groundwater resources (including direct discharges to surface water) and moderate to high acid drainage potential does increase the risk of water quality impacts.

Mines with Moderate to High Contaminant Leaching Potential. The following mines are have a relatively shallow depth to groundwater (0 to 50 feet), have springs on site or discharge to groundwater, and have a moderate to high contaminant leaching potential:

- McLaughlin, California
- Black Pine, Montana
- Golden Sunlight, Montana
- Stillwater, Montana
- Zortman and Landusky, Montana
- Florida Canyon, Nevada
- Jerritt Canyon, Nevada
- Lone Tree, Nevada
- Rochester, Nevada
- Twin Creeks, Nevada
- Flambeau, Wisconsin

Of these 11 mines, all but four (McLaughlin, Stillwater, Florida Canyon, Flambeau) also have moderate to high acid drainage potential and were discussed above. As noted above, all of these seven mines have had some impact to groundwater or springs/seeps as a result of mining activity with the possible exception of the Lone Tree Mine in Nevada, which has exceedences in groundwater that may be related to baseline conditions.

The McLaughlin Mine in California has been touted by the mining industry as an example of a mine with laudable environmental behavior and has received numerous environmental awards. When the state of Wisconsin passed a requirement for new mines in sulfide ore bodies to demonstrate that other mines with net acid generation potential have operated and been closed for at least 10 years with out polluting groundwater or surface water (Wisconsin Act 171 (Statute §293.50), passed in 1997), the McLaughlin Mine was one of the three examples used by Nicolet Minerals in their application for a permit for the Crandon Mine (Nicolet Minerals, 1998). The McLaughlin Mine has a regulatory exclusion for groundwater at the site, so no groundwater enforcement actions can be brought by Regional Water Quality Control Board (RWQCB). At the McLaughlin Mine, wells downgradient of the tailings impoundment had exceedences of TDS (up to 12,000 mg/l), $Cl^-$, $NO_3^-$ (up to ~37 mg/l), and $SO_4^{-2}$, and increases of Cu (up to 280 µg/l) and other metals from 1984 – 1992 (mine began operation in 1985). Wells downgradient of waste rock dumps had increasing concentrations of $SO_4^{-2}$ (up to 5,000 mg/l), B, TDS, Ca, Fe, Mn, and other constituents from 1985 to 1998 and Zn (up to 1.7 mg/l) after this timeframe.

The Stillwater Mine in Montana has also received environmental awards, and acid drainage has not developed on the site to date, likely due in part to the unique ultramafic host rock and associated mineralogy. Depth to groundwater at the mine is 40 to 90 feet, and there are three springs on site. The mine discharges adit water to percolation ponds and a land disposal area on the site. Groundwater at the Stillwater mine in the area of the East Land Application Disposal Area has exceeded drinking water standards for Cr, but the cause appears to be tailings from an historic government-operated World War II-era mine. The adit water that percolates to groundwater is unimpacted except for $NO_3^-$ contamination but contains Cd, Cu, Pb, Mn, Zn, and N concentrations in excess of baseline surface water values. Groundwater downgradient of the land application facility has slight elevations of $SO_4^{-2}$, $Cl^-$, P, Cd, Fe, and Zn, but these appear to be a baseline issue.

The pre-mining regional groundwater table at the Florida Canyon Mine was quite deep (~400 feet), but alluvial groundwater exists at 0 to 250 feet deep. A contaminant plume with elevated concentrations or exceedences of WAD CN, Hg, $NO_3^-$, $Cl^-$, and TDS exists in groundwater downgradient from the leach pad. Other groundwater monitoring wells on the site show exceedences of drinking water standards for Al, As, Cd, $Cl^-$,Fe, Mn, Ni, and TDS.

Depth to groundwater at the Flambeau Mine is Wisconsin before mining began was generally <20 feet and flowed toward the Flambeau River. Samples taken from a well between the river and the backfilled open pit showed elevated levels (compared to baseline values) or exceedences of drinking water standards for Fe, Mn, pH, $SO_4^{-2}$, and total dissolved solids. Concentrations appeared to peak in 2000 and have been slowly decreasing for Mn, $SO_4^{-2}$, and TDS, but are continuing to increase for Fe. Zinc concentrations are variable and still (as of 2003) ~700 µg/l (Lehrke, 2004).

Of the mines that have close proximity to groundwater, springs on site, or that discharge to groundwater – and have a moderate to high contaminant leaching potential, 8 of 11 mines (73%) had groundwater quality impacts, and two of the remaining three had seeps that were adversely impacted from mining activity (91% have mining-related impacts to groundwater, seeps, springs, or adit water). The remaining mine, the Lone Tree Mine in Nevada, has had exceedences of primary and secondary drinking water standards in groundwater, but it is not clear if the cause is baseline conditions or seepage from mine facilities. All of the 11 mines have exceedences of standards in groundwater (8), or seeps, springs, or adits (4). Therefore, the combination of close proximity to groundwater and elevated contaminant leaching potential appears to be a good indicator of future adverse groundwater quality impacts. Of the 11 mines in this category, all but one (the McLaughlin Mine) predicted low groundwater quality impacts after mitigations were installed. The Stillwater Mine predicted low impacts to groundwater, and no exceedences of standard have thus far resulted from current operations or operators. The Lone Tree Mine in Nevada also predicted low groundwater impacts, and current information suggests that this is true (assuming the exceedences are a baseline issue). However, the lowered water table likely prevents the observation of impacts to groundwater. EIS water quality predictions made before the ameliorating effects of mitigations were considered ("potential" water quality impacts) were more accurate at predicting operational water quality than predictions based on assumed improvements from mitigations. Therefore, of the 11 mines in this category, eight (73%) underestimated actual impacts to groundwater resources from mining activity.

Taken as a whole, there are 15 mines with close proximity to groundwater, springs on site, or discharges to groundwater – and with moderate to high acid drainage or contaminant leaching potential (see Table 4b). Of these 15 mines, all but one (93%) have had mining-related impacts to groundwater, seeps, springs, or adit water (with the one possible exception being the Lone Tree Mine in Nevada). Eleven of the 15 mines (73%) have had adverse mining-related impacts to groundwater; of the remaining four mines, three have mining-related impacts to spring, seeps or adit water, and only one (the Lone Tree Mine) has exceedences in groundwater that may be related to baseline conditions. These results, although not comprehensive, suggest that the combination of proximity to groundwater resources (including discharges to groundwater) and moderate to high acid drainage or contaminant leaching potential does increase the risk of water quality impacts.

## Conclusions

The identification of geology and mineralization, as currently conducted in EISs, is generally a blunt tool for predicting water quality impacts. Geologic and mineralogic information is usually focused on the ore body rather than on all mined materials that could potentially impact water resources. We found relatively weak relationships between geology and mineralization/ore association and acid drainage potential. Similarly, we found a relatively weak relationship between geology and mineralization and the potential for water quality impacts. The discrepancy or lack of good agreement between identified mineralization and acid drainage potential highlights the importance of coordinating mineralogic and acid drainage potential evaluations in the NEPA process. As noted in the companion report (Maest et al., 2005), the same geochemical test units should be used for testing of all parameters used to predict water quality impacts. In addition, more extensive information on mineralogy and mineralization should be included in EISs.

The EISs reviewed in detail spanned a period from 1978 to 2004. The availability of geochemical characterization data affects our ability to determine the potential for mines to release contaminants to water resources. Starting in 1980, mines began to provide basic information on geochemical characterization, such as static and short-term leach testing. After 1990, many of the mines were conducting combinations of kinetic testing and static or short-term leach testing. EISs performed after about 1990 should have more reliable information on water quality impact potential than those with EISs completed before this time.

Mines with close proximity to surface water or groundwater resources and with a moderate to high acid drainage or contaminant leaching potential have a relatively high risk of impacting water quality and must rely on well executed mitigation measures to ensure the integrity of water resources during and after mining. These results, although not comprehensive, suggest that the combination of proximity to water resources (including discharges to surface water or groundwater) and moderate to high acid drainage and contaminant leaching potential does increase the risk of water quality impacts. These combined factors at a mine appear to be a good indicator of future adverse water quality impacts. Mines in this category are also the most likely to require perpetual treatment to guarantee acceptable water quality.

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## Literature Cited

Kuipers, J., A. Maest, K. MacHardy, and G. Lawson. 2006. Comparison of Predicted and Actual Water Quality at Hardrock Mines: The Reliability of Predictions in Environmental Impact Statements. Available at: www.kuipersassoc.com.

Lehrke, S. 2004. Memorandum from Stephen Lehrke, Foth & Van Dyke, to Jana Murphy, Flambeau Mining Company. Re: Flambeau Mining Company – 2003 Annual Report Groundwater and Surface Water Trends. January 1, 2004.

Maest, A., J. Kuipers, C. Travers, and D. Atkins. 2005. Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-of-the-Art. Available at: www.kuipersassoc.com.

Nicolet Minerals Company, 1998. Wisconsin Statute §293.50 Compliance Demonstration. Submitted to Wisconsin Department of Natural Resources (in response to the 1997 Wisconsin Act 171, codified at Wis. Stats. §293.50).