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A RANKING SCHEME DEVELOPED TO ASSESS THE RELATIVE POTENTIAL OF ABANDONED MINE SITES IN NEVADA TO RESULT IN SURFACE WATER AND GROUNDWATER DEGRADATION

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EXECUTIVE SUMMARY

A pilot project was completed in which a ranking scheme was developed to assess the relative potential of inactive and abandoned mines in the state of Nevada to impact water quality. This ranking scheme uses existing data and was applied in Clark County to serve as a test case. Geographic, hydrologic and geologic information was compiled and assembled into a geographic information system (GIS) database. Using data relevant to the evaluation of potential environmental impacts of abandoned mines, mining areas were ranked according to relative risk of water quality degradation. Natural hazards associated with a particular deposit type are the focus of this work because insufficient data are available on the presence of processing chemicals at a site or other chemicals introduced during mining or milling. Hence, this model does not address chemicals introduced by man (e.g., cyanide or mercury use for amalgamation), and this aspect may be a significant factor at some sites in an all-inclusive ranking system.

In order to assess the potential of mine sites to adversely affect water quality from leaching of the various mineral deposits, four main factors are considered: (1) the type of geologic deposit in the mined area, (2) the availability of water to interact with the deposit, (3) the distance to 'affected waters,' and (4) the total number of mining excavations in the area. Mineral deposit type is critical in determining the likelihood of water quality degradation because the deposits are the potential source of elevated metal concentrations. We have derived a deposit classification scheme based on (1) the abundance of pyrite, calcite and other minerals that could generate or neutralize acidity, and (2) the abundance of environmentally sensitive trace elements such as Pb, As, and Hg. Areas with higher precipitation and lower evapotranspiration (ET) are more likely to result in water percolation into mining waste dumps, and ultimately in leachate formation, than sites with lower precipitation and higher ET. Sites with similar geology and climate will be more likely to impact shallow rather than deeper groundwaters, and will impact surface waters close to the mining site to a greater extent than distant waters. Given the same hydrologic and geologic setting, the greater the number of mining excavations and dumps, the greater the likelihood of water interaction with geologic materials that were exposed through mining activities, and which would not have been exposed in the absence of mining. These various factors and their interrelationships are combined to assess which mining sites in Clark County are more or less likely to result in adverse environmental impacts through water quality degradation. The results of this type of ranking can be used to prioritize sites for additional study. Results from the current work can also be used to further refine and calibrate the initial model developed here to be more realistically applicable to the remainder of the state.

For the purposes of computations, Clark County was subdivided into 21,241 1-km^2 cells, each of which was assigned a ranking from which priorities for additional studies can be set. Total risk values for the cells range from 1 to 85,269. Only five of these 1-km^2 cells were ranked in the highest 10% of the numeric values in the county. The highest ranking sites in Clark County occur in the following mining districts: Alunite, Eldorado, Goodsprings, and Searchlight. The highly ranked cells in the Eldorado, Goodsprings, and Searchlight districts have very high numbers of mining features, and moderately highly ranked deposit types (polymetallic vein and mafic intrusive Ni-Cu-platinum group elements). The cells in the Alunite district have moderate numbers of mining excavations, yet have the highest ranked deposit type (quartz-alunite). Waters have been collected from three of the highly ranked grid cells as part of a separate project, and none of the sites had particularly poor water quality, yet all exceeded the Nevada drinking water standard for total dissolved solids. Therefore, even highly ranked sites in Clark County are not necessarily associated with adverse environmental impacts, and it is expected that other portions of the state will have a higher potential of adverse impacts on water quality because of higher rainfalls and lower ET than in most of Clark County.

We currently have insufficient data to rigorously evaluate and calibrate the model. For instance, very high modeled values are more likely to be associated with sites that could result in adverse environmental impacts than sites with low values. However, it is not specifically known how much higher the actual risk would be. Some revisions to the initial model presented here should be evaluated and considered in future work. The revisions identified in the current work include: (1) de-emphasizing the weighting of the number of mining excavations; (2) de-emphasizing the effects of evapoconcentration in weighting of the shafts; (3) placing greater weight on the deposit type; and (4) identifying differences between the various polymetallic vein deposits in the state. In order to better evaluate the existing model in an unbiased manner, field evaluations of selected grid cells should be conducted to assist in model calibrations, and to determine how ranking numbers should be grouped for prioritization of sites (i.e., is a rank of 10,000 significantly different than one of 20,000?). These questions can only be resolved through field evaluation of our model. This pilot study in Clark County resulted in a numerical classification scheme which can now be tested, modified as needed, and used throughout the state of Nevada to help prioritize abandoned mine sites.

INTRODUCTION

Abandoned hard rock mines have been called "a serious threat to public health and safety" (USGS, 1995; King, 1995). This issue is particularly important in Nevada, which probably contains a greater number of mines than any other state. There are 526 mining districts in the state (Tingley, 1992), each containing as many as 2,000 separate mining related excavations. Recognizing the large number of abandoned mines in the western U.S., the Bureau of Land Management (BLM) set forth a strategy for implementation of an Abandoned Mined Land Inventory (BLM, 1993). The Nevada Bureau of Mines and Geology (NBMG) is contributing to this effort by providing GIS databases of information compiled from existing sources of data. In support of this overall effort, NBMG was asked to develop and implement a numerical classification scheme with the use of GIS to help evaluate abandoned mines for their potential to result in water quality degradation. Following compilation of relevant data and development of a prototype model, Clark County was selected for application of the model as a pilot study for the state of Nevada.

Clark County is the most populous county in the state of Nevada, and numerous mineral deposits throughout the county have produced or have been prospected for gold, silver, copper, nickel, uranium, colemanite, silica, limestone and gypsum (Tingley, 1992). Because Clark County is populous and arid, groundwater quality is a particularly vital issue. Clean water supplies are increasingly needed in Clark County due to the expanding population, yet there are numerous active and inactive mines in the county (i.e., see Longwell et al., 1965 for deposits of Clark County, and Tschanz and Pampeyan, 1970 for deposits of Lincoln County). Given the large number of abandoned mine sites and the associated data in this county, it is prudent to utilize a system allowing visualization and correlation of relevant data to help in evaluating which mine sites may have an impact on water resources. A Geographic Information System (GIS) is ideally suited for visualizing and evaluating large amounts of spacial data.

Although the number and size of abandoned mine sites in Clark County is probably less than in other counties in Nevada, their potential impacts on surface and groundwater, and ultimately to the population, is a concern. At present, the potential adverse effects of abandoned mine sites on surface and groundwaters is unknown. Clearly, it is not feasible to conduct detailed characterization at each mine site and excavation in the county or the state, yet it is prudent to evaluate existing data in order to identify potential adverse effects that particular abandoned mines may have on local surface waters and groundwaters. Following identification of abandoned mines which may threaten the quality of potable water currently or potentially in use, more detailed studies may be required to determine the extent to which water is being contaminated, and how to mitigate the adverse effects.

PURPOSE

The purpose of this work is to develop an automated numerical ranking scheme for the state of Nevada, the results of which can be used to evaluate abandoned mine sites for additional studies based on their relative potential to result in water quality degradation. Another purpose of this work is to document the compilation of relevant geographic, geologic and hydrologic data for Clark County. An inventory of abandoned mines in the County has been compiled, and the data are used with the developed model to evaluate potential impacts of abandoned mining sites on surface and groundwater quality. Numerous data collection sites occur throughout the district. Clark County alone contains 629 of the MILS (Minerals Availability System, 1994) sites in Nevada along with 215 sites from the MRDS (U.S. Geological Survey (USGS), Mineral Resource Data System), and 204 sites from the NBMG Geochemical data sets. Hydrologic data used in this work are contained in the U.S. Environmental Protection Agency STORET database (which contains USGS WATSTORE data). The compilation and construction of maps discussed here are used to identify (1) known abandoned mine locations, (2) data gaps, (3) potential adverse impacts on surface waters and groundwaters, (4) possible improvements and refinements to the initial model, and (5) sites potentially requiring additional, more detailed studies.

METHODS

Compilation and Manipulation of Existing Data

NBMG has compiled an abandoned mine GIS database that emphasizes data used to rank abandoned mine sites by their relative risk to result in adverse environmental impacts via either acid leachate generation or mobility of elevated metal concentrations into local surface waters and groundwaters. Several factors are relevant in evaluating these risks at a particular abandoned mine site. Both hydrologic and geologic data are used in calculations to estimate the relative ranking of the mine sites. These various parameters are listed below, and described in greater detail in the subsections that follow.

Geologic Parameters	Hydrologic Parameters	Physical Information
Mineral/deposit type	Precipitation	Number of shafts
Host rock	Evapotranspiration	Number of adits
	Depth to groundwater	Number of pits
	Distance to surface water	Area of waste dumps
		Area of tailings ponds
		Area of tailings piles
		Mill/smelters

The county was gridded into 1-km cells for use in the GIS calculations (GRID, ESRI, 1991). All of the previously noted parameters are incorporated into the calculations such that the relative risks in a cell, 1 km square, within the grid of the County can be estimated.

Mineral Deposit Classification

One of the most critical factors in assessing the potential environmental impact of an abandoned mine is the kind of mineral deposit the mine exploited. We have devised a mineral deposit classification scheme for all sites in Nevada, and have classified every mining area in Clark County according to this scheme. Further, we have assigned a numeric ranking from 1 to 100 for each deposit type (Table 1). A value of 1 indicates a very low potential for adverse environmental impact, whereas a value of 100 indicates the greatest potential for impact from the deposits. To understand the rationale for doing this, one must understand what a mineral deposit is.

In general, a mineral deposit is a natural concentration of chemical elements and minerals in the Earth's crust. Deposits are broadly considered metallic or nonmetallic. Examples of metallic deposits include gold (Au), lead (Pb), and copper (Cu); examples of nonmetallic deposits include gypsum ($CaSO_4 2H_2O$), clay, sand and gravel. Every chemical element is present in all natural material at some concentration, but most rocks contain far too little of an element to be mined economically. For example, the average abundances of gold (Au), copper (Cu), and lead (Pb) in the crust are about 0.004 ppm (parts per million by weight), 55 ppm, and 12.5 ppm, respectively (Levinson, 1974). Minimum concentrations necessary for mining depend upon many factors, including the presence of other mineable minerals, total tonnage of a deposit, location and difficulty of mining, processing costs, and regulatory requirements. Nevertheless, typical minimum grades for Au, Cu, and Pb are 0.7 ppm (0.02 oz/ton), 3000 ppm, and 5000 ppm (Cox and Singer, 1986), or enrichments of 50 to 400 times over average crustal concentrations. Average grades in mined deposits typically are several times the minimum values (Cox and Singer, 1986). Element enrichment is necessary to create mineral deposits but is also a potential problem because some elements that are enriched in mineral deposits, such as Pb, As, or Hg, can be environmental hazards.

Mineral deposits are also enriched in specific minerals. Pyrite (iron disulfide; FeS_2), is a common mineral in many metallic deposits, although it is not normally itself an ore mineral (Park and MacDiarmid, 1975; Cox and Singer, 1986). Pyrite is stable in the high-temperature, un-oxygenated environments in which many ore deposits form. However, it breaks down in oxidizing environments, for example, where exposed at the earth's surface by natural erosion or by mining excavations (Ficklin et al., 1992, 1994). Oxidation of pyrite, marcasite (another form of FeS_2) and, to a lesser extent, other sulfide minerals, generates acidity by the following reactions:

$$FeS_2 + \frac{7}{2} O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

$$FeS_2 + 2H_2O + 4O_2 = FeOOH + 2SO_4^{2-} + 4H^+ \quad (2)$$

These reactions are responsible for creating what is generally termed acid mine drainage. Acid water is itself a problem for human use and for many aquatic species, and acidic water can contain greater concentrations of some potentially toxic elements, such as Pb, than can neutral water.

Fortunately, other natural reactions, particularly with the common, rock-forming minerals calcite ($CaCO_3$) or dolomite ($CaMg[CO_3]_2$), neutralize acidity:

$$H^+ + CaCO_3 = HCO_3^- + Ca^{2+} \quad (3)$$

$$2H^+ + CaMg(CO_3)_2 = 2HCO_3^- + Ca^{2+} + Mg^{2+} \quad (4)$$

Oxidation of pyrite, acid generation, and acid neutralization are all natural processes that occur in and around mineral deposits regardless of mining activity (Ficklin et al., 1992, 1994; Plumlee et al., 1992). However, mining changes the natural setting by allowing greater access of rain, surface water, or groundwater to the deposits which were previously not exposed at the surface. Underground workings provide pathways for surface water to enter and react with a deposit. Waste rock taken from a mine and disposed on the surface is more accessible to rainfall, percolation and runoff. Moreover, the waste is broken up so that the surface area available for reaction is greatly increased.

Mine water need not be acidic to be a problem. Several trace elements that are concentrated in Nevada mineral deposits are soluble in neutral water, including As, Hg, and Se. Naturally high concentrations of these elements, particularly As, have been found around unmined deposits (Welch et al., 1988; Lico, 1992).

Recognizing these deposit characteristics and geochemical processes, we have devised a classification based on the occurrence and abundance of chemical elements, such as Au, Pb, and Cu, and of associated minerals, such as pyrite, calcite, and gypsum (Table 1). This information can be used to make initial predictions about the quality of water that would result from interaction with rock at a particular mine and deposit. Our classification is developed for use throughout Nevada. Types that occur in Clark County, the pilot study area, are shown in bold on Table 1. Several examples of mineral deposit types that are common in Clark County illustrate how rankings were assigned to them.

One of the most abundant mineral deposit types in Clark County is #7, base metal skarn and replacement. Most of the deposits in the Goodsprings and Charleston districts west of Las Vegas are of this type. These deposits are enriched in Pb, Zn, Cu, and many other elements and contain abundant pyrite. However, base metal replacement deposits invariably form in limestone, which contains abundant calcite. Therefore, any acid water created by oxidation of pyrite should be quickly neutralized. Acid drainage from abandoned base metal mines is unlikely. Additionally, although some of the elements concentrated in these deposits are of environmental concern, such as Pb, Zn, and As, all but As are only soluble in acidic water. Therefore, these elements are unlikely to occur in high concentrations in water draining from abandoned mines. This deposit type, hence, has a relatively low ranking of 20 (Table 1).

Deposit types #10, quartz-adularia precious metal, and #11, quartz-alunite precious metal, illustrate the importance of differences in mineral constituents. Both types are enriched in Au, As, and other elements. However, quartz-adularia deposits generally contain lesser amounts of pyrite than do quartz-alunite types, and far greater amounts of calcite and other minerals that will neutralize any acid water that is produced from oxidation of sulfides. Therefore, mine drainage from quartz-alunite deposits is much more likely to be acidic and to carry high concentrations of metals. These differences are reflected in their rankings: 10 for quartz-adularia, and 100 (the highest value) for quartz-alunite.

Because Clark County is expanding rapidly, mines and quarries for #23 gypsum, #24 clay, and #25 sand and gravel are common. With rare exceptions, these deposits do not contain pyrite and are not enriched in metals. Therefore, mine drainage is not acidic and does not carry significant concentrations of metals. These deposit types were assigned a low ranking: 1 for these industrial mineral types, and 8 for saline minerals. In addition, placer deposits (type 14) typically do not contain pyrite and are similarly assigned a low weighting factor of 1.

Our numeric rankings were tested and further calibrated using an initial sampling program from abandoned mines in Nevada funded by the U.S. Environmental Protection Agency through the Western Governor's Association (Price et al., 1995). Waters draining from adits or standing in shafts were analyzed in this work. Highly acidic water was found in quartz-alunite deposits (type 11) and in an unusual type of quartz-adularia deposit that does not occur in Clark County. Moderately acidic water was found in porphyry deposits (type 5) and in a small percentage of polymetallic vein deposits (type 6). All other deposit types sampled and that occur in Clark County, including mafic intrusive (type 1), tungsten vein (type 3), base metal skarn and replacement (type 7), and saline mineral (type 23) had water with neutral pH. These results are reflected in the categorizations of Table 1, which assigns the highest value of 100 (greatest potential environmental impact) to quartz-alunite deposits, moderately high value of 50 to polymetallic vein, and a low value of 20 to base metal skarn.

This deposit classification scheme (Table 1) works well for many of the deposit types because many deposits have a fairly narrow range in characteristics (e.g., metals and pyrite content). However, much greater variability is observed in other categorized deposit types. For instance, large variabilities occur in trace metal abundances in polymetallic vein deposits. This type of deposit is also very heterogeneous in its pyrite content. Hence, a more thorough classification scheme could be devised which accounts for these large variations. However, the currently available data are inadequate to allow for finer subdivisions of this type of deposit. During ranking of abandoned mine sites present in polymetallic vein deposits, it should be recognized that very good and very poor quality waters have been associated with this deposit type in different locations in Nevada (Price et al., 1995).

Different mineral-deposit classification schemes are possible and have been devised and used for mineral exploration (e.g., Cox and Singer, 1986;). In some cases, these schemes recognize more than 100 deposit types. In addition to being cumbersome, classifications for exploration are not intended for predicting environmental impacts, the purpose of our study, so these were not used here. Our scheme was developed and used in preference to use of specific entries of chemical analyses from the NBMG database, or the use of commodities, property types, size and mill method derived from the MILS/MRDS database as is used in the U.S. Bureau of Mines (1993) ranking scheme. The reason for using a more generalized classification scheme is that it is likely that many of the areas do not contain data for some, or all, of the parameters listed above. Without complete data from an area, it's ranking is in serious question. With the deposit classification scheme, areas containing mining disturbance were classified using readily available published information. With these data, large groups of gridded areas were selected using ArcView II, and an entry on deposit type was added to all MILS/MRDS data points lying within the selected area.

Next, the entirety of each mining district (Tingley, 1992) was assigned the deposit type assigned to the greatest number of MILS/MRDS points within the district. In many cases, more than one deposit type was found within a particular mining district. In these cases, these different deposit types were retained for the particular 1-km grid cell to which they were initially assigned. In this way, all grid cells within a mining district boundary have a deposit type classification assigned to them, whether or not shafts or adits are present. Some shafts and adits are located outside of mining districts, yet also have a deposit classification associated with them. However, 29 individual grid cells have shafts or adits, yet no deposit classification could be assigned to these locations due to lack of information. Hence, only the physical hazards could be calculated for these grid cells because these are not a function of deposit type (physical hazard grid cell numbers 1, 2, 3, 7, 9, 10, 11, 12, 22, 29, 30, 31, 52, 53, 54, 56, 82, 86, 143, 144, 146, 147, 159, 164, 175, 213, 250, 353, 355), and caution should be exercised when interpreting final rankings of these grid cells.

Host Rocks

Different mineral deposit types typically occur in specific types of host rocks. Therefore, host rock is inherent in our mineral deposit classification. However, we have also independently determined the host rock for each deposit as a check on the classification. This was done by digitizing the geologic map of Clark County (Longwell et al., 1965), which shows what type of rock occurs at the surface throughout the county. Host rock determined by the two methods agree.

Precipitation

Precipitation data for Nevada were acquired from the U.S. Soil Conservation Service, and the data supplied were calculated using the PRISM method (Daly et al., 1993). The PRISM model uses linear regression to obtain precipitation for the state of Nevada as a function of topographic and elevation effects. The PRISM model used three climate datasets to create the precipitation maps: (1) the National Climatic Data Center 1961 to 1990 dataset from the National Weather Service Cooperative Network, (2) the Natural Resources Conservation Service (NRCS) SNOTEL (SNOwpack TELemetry) dataset, and (3) datasets submitted by the State Climatologist. PRISM uses a 3-arc second Defense Mapping Agency digital terrain elevation dataset in calculating the spatial distribution of precipitation (Natural Resource Conservation Service, 1995). Monthly average precipitation data from PRISM were used in the current study along with monthly evapotranspiration as one factor influencing the likelihood of adverse environmental impacts from abandoned mines.

The Nevada PRISM dataset was evaluated by the Nevada state climatologist. It was found that the PRISM data tended to overestimate precipitation at the higher elevations because the model uses a constant linearly increasing precipitation with elevation model based on data from lower elevation stations, when in fact, there is an elevation above which this relationship does not hold true (John James, pers. comm. 1995). This effect appears to be more reliably accounted for in southern Nevada (John James, pers. comm., 1995), which is the area of interest in the pilot study. Extrapolation of the ranking model to the remainder of Nevada may require corrections to be made to the precipitation data at higher elevations in the northern part of the state.

Estimation of Evapotranspiration

As one component of evaluating the potential for adverse environmental impacts from abandoned mine sites, an empirical method was used to estimate evapotranspiration for the state of Nevada (Shevenell, 1995; 1996). For instance, leaching of rocks in waste rock dumps is more likely to occur in areas with high precipitation rates, and low evapotranspiration (ET) rates than in areas with high ET and low precipitation. A state-wide GIS model was constructed at the Nevada Bureau of Mines and Geology which estimates ET for each of the 12 months of the year (Shevenell, 1995; 1996). These coverages were used as part of the overall ranking scheme described in the Model Formulation section.

Although ET occurs through sublimation during periods of freezing, when snow is present ET values are assigned a value of zero. In the model used, ET calculated using temperatures are always negative when temperatures are below freezing, and hence, these values are reset to zero. Percolation will generally not occur during winter months at locations covered with snow, and an ET value of zero will not bias results when the objective is to determine the times of maximum likelihood of percolation. The ET data mimic the topography, with lower ET occurring at the higher elevations. This is in contrast to precipitation data in which higher precipitation is associated with higher elevation. The resulting contour of ET for the state, provides a realistic regional view of the variability of ET in the state by latitude and elevation.

Percolation is more likely to occur during particular months in certain parts of the state at particular elevations. January is the month with some of the highest precipitation at all stations in Nevada (see Figures 1 and 2 for examples of northern and southern Nevada precipitation and ET values), and evaporative demands are low. However, if average temperatures are less than freezing, the precipitation falls as snow, and does not pose a risk of leachate generation during January, but rather, later during snowmelt. Hence temperatures are relevant in determining which month has the maximum likelihood of production of leachate, and temperature is a function of both latitude and elevation. Based on temperature data from all stations in southern Nevada (Western Regional Climate Center), the average monthly temperatures for the coldest month at all southern Nevada stations located at elevations <3,900 ft are >32°F, indicating rain generally occurs during the coldest month which has the lowest ET rates. For these lower elevation stations in southern Nevada, January appears to be the month with the maximum potential for water infiltration due to relatively high precipitation rates and low ET. However, at some sites, the water deficit in the soil produced during the previous year may be rather large and consume much of the January precipitation. For a precipitation event to result in recharge, the amount of precipitation must exceed the ET demands for the following days as well as exceed the existing soil water deficit from the previous season. Hence, infiltration may not occur past the soil zone until February, given suitable precipitation. A study near Beatty, NV showed such an effect in recharge studies during 1968, 1973 and 1976, though the study indicated that recharge was unlikely to occur in vegetated areas (Nichols, 1987). Nevertheless, infiltration of water into the soil zone was seen to occur during January, and thus water would be in contact with and reacting with any mining waste during this month, but may not be mobilized and recharged to deeper levels until additional rain events in February.

The timing of maximum percolation potential in other elevations and parts of the state can be more variable than for the low elevation areas in southern Nevada. Even though many stations throughout the state show snowpacks during March through May, melting and runoff also occur intermittently during these months, with the snow pack being more persistent at the higher elevations. Snow is often transient at intermediate elevations (e.g., 3,900 to 6,000 ft) and melts off relatively rapidly between storms. The maximum potential for leachate generation likely occurs during April and May in northern Nevada when most melting and runoff occur.

Due to the relatively high temperatures during the months of June through September throughout the state (Houghton et al., 1975), it would appear that there is little potential for leachate generation at many elevations due to high evaporation rates. However, during these months, flash flooding events can occur which will result in some infiltration, yet mass transport is more important than rock leaching. High intensity rainfall usually results in greater amounts of runoff than infiltration (Nichols, 1987). Although ET may be higher and precipitation lower in the months of April through June (or July) than in colder months such as January, comparison of ET versus precipitation data should not be conducted on a monthly basis for the state as a whole. Higher precipitation and lower ET occur in January versus May or

June, yet percolation is limited in norther Nevada at lower elevations, and likely absent at higher elevations in January due to the presence of snow. In contrast, lower precipitation occurs in spring months when ET is higher, yet water which may percolate originates from rain occuring during the particular month, as well as from melt water from snow accumulated over the previous months. The relationship of the amount of precipitated water to consider in any ET versus precipitation calculations will vary temporally and spatially in a fashion which is not easily predictable. Hence, there are uncertainties related to identifying which month may result in maximum leachate generation as a result of percolation potential being at a maximum. Therefore, in future state-wide modeling efforts, yearly average ET and precipitation values should be used to evaluate percolation potential.

Depth to Groundwater

Water levels in wells are routinely measured in Las Vegas Valley by the Las Vegas Valley Water District and by the U.S. Geological Survey in areas within and outside of the Las Vegas Valley. However, the vast majority of the measurements are in Las Vegas Valley. Selected municipal pumping and injection wells, domestic water supply wells, rural and public wells are monitored on a monthly basis. Data from the monitoring of these wells was provided by the Las Vegas Valley Water District, and the USGS Water Resources Division GIS personnel in Carson City. Data for March and September 1993 and 1994, and for September 1989, 1990, 1991 and 1992 were requested in order that seasonal and temporal changes in water levels could be identified.

These data files are included as a coverage in the GIS database. However, insufficient data were available on water level on a county-wide basis from which reliable water level contours could be constructed. Hence, general trends in these water level depth data and DEM (USGS, 1990) elevation data were consulted. Probable water level depths were assigned to each 1-km grid cell based on these data types. Sites at higher elevations generally have deeper water tables than those at lower elevations in the valleys, although there are exceptions, particularly in the case of perched water tables. In general, deeper waters (i.e., >100 ft deep) under higher elevation peaks are far less likely to be adversely impacted by the abandoned mine sites than are shallow (≤10 ft) groundwaters. The range of elevations was subdivided such that three separate weighting factors were assigned to the different inferred water level depths throughout the range of elevations. Only three subdivisions were assigned because of the uncertainties in the assumptions of water level depths below particular elevations. For instance, although deeper waters are generally expected beneath ridges, rather than valleys, high elevation perched water tables are possible, yet available data are insufficient to detect these types of variations in depth to water. Shallow water tables, on the other hand, are generally associated with valley floor locations, which are often discharge locations, hence a high weighting should be associated with these areas.

Distance to Surface Water Drainages

Major surface water features were incorporated as a GIS coverage for with the data originating from U.S. GeoData 1:100,000 digital line graphs (USGS, 1994). Within a 1-km grid cell, the center point of the cell was determined. The distance between this center point and the closest surface water was calculated, because the closer a stream to abandoned mine features within the grid cell, the greater the potential for its being adversely impacted by the mine sites. The surface waters occurring in Clark County in the digital file were attributed as follows:

Column A	Column B
Shoreline	Indefinite shoreline
Man-made shoreline	Apparent limit
Closure line (water-water)	Dam or weir
Rapids	
Stream	
Ditch or canal	

Aqueduct
Wash or ephemeral drain
Right bank
Left bank

Left bank and right bank are noted for waters which are sufficiently wide (e.g., Colorado River) for the two sides of the river to be digitized separately. Left and right bank are defined with the viewer looking downstream. Two separate categories were selected with all entries in the column A being used in the model, and all items in the column B being eliminated from the dataset. In addition, a minor code attribute is associated with all of the above names which indicates if the the feature is intermittent. Although there is no way to determine the frequency with which the various intermittent streams or washes may flow, water is clearly present in the intermittent features much less frequently than in the perennial streams and rivers. This aspect is considered in the Model Formulation section by including two separate terms for surface water. One includes the perennial surface waters, and the other includes the intermittent surface waters, which are weighted at 5% of the weighting of the perennial surface waters because, in general, they are likely to be far less important than the perennial waters. When both types of surface water are associated with a grid cell, the perennial water will dominate. However, many grid cell centers may be at distances >1 km from a perennial surface water. In these cases, the perennial surface water term is set to zero, and the intermittent term is the one defining the surface water risks.

Number of Shafts, Adits, Waste Dumps and Pits

Point locations for shafts, pits, adits, prospects, and waste dumps were digitized from 7.5' quadrangle maps. These data, excluding prospects which are assumed to be small, insignificant features, are relevant because a site with larger numbers of mining excavations, or greater areal coverage of waste, may have a higher risk of adverse environmental impact in a given geologic and hydrologic setting. Clearly an area with no mining excavations will result in no hazard to the environment from abandoned mine sites. Excavations and mine dumps potentially expose rock to waters resulting in a higher probability of adverse impacts on local waters than if no mining had taken place. Larger numbers of excavations, and greater areas of dumps, result in greater surface areas over which waters can interact with disturbed rock. The greater the number of mining excavations and dumps, the greater the likelihood of water interaction with geologic materials which were exposed through mining activities, and which would not have been exposed in the absence of mining. Clearly, even one adit in a geologic setting such as in a quartz-alunite deposit can be associated with poor water quality. However, ten excavations in the same deposit type have even greater potential to impact water quality. Hence, the total number and size of mining features may be relevant in assessing the potential of abandoned mine sites to result in water quality degradation, and the number of these features was incorporated into the model in the initial, pilot study.

When the area of a waste pile, leach pad, tailings pile, pond or pit was noted on these maps, the outlines were digitized in order that an area of the feature could be determined. If it was noted that a pit occurred near a feature identified as tailings on the 7.5' quadrangles, aerial photographs were consulted to determine if the feature was indeed a tailings pile, or if it was actually a waste rock dump. In several cases, the features identified as tailings were re-digitized to reflect the fact that part or all of the area was actually a waste rock dump. These dumps ranged in size from 1,300 to 104,484 m^2, whereas the tailings piles were up to 2,000,000 m^2, and the tailings ponds up to 2,500,000 m^2 in area. Clearly, many of the dumps and tailings encompass more than one grid cell. Hence, relative rankings for these features were based on the percentage of the 1-km grid cell which was covered with the dump or tailings. For instance, if 100% of the grid cell area was covered by tailings, the cell was assigned a high weighting factor of 10 for the feature. If only 10% of the cell was covered with tailings, a low weighting factor of 1 was assigned. Tailings include ore material, high metals contents, and possibly sulfides, as well as chemicals (e.g., cyanide) used in leaching, whereas waste rock dump likely have lower contents of metals, and no processing chemicals. Hence, it is assumed that given an equivalent area of tailings and dumps, that the dumps should result in lower risk to the environment due to the lower metals and chemical contents. Therefore, in the ranking equations presented in a later section, dumps are weighted at 80% of the full weight of the tailings and leach ponds.

Mills and Smelters

The presence of mills and smelters within an abandoned mine area was determined by searching the MILS and MRDS (USGS Minerals Information Office, Mineral Resource Data System) databases compiled. If there were no MILS/MRDS data points within a grid cell, it was assumed that no mill occured within the cell. The reliability of the MILS/MRDS data on precious metal mills were evaluated by consulting with individuals familiar with historical mining and milling in the state (J. Tingley, pers. comm., 11/95) and by consulting the yearly Nevada Bureau of Mines and Geology publication 'The Nevada Mineral Industry,' available for the years 1979 to 1994 (NBMG Special Publication MI-1979 through MI-1994, 1979-1994). Several of the MILS/MRDS sites listing data for mills or mining operations were actually never functional (J. Tingley, pers. comm., 11/95). Most of the 69 MILS/MRDS sites in Clark County are listed as sand, gravel, gypsum or other industrial minerals, and there is no reason to believe that there are errors in these particular citings of mills. However, several of these mills were constructed for promotion only and and these mills were never operated, yet some of these sites appear in the MILS/MRDS database. Hence, these sites were eliminated from the subset of the data used in the current work if no independent information on the mill site confirmed its presence.

Thirty-nine gold or precious metal mills are noted in the NBMG Mineral Industry reports for the 17 years for which records were maintained. Thirty-three of the MILS/MRDS sites were apparently mill sites for gold/precious metals, only 17 of which are identical to 17 of the 39 sites noted in the NBMG reports. One of the MILS/MRDS sites appeared to be a duplicate, and was deleted; nine sites likely never had an operating mill, and these were also deleted from the data set. At four of the sites, it was possible that a mill had operated, though this could not be verified. Hence, these possible gold milling operations were given a lower ranking than other gold sites due to this uncertainty (ranking of 4). Other gold processing mills (19 total) were given a ranking of 6. All industrial types of minerals were given a ranking of 1. The sites indicating the processing of copper were given a rank of 9.

Ranking of Mine Sites by Relative Risks to the Environment

In this section, a scheme is described by which abandoned mine sites can be ranked by their relative risk to result in adverse environmental impacts via either acid leachate generation or mobility of elevated metals concentrations into local surface and groundwaters. Several factors are relevant in evaluating the risk of adverse environmental impacts at a particular abandoned mine site, and these data have been described in the previous sections. These various parameters are evaluated along a grid of Clark County, where the areas investigated are 1 km on a side.

Model Formulation

The calculated and extrapolated ET values are used in conjunction with precipitation, geologic information, and numbers of mining features, to compare the different abandoned mine sites for their relative potential to produce acid leachate or result in metal mobility. Data were compiled for Clark County to be used as a test case for the model. Each 1-km grid cell within the county was searched for the parameters noted previously. A linear classification scheme was developed such that individual factors are weighted. Sites with similar numbers of excavations will not necessarily rank the same because one site may be closer to surface waters or lie above a shallow water table, whereas another site may be more distant from surface and groundwaters. The effects of the quantity of precipitation minus ET vary depending on which types of features are present. With low precipitation and high ET, a site may be ranked lower if the site dominantly contains waste piles and adits (where infiltration is important), but may be ranked higher if it contains open pits or leach ponds because a small amount of water may pool and be in contact with the rock, and evaporation may help to concentrate contaminants. Hence, the range of precipitation minus evaporation value (PE; see equations 6 through 8) are subdivided and weighted as indicated in

Table 2. The PE values show that weighting factors are higher for higher PE values when considering dumps and tailings piles (PE'; see equations 6 through 8), and lower for higher PE values when considering shafts and pits.

The following equation was used to calculate relative risk of adverse environmental impacts at the gridded locations. The equation used in this work is composed of five terms comprised of risks to groundwater supplies, risks to nearby surface waters and intermittent streams, physical hazards associated with human entry, and risks related to mill processing which may have occurred at a site.

$$\text{Risk} = \text{Groundwater} + \text{Surface Water} + \text{Intermittent SW} + \text{Physical} + \text{Mill Type} \quad (5)$$

Note, because Clark County has few mills, most sites have no risk associated with a mill. The formulation of each of the terms follows:

$$\text{Surface Water} = ((((S + P) \times PE + (Pd \times PE)) \times 0.75 + \quad (6)$$

$$A \times PE' + (L + T + 0.8 \times D) \times PE') \times DC) \times SW$$

$$\text{Intermittent Surface Water} = [\text{Surface Water}] \times 0.05 \quad (7)$$

$$\text{Groundwater} = (((S + P) \times PE + Pd \times PE + A \times PE' + \quad (8)$$

$$(L + T + 0.8 \times D) \times PE') \times DC) \times GW$$

$$\text{Physical Hazards} = (10 \times S) + (7 \times P) + (4 \times A) \quad (9)$$

$$\text{Mills} = MT \quad (10)$$

Explanation of the variables follows:

S = number of shafts in the 1-km grid cell. Weightings listed in Table 2.

P = number of pits and strip mines in the 1-km grid cell (excluding sand, gravel, and borrow pits, and rock quarries). Weightings listed in Table 2.

Pd = area of tailings ponds in the 1-km grid cell.

L = area of leach pads in the 1-km grid cell (none appear on 7.5' quadrangles within Clark County).

A = number of adits in the 1-km grid cell. Weightings listed in Table 2.

T = area of tailings piles in the 1-km grid cell.

D = area of waste rock dumps in the 1-km grid cell (none located on 7.5' quadrangles within Clark County).

PE = precipitation minus evaporation with lower values being associated with greater weighting factors (greater risk). Weightings listed in Table 2.

PE' = precipitation minus evaporation with lower values being associated with smaller weighting factors (lesser risk). Weightings listed in Table 2.

DC = deposit classification scaled according to the values in Table 1.

SW = distance to surface water, scaled (weighted) according to the values in Table 2. The factor of .75 in the first term is included to account for the fact that leachate from shafts, pits and ponds is more likely to affect groundwaters than surface waters because these features have boundaries and may result in vertically downward flow as a result of increased hydraulic heads as the features fill.

GW = depth to groundwater, weighted according to the values in Table 2.

MT = mill type.

The range in areas digitized from 7.5' topographic maps was calculated for each category (Pd, T, D, L) and was converted to a scale from 1 to 10 depending on the percentage of the cell which was covered with the feature. The physical hazard component of the equation was calculated assuming that shafts produce the greatest hazard of a person inadvertently falling, pits secondary because they may be more visible, and adits less hazardous because one must deliberately enter these features. Hence, each of these physical hazards were weighted by these relative hazards of shafts, pits, and adits.

Equations 5 through 10 were used at each 1 km grid cell in the county to calculate the relative rankings of each cell. Figures 3 and 4 illustrate how rankings were calculated using these equations and Table 2. Note that each of these figures illustrates an example grid cell which does not precisely correspond with the 1 km grid cells formed in the GIS calculations. The figures are for illustrative purposes only and show one site with many mining excavations, and moderately weighted deposit classification (Figure 4), and another site with much fewer excavations but the most highly weighted deposit classification (Figure 3). Within each of these cells, the number of mining features was counted, and these values, along with the weighting factors from Table 2, appear in the table to the right of the illustrated cell. In Figure 3, there are 5 shafts, 3 adits and no noted pits, tailings or mine dumps. The deposit classification is quartz alunite, which has a weighting factor of 100 (the highest value in Table 2). From topographic contours, the average elevation at the site is approximately 2600 ft, which corresponds to a groundwater weighting factor of 9 on Table 2. No perennial surface waters are within 3000 ft of the cell (weighting of 0), whereas intermittent water is very close (<100 ft) to the center of the grid cell (weighting of 10). From the GIS database, the PE contour through this cell has a value of -20 mm, which corresponds to a PE weighting of 9 and a PE' weighting of 2 (Table 2). These various weightings are inserted into equations 5 through 10 (see Figures 3 and 4). For the example cell in Figure 3, the cell has a ranking number of 0 for SW, 2550 for intermittent SW, 45,900 for groundwater, 0 for mill type, and a final ranking of 48,512. Because the total range of values for surface waters and groundwaters is large and similar to one another, and that of the physical hazards and mills is small, and are similar to one another, the rankings in the cells are generally best evaluated by comparing the individual rankings separately, rather than in a combined form as in equation 5.

RESULTS

Data Compilation

Existing data, along with the latitude, longitude, elevation and site name, were compiled into an ArcInfo accessible database including the following data files:

EarthInfo data/STORET	Major element chemistry of waters Trace element chemistry of waters field parameters for sampled waters
Digitized County Geologic Map	1:250,000 scale geologic map faults
MILS data	mine type, lithologies, presence of mills/smelters commodities, deposit type and size alteration, rock type, etc.
MRDS data	mine type, lithologies, presence of mills/smelters commodities, deposit type and size alteration, rock type, etc.
NBMG rock geochemical data	percent major oxides trace element concentrations
1992 Soil Conservation Service	Precipitation point data

Evaporation data	Calculated from ≥20 yrs of temperature data for all available stations
TIGER FILES	Road network
USGS 100K DLG (USGS, 1994)	Major rivers and streams
Latitude, Longitude lines	
7.5' quadrangle boundaries	
1 X 2° quadrangle boundaries	
County boundaries	
Mining district areas	
Active mine sites	
7.5' quadrangle digitized shaft, pit, adit locations	
7.5' quadrangle digitized waste dump areas	
7.5' quadrangle digitized leach pad areas	

Calculated Grids

Values were calculated for all variables noted in equations 6 through 10 based on the weightings indicated in Tables 1 and 2. Figures 5 through 8 illustrate selected grids constructed in GIS in this pilot project. Although all figures were originally constructed in color with 10 separate subdivision, figures are illustrated here in black and white with five separate subdivisions. The lowest subdivision includes original categories 1 and 2 (lowest ranking), whereas the highest subdivision includes original categories 9 and 10 (highest ranking). The grids (not shown here) for the physical types of hazards (i.e., shafts, adits, pits and tailings piles) were constructed by counting the number of each of these features within a 1 km cell, and assigning a weighting factor to the grid based on Table 2. For instance, if there were three shafts and one pit within a particular cell, the shaft grid cell was assigned a value of 3 and the pit grid cell was assigned a value of 4. In the case of the tailings, if 35% of a particular grid cell was covered with a tailings pile, the cell was assigned a weighting factor of 4. These designations were made in this initial model development because it was assumed that the greater the surface area and number of mining excavations within an area, the greater is the opportunity for waters to interact with materials disturbed through mining. Hence, given the same deposit type, there is a greater chance for waters to interact with disturbed materials when there is a greater amount of this material present.

The grids for surface waters and groundwaters appear in Figures 5 and 6. These grids were constructed in a similar fashion to those for the physical characteristics based on data in Table 2. Figure 5 shows the perennial surface water grid. The intermittent surface water grid is not included here, yet it is essentially composed of a weighting for every grid cell in the county, exclusive of the main perennial waters shown in Figure 5. Figure 7 shows the grid constructed from the weightings of the precipitation minus evaporation which were used to estimate risks associated with shafts and pits (equations 6 - 8). The lower PE values are associated with greater evaporation in the PE term. In the case of pits, higher evaporation could result in evapoconcentration of the waters, and hence lower values are associated with higher weighting factors as indicated in Table 2. No plot of the PE' grid is included here because it is essentially opposite to the one depicted in Figure 7. Finally, the grid constructed for the deposit classification appears in Figure 8. A listing of the mining districts and commodities associated with the large numerals on Figure 8 appears in Table 3.

Ranking of Sites in Clark County

Using the previously noted grids (e.g., Figures 5 through 8), and equations 6 through 10, a risk number was calculated for each of the following: physical hazards (Figure 9), risks to surface waters (Figure 10), risks to intermittent surface water, risks to groundwater (Figure 11), risks associated with mill type (Figure 12), and total ranking of the site based on the summation of the grids (Figure 13). These maps are included to illustrate how an automated, calibrated ranking scheme can be used to visualize areas of higher and lower potential for environmental impacts. Because the magnitude of the different rankings differ, in practical applications it will likely be better to compare the individual rankings between sites rather than the total, summed ranking.

Figures 9-13 illustrate how various stages of a final ranking scheme could be used to help identify areas more likely to contain poor water quality. Table 4 lists the range of values associated with each of 10 equal subdivisions of the ranked values. On Figures 9 - 13, only five subdivisions are noted and they correspond to the combined categories of 1 and 2, 3 and 4, 5 and 6, 7 and 8, and 9 and 10 listed on Table 4. The total risk values in the 21,241 cells in the grid ranged from 0 (no mining excavations) to 85,269 (Table 5), but it is emphasized that these are relative numbers, and the particular values have no absolute meaning.

Table 6 lists the frequency in the grid at which each feature has a weight of 1 to 10. In the physical hazards grids (number of shafts, adits, etc.), the majority of the features show large numbers of cells with low weightings (weightings of 1 or 2) indicative of few mining excavations within the cells. A small percentage of the cells have high weightings of 10, indicating that very few 1 km cells have a large number of mining excavations (10 cells have >9 shafts, 11 cells have >9 adits and 3 cells have 3 pits). Note that most cells in the county (>20,990 cells, or >98% of all cells in the county) have no mining features (Table 6). In contrast, numerous cells (15,760) had a high weighting factor for groundwater, and hence, this parameter often dominates the total calculated risk in equation 10 when there are mining excavations present in the grid cell (see Table 7). The groundwater numbers (Table 7), derived from the groundwater grid noted in Table 6, generally dominate the total risk value, except in the case of cell 170 in the Goodsprings district, where surface water risks are also high. Table 5 shows that few cells have high rankings for any of the individual factors considered, which suggests that few sites in Clark County are likely to adversely impact the environment.

Using the pilot study model, the highest ranking sites in Clark County occur in the following mining districts: Alunite, Eldorado, Goodsprings and Searchlight. Given that the Alunite district contains the deposit with the highest weighting factor, it is likely that highly ranked sites in this district should be investigated in the field. Table 8 lists the higher ranked cells of the grid in all the mining districts in the county. Most areas have very low potential for adverse environmental impacts. In future field work, the five 1-km cells with ranked values of 10 in Table 8 (in bold) should be investigated to begin a determination of mining hazards in this county. Table 7 lists the highest ranked grid cells in the county for the four mining districts listed with the greatest potential for adverse impacts. In most cases, the most significant risk is to the groundwaters in the district. However, two cells in the Eldorado district indicate a significant risk to surface waters, and one cell in the Goodsprings district also indicates risks to surface waters. Most of these highly ranked cells also indicate that risks to intermittent surface waters are possible. However, because water flow in these features is only likely to occur infrequently, the model equation weights these at only 5% of the surface water risks. Hence, these values are much lower than most surface or groundwater risks. Waters have been collected from three of the higher ranked grid cells (173, 258 and 272) as part of a separate project (Price et al., 1995). All three sites have elevated TDS, yet none of the sites had particularly elevated trace metal concentrations. Therefore, these water chemistry data also indicate that even relatively highly ranked sites in Clark County may not necessarily be associated with adverse environmental impacts.

Model Performance

For the purposes of discussion and comparison, the total ranking is referenced below, although in practical applications it may be better to evaluate each factor separately. The total risk values ranged from 1 to 85,269, but it is emphasized that these are relative values, and the particular values have no absolute meaning. We assume, for instance, that a value of 40,000 is "worse" than a value of 10,000, yet the degree to which it is worse needs to be tested from (1) available data, which are incomplete (and are discussed below), and (2) field studies. Figures 3 and 4 show cells with total ranks of 48,512 (rank of 6,

Table 4) and 61,101 (rank of 8, Table 4). Although Figure 3 shows a site with potentially the most hazardous deposit type, few mining excavations occur within the example grid cell. The area of Figure 4, on the other hand, has many mining features, but a less hazardous deposit. Nevertheless, the overall ranking of Figure 4 is higher than Figure 3 because the number of mining excavations is so much larger (21 in Figure 4 versus only 8 in Figure 3). Even though these two example sites have apparently different rankings, both sites may need to be visited to further evaluate potential adverse environmental impacts. For instance, only 8 cells in the county had total ranking values of >48,000, whereas the other 468 cells with mining excavations had values ≤48,000. Hence, a value of 48,000 may not really be significantly different than a value of 61,000 in the current, uncalibrated scheme.

Once the ranking was conducted on each grid cell in the county, selected sites with high and low potential for adverse environmental impacts were chosen for evaluation of the ranking. The calculation scheme described above is tested at sites where data are available from either NBMG August, 1995 sampling sites (Price et al., 1995), NBMG rock geochemical data, or from the EPA STORET database (Earth-Info, 1993). Note that most ranked grid cells did not have any of these three types of associated data and comparisons of rankings with other sites could not be made. The EPA database was searched for water quality to determine if any of the highly ranked abandoned mine sites are associated with poor surface or groundwater quality.

The grid cells which have associated NBMG rock or water chemistry data, or STORET data, were selected and tabulated in Table 9. Note that the NBMG rock geochemical data are from samples collected from mine dumps, and hence, all analyses are biased toward samples collected in more mineralized areas. Multiple entries after a well or spring in a particular cell indicates that there was more than one such feature for which data were available within the cell. Rankings and relative differences between selected water and rock chemical parameters do not correlate directly for several reasons. Data for each of the parameters listed were not available for both waters and rocks at all of the sites. In addition, it is highly unlikely that geologic features within any given grid cell are homogeneous. Whereas a particular deposit classification is associated with each cell, it may not occur throughout the cell, and a well or spring water may be representative of waters issuing from a different geologic setting in the cell. For instance, domestic water wells would be more likely to be sited in a non-mineralized area to avoid potentially elevated metals in the drinking water.

Nevertheless, there appears to be a general correlation between measured chemistry in mineralized rock and cell rankings in the Searchlight district (cells 374, 430, 443). Higher Pb and Zn concentrations occur in the higher ranked cells:

Cell #	Rank	Pb (ppm)	Zn (ppm)
374	14,620	150	35
430	42,596	2,000	750
443	47,216	15,000	800

These data indicate that the results of the ranking scheme are consistent with data collected from mineralized rock. No water analyses were available in these cells from which additional evaluations could be made. Limited data preclude making additional comparisons of this type.

In summary, we currently have insufficient data to rigorously evaluate and calibrate the model. In order to evaluate the existing model in an unbiased manner, field evaluations of selected cells should be conducted (1) to assist in model adjustments and calibrations, and (2) to determine how ranking numbers should be grouped for prioritization of sites. These field studies may demonstrate that all rankings between some range of lower values indicate nearly equal, low environmental risk and should be grouped into one category not to be considered in future field evaluations. Again, for example, selected grid cells with higher values may show some indication that additional detailed studies are warranted at all sites with values in excess of a particular value. These questions can only be resolved through field evaluation of our model.

Comparison of rankings for a small number of sites in the state for which water samples are available reveals that parts of the model will require refinement before a rigorous state-wide ranking can be conducted. Sufficient data have not yet been compiled in the remainder of the state for the GIS ranking to be conducted and compared to the Clark County values. However, available data from existing GIS coverages and water chemistry (Price, et al., 1995) can be used to begin evaluation of the current model and identify parts of the model requiring refinement. GIS databases were used to identify mining excavations, distances to surface waters, etc. for sites where water samples were collected by NBMG in August of 1995 (Price, et al., 1995). All mining excavations in the state have been digitized and a 1 km grid for the state was constructed in order to identify the number of features within a grid. This new grid did not precisely correspond with the one constructed for Clark County alone. In addition, in order to compare sites throughout the state, the average yearly precipitation minus evapotranspiration was calculated and it's value at each sampling point recorded. Distances of sampling points to surface waters and groundwaters were estimated from GIS coverages of DLG surface water locations and elevation maps. All the various data were recorded and entered into a spreadsheet in which various calculations could be changed in an attempt to better calibrate the model to reflect the poor water quality noted during field sampling at some of the sites.

The spreadsheet calculations were first made using the original pilot study model, which weights the number of mining excavations heavily. This method clearly weights the number of excavations too heavily as site rankings correlated poorly with the presence of either good or poor water quality. Hence, a variety of changes were made to the original model in an attempt to improve the ranking. For instance, as noted previously, evapoconcentration of waters in shafts is likely to be much less than in pits. The high ranking can also be attributed to the manner in which PE is assigned to shafts. Because precipitation minus evaporation is a large negative number, PE has a high weight of 9 because water in shafts and pits can become evapoconcentrated. However, it is likely that the amount of evapoconcentration occuring in any given shaft is much less than would occur in a pit because of the much smaller surface area of water in the shaft, and the depth of this water below ground surface. One method to account for this would be to weight the PE term for shafts at only 10% of that for the pits, for example. When this is done for an example grid which ranked unrealistically high (CL-778), the revised total ranking of the cell was reduced by approximately 50%. However, because shafts tap groundwaters, it may be more realistic to multiply this factor by the same factor (PE') as for the adits because much of the water intersect by shafts is groundwater which also must have percolated through the unsaturated zone. In addition, rather than counting the number of excavations, their presence or absence was included in the model by assuming a 1 if present, 0 if not present.

In future modeling using the general approach described here, additional experimentation should be conducted to identify the best way to adjust the various factors such that the model more realistically shows the water quality trends identified from field sampling. The various factors which will require adjustment from the pilot study model include: de-emphasizing the weighting of the number of mining excavations, de-emphasizing the PE weighting of the shafts, and placing greater weight on the deposit type. Some of these changes resulted in notable improvements in the predictive capabilities of the model for the limited number of sites where water samples are available.

Table 10 lists weighting factors, rankings, and selected, relevant chemical data for sites where water quality data are available (Price et al., 1995). All calculations on this table were conducted using the excavations noted on the newly formed state-wide grid. Sample locations for these sites are illustrated in Figure 14. Many of the lower ranked sites have relatively good water quality based on samples collected within the grid. The sites within the highest weighted deposits rank higher than any of sites within the lower weighted deposits. Note that the highest ranked grid cell is at the Rio Tinto Mine where water from Mill Creek was sampled after flowing along the side of tailings piles. The quality of the water sample collected at this site in 1995 was good. The deposit at this mine is a massive sulfide containing abundant pyrite. In addition, abundant limonite is present in the stream bed (Price et al., 1995) indicating acid drainage is probable at this site and the water sample collected may not be representative of conditions at the site during other time periods.

Obvious discrepancies in the ranking of the various sites can be seen. Controlling factors are related to the weighting of the deposit types and the numbers of features within the grid cells. For instance, note the low ranking of sites EU-1 and MI-369 (Table 10). Although the water quality at these sites is generally good, As is significantly elevated in both. Hence, in a revised ranking scheme to be used on a state-wide basis, greater emphasis should be placed on deposit types known to have significantly elevated concentrations of As. In addition, some sites are ranked unrealistically low even though they are contained within relatively highly weighted deposit types. For instance, water at site HU-217 has low pH with significantly elevated Fe concentrations, but is ranked lower than sites where water quality was good. Similarly, some sites are ranked unrealistically high (CL-13 and CL-778). Although these two sites have elevated TDS relative to drinking water standards (>1000 mg/L), their pH and trace metals concentrations are generally not significantly elevated above drinking water standards. The high ranking results because the two grid cells contain several types of mining excavations (3 or 4 rather than only 1 or 2 as is noted in most other grids). Although greater numbers of mining features in a grid should result in a greater probability that water (if present) will be able to interact with disturbed material, the number of features needs to be further de-emphasized in future work because even one feature in a deposit type such as quartz alunite is more likely to be associated with poor water quality than a site in a quartz adularia deposit. In a revised, calibrated model for the entire state, greater emphasis should be placed on mineral deposit type, and much less emphasis should be placed on the number of mining excavations.

Many of the sites where water was sampled occur in polymetallic vein deposits. The rankings of these sites spans a large range (values of 1765 to 8072, Table 10), and the quality of water varies appreciably as well, though poor quality water is not always associated with the higher ranking. Water at some sites (EU-1 and MI-369) has very high concentrations of As, whereas others contain significant Fe and Mn concentrations (WA-210 and LA-157). Based on the results, it appears that the polymetallic vein category is currently too broadly defined, and the current classification is primarily oriented toward identification of potential acid formation. Future work should be conducted to account for some of the expected variations in deposits within this classification in order that those more likely to result in elevated As, Fe, Mn (and others) can be better anticipated.

CONCLUSIONS

Summary

The model developed here provides a template from which future ranking of abandoned mine sites in Clark County and the entire state can be conducted. Following some revisions and calibrations, sites throughout the state may be ranked by their potential to result in adverse environmental impacts. Relevant factors such as mineral deposit characteristics, precipitation, evaporation, and distances to surface and groundwaters were incorporated into the model to help in evaluating which sites may impact water supplies.

The number of mine features (shafts, adits, pits, etc.) was weighted heavily in the initial model, but may need to be de-emphasized in future work. In contrast, geology and deposit type, which were already heavily weighted, may need to be emphasized to a greater extent. Although the number of mining excavations is important when comparing sites in similar geologic settings, the differences in geologic settings between sites is more important than the number of excavations in determining which sites are more prone to result in adverse environmental impacts. Those deposits found to consistently have poor water quality should be given greater emphasis, and a greater range in weighting values between the deposit types may help in better differentiation between sites with the potential for better and worse water quality. Better differentiation within the polymetallic vein deposit type should be attempted given the wide variability in its characteristics and associated water quality. An environmentally sensitive deposit type such as quartz-alunite has a high weighting factor of 100, whereas more benign deposits such as epithermal manganese or fluorspar have considerably lower weighting factors (8 and 10, respectively). A quartz-alunite site with even one shaft or adit is probably a greater risk to the environment than an epithermal manganese site with 10 of these features, and a revised scheme should better account for this factor. The quartz-alunite deposits are much more likely to be associated with poor water quality, and these areas should be emphasized to an even greater extent than is currently handled by the model. For instance, of the waters sampled from 39 shafts, adits and pits throughout the state (Price, et al., 1995), most of the samples were near neutral. However, sampled water issuing from two adits in quartz-alunite deposits had pH of <3.0, Fe contents of up to 1380 mg/L, and high concentrations of Cu, Mn and As (451 mg/L, 19 mg/L, and 16 mg/L, respectively). Hence, if any water interacts with these deposits, the resulting water could be of very poor quality.

Future Work and Limitations of this Study

Additional studies related to this work should include applying a revised, calibrated risk assessment methodology to the remainder of the state, field checking specific sites, and conducting detailed geologic and hydrologic studies at the small percentage of sites which have adversely impacted the environment. The current work has identified some of the areas in which the model should be revised in order to obtain more realistic state-wide ranking values. Although other such revisions should be evaluated and considered in future work, the revisions identified in the current work include: (1) de-emphasizing the weighting on the number of mining excavations; (2) de-emphasizing the PE weighting of the shafts; (3) placing greater weight on the deposit type; and (4) conducting literature reviews and field work to identify differences between the various polymetallic vein deposits. Clark County is not representative of the rest of Nevada because (1) it is more arid than many portions of the state, and (2) there is less mining activity than in some other parts of the state. Use and calibration of the model state-wide will allow for better discrimination between sites throughout the state because a greater range in deposit types occurs in the remainder of the state than was modeled in the pilot study in Clark County alone.

Other factors of concern to the U.S. Bureau of Land Management and the Nevada Division of Minerals could also be incorporated into the final model formulation for the state. For instance, distances to population centers and paved roads could be incorporated as a weighting factor in a revised model. Proximity to features such as schools, fisheries or water intakes could be more heavily weighted than sites in proximity to industrial areas. This is particularly important in the analysis of physical hazards. The Nevada Division of Minerals has examined over 6,400 abandoned and inactive mine sites in its program to protect the public. Most of the sites that the Division has secured are near population centers or relatively easy to access from paved highways. The results of a statewide analysis of the location and number of mining excavations as has been done in this study for Clark County would assist the Division in setting priorities for future work.

In developing and improving this type of risk assessment for the entire state, several refinements can be attempted. As mentioned in previous sections, the overall model should be calibrated with available data on environmental hazards. These data are being developed in other studies by NBMG and BLM. Additional information from the USGS (in particular from studies of environmental ore deposit models and compilations of baseline geochemical data) can be incorporated into the model. The groundwater component of the model can be improved through detailed studies of relationships between geology, topography, precipitation, and ET. Existing reports could be scanned to identify areas of known perched groundwater, and these data could also be incorporated as a GIS layer.

The approach used in this study is only a first step in evaluation of the potential of environmental impacts from abandoned and inactive mines. Because the type of study described here is limited in its incorporation of site-specific data, results from a revised ranking model should not be used in site-specific land management decisions, but should be used only to prioritize sites for more detailed studies. For instance, this study uses the 1:250,000-scale geologic map of Clark County, which provides a broad picture of the rock types in the county. For site specific investigations and decisions, however, geologic mapping at scales of 1:24,000 or greater would be necessary. In addition, site investigations would be necessary prior to any land-management decisions to evaluate assumptions about mineral deposit type (and variations from the standard types), map variations in wall rock alteration (which can control neutralization potential for any acidic waters), physical hazards, surface and groundwater geochemistry, and three-dimensional hydrogeology of the site and areas that may be affected.

ACKNOWLEDGMENTS

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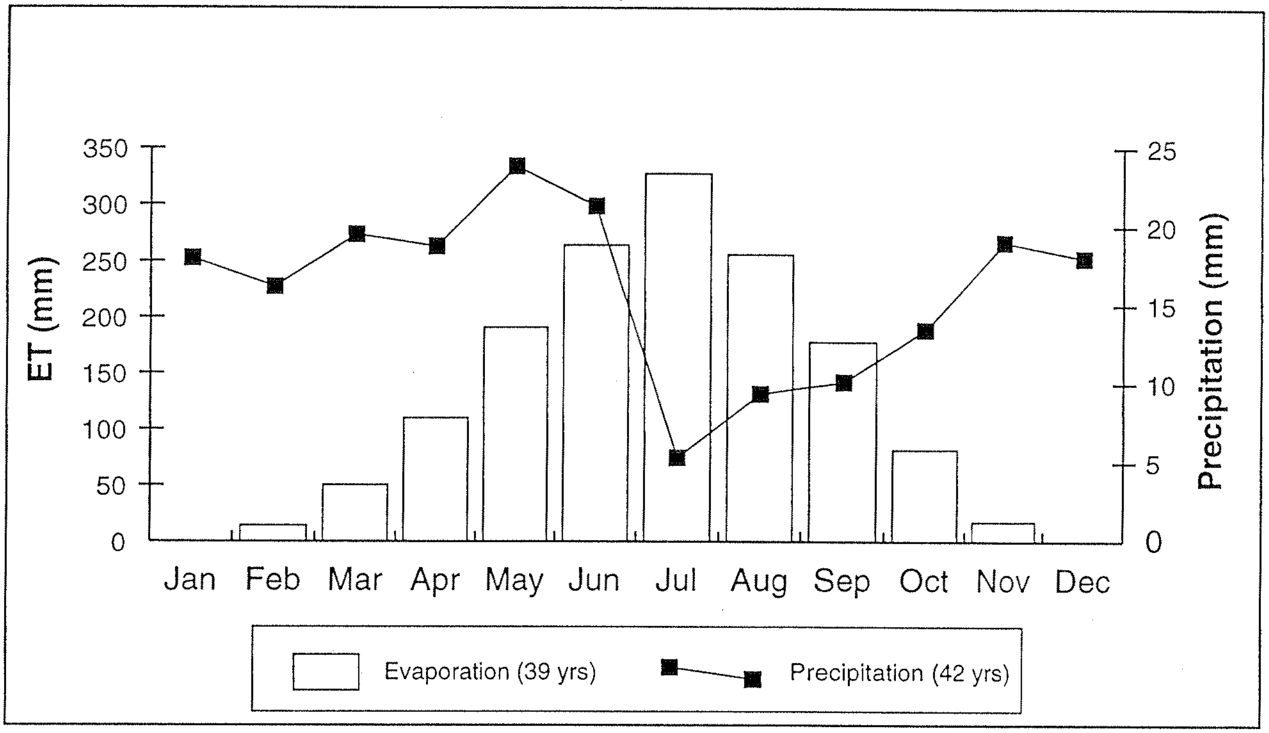


Figure 1. Evapotranspiration and precipitation versus time at the Imlay weather station.

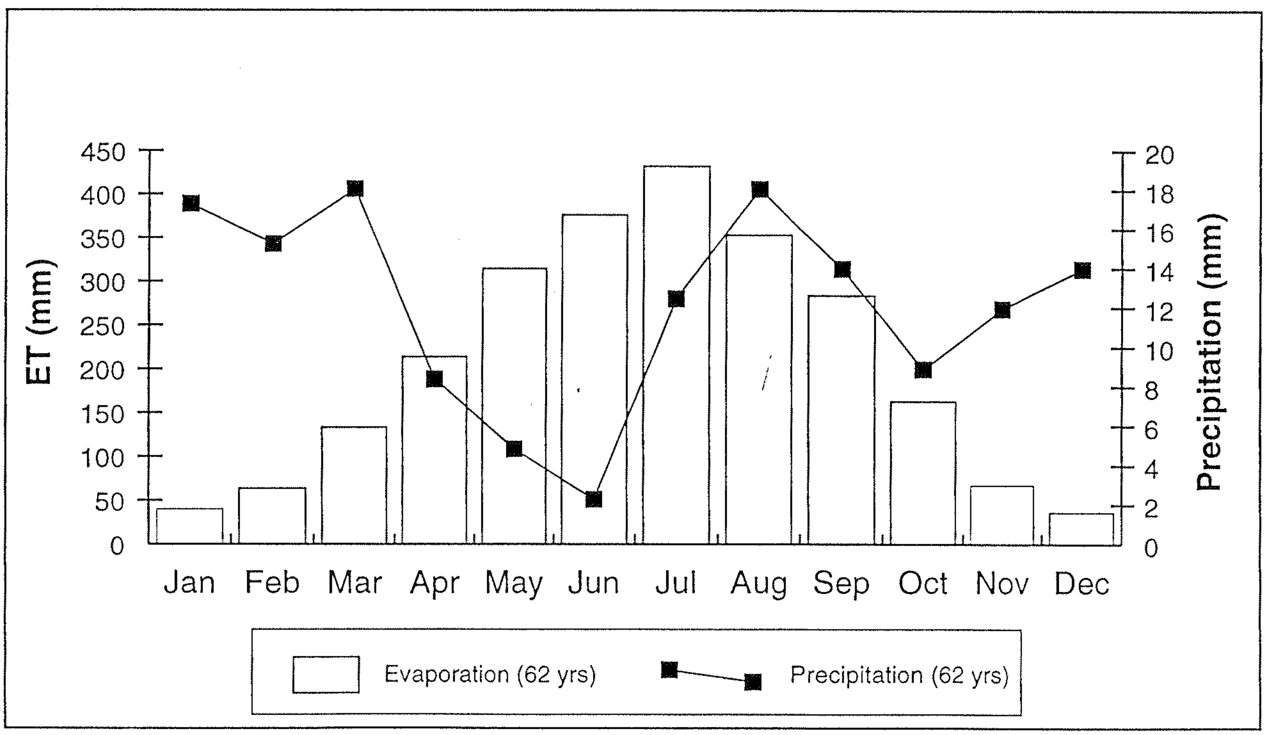
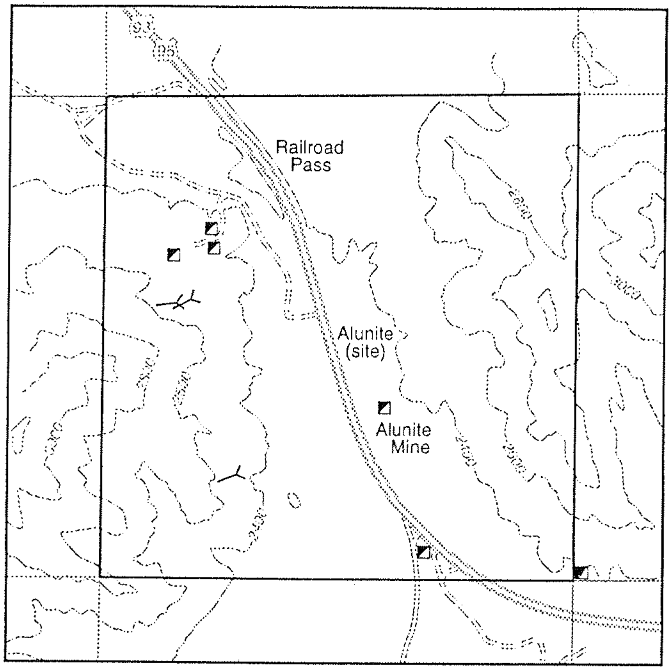


Figure 2. Evapotranspiration and precipitation versus time at the Boulder City weather station.



	#, size, type	Weight
Shafts (S)	5	5
Adits (A)	3	3
Pits (P)	0	0
Tailings (T)	none	0
Tailings ponds (Pd)	none	0
Leach ponds (L)	none	0
Mine dump (D)	none	0
Mill (MT)	none	0
Deposit Classification (DC)	Quartz-alunite	100
Depth to groundwater (GW)		
Elevation (ft)	2600	9
Dist. to Surf. water (SW; ft)	>3000	0
Dist. to Int. Surf. water (ISW; ft)	<100	10
PE	-20	9
PE'	-20	2

Alunite Mine area

Equation 11:

SW rank = ((((S + P) × PE + (Pd × PE)) × 0.75 + A × PE'+ (L + T + 0.8 × D) × PE') × DC) × SW
SW rank = ((((5 + 0) × 9 + (0 × 9)) × 0.75 + 3 × 2 + (0 + 0 + 0.8 × 0) × 2) × 100) × 0
SW rank = 0

Equation 12:

Int SW = (((((S + P) × PE + (Pd × PE)) × 0.75 + A × PE'+ (L + T + 0.8 × D) × PE') × DC) × ISW) × 0.05
Int SW = (((((5 + 0) × 9 + (0 × 9)) × 0.75 + 3 × 2 + (0 + 0 + 0.8 × 0) × 2) × 100) × 10) × 0.05
Int SW = 2550

Equation 13:

Groundwater = (((S + P) × PE + Pd × PE + A × PE'+ (L + T + 0.8 × D) × PE') × DC) × GW
Groundwater = (((5 + 0) × 9 + 0 × 9 + 3 × 2 + (0 + 0 + 0.8 × 0) × 2) × 100) × 9
Groundwater = 45,900

Equation 14:

Physical Hazards = (10 × S) + (7 × P) + (4 × A)
Physical Hazards = (10 × 5) + (7 × 0) + (4 × 3)
Physical Hazards = 62

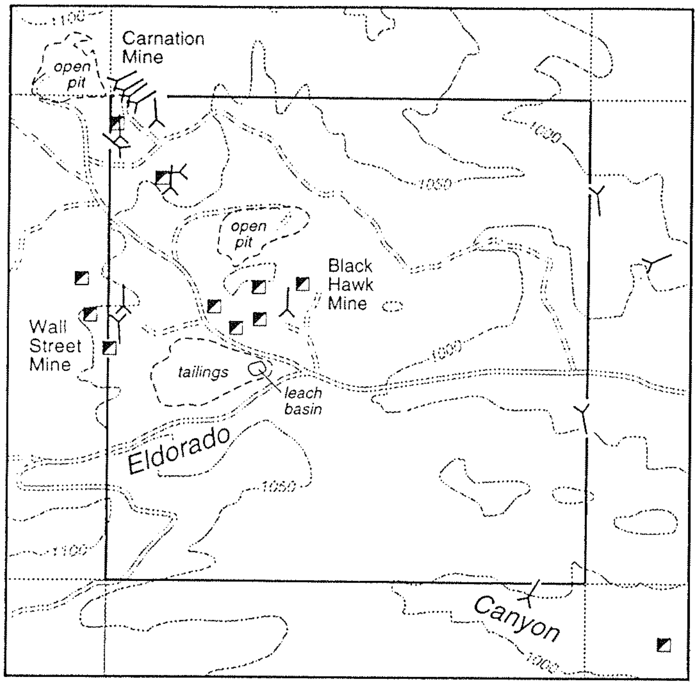
Equation 15:

Mills = MT
Mills = 0

Equation 10:

Risk = Groundwater + Surface Water + Intermittent SW + Physical + Mill Type
Risk = 45,900 + 0 + 2550 + 62 + 0
Risk = 48,512

Figure 3. Example grid cell and calculations near Alunite.



	#, size, type	Weight
Shafts (S)	8	8
Adits (A) 10	10	
Pits (P)	1	4
Tailings (T)	<10% of cell	1
Tailings ponds (Pd)	none	0
Leach ponds (L)	<10% of cell	1
Mine dump (D)	none	0
Mill (MT) none	0	
Deposit Classification (DC)	polymetallic	50
Depth to groundwater (GW)		
Elevation (ft)	3280	9
Dist. to Surf. water (SW; ft)	>3000	0
Dist. to Int. Surf. water (ISW; ft)	100 to 500	9
PE	-5	8
PE'	-5	3

Black Hawk Mine area

Equation 11:

SW rank = ((((S + P) × PE + (Pd × PE)) × 0.75 + A × PE'+ (L + T + 0.8 × D) × PE') × DC) × SW

SW rank = ((((8 + 4) × 8 + (0 × 8)) × 0.75 + 10 × 3+ (1 + 0 + 0.8 × 0) × 3) × 50) × 0

SW rank = 0

Equation 12:

Int SW = (((((S + P) × PE + (Pd × PE)) × 0.75 + A × PE'+ (L + T + 0.8 × D) × PE') × DC) × ISW) × 0.05

Int SW = (((((8 + 4) × 8 + (0 × 8)) × 0.75 + 10 × 3+ (1 + 0 + 0.8 × 0) × 3) × 50) × 9) × 0.05

Int SW = 2903

Equation 13:

Groundwater = (((S + P) × PE + Pd × PE + A × PE'+ (L + T + 0.8 × D) × PE') × DC) × GW

Groundwater = (((8 + 4) × 8 + 0 × 8 + 10 × 3+ (1 + 0 + 0.8 × 0) × 3) × 50) × 9

Groundwater = 58,050

Equation 14:

Physical Hazards = (10 × S) + (7 × P) + (4 × A)

Physical Hazards = (10 × 8) + (7 × 4) + (4 × 10)

Physical Hazards = 148

Equation 15:

Mills = MT

Mills = 0

Equation 10:

Risk = Groundwater + Surface Water + Intermittent SW + Physical + Mill Type

Risk = 58,050 + 0 + 2903 + 148 + 0

Risk = 61,101

Figure 4. Example grid cell and calculations near Black Hawk Mine.

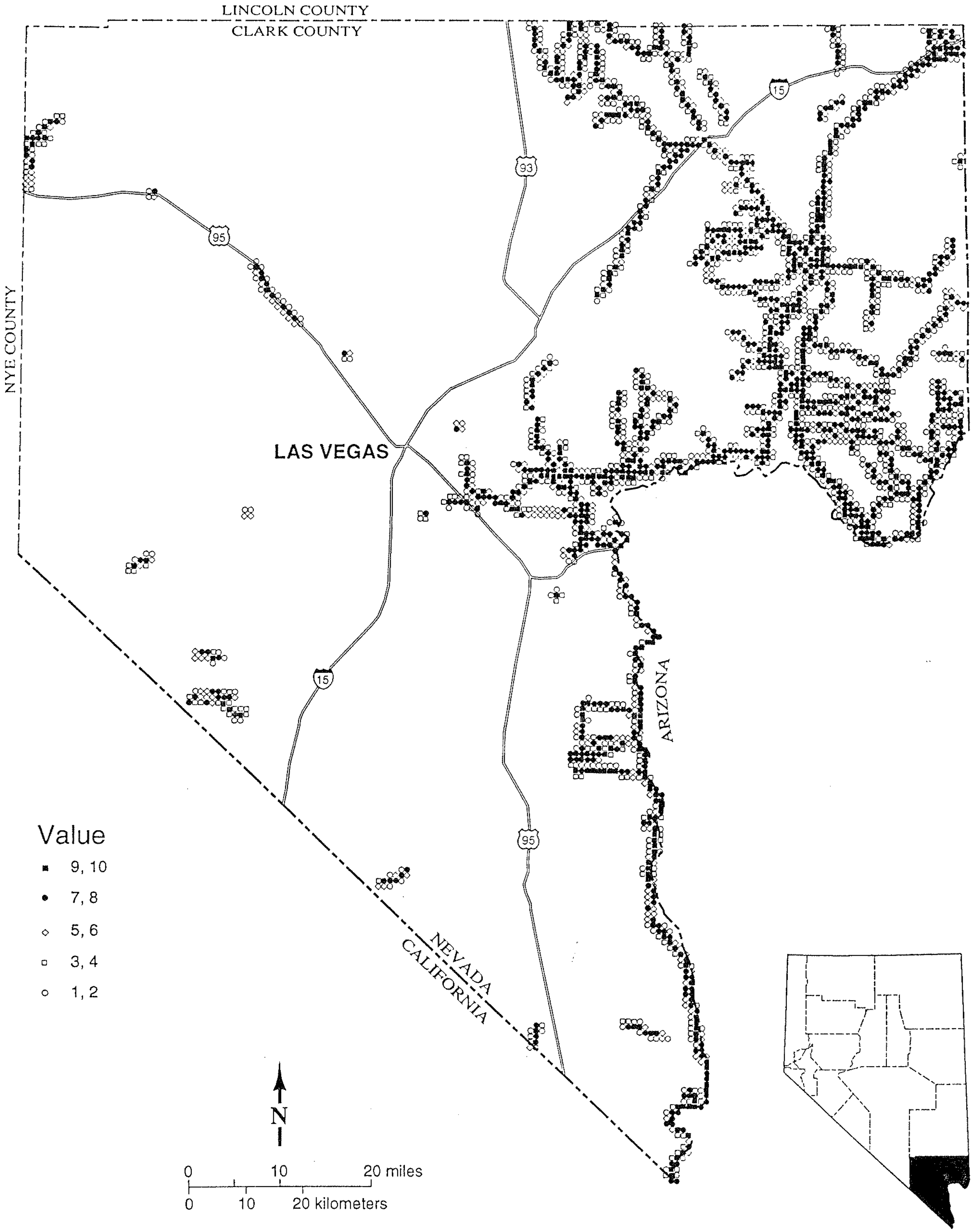


Figure 5. Weighted grid map for surface waters in Clark County based on values in Table 4.

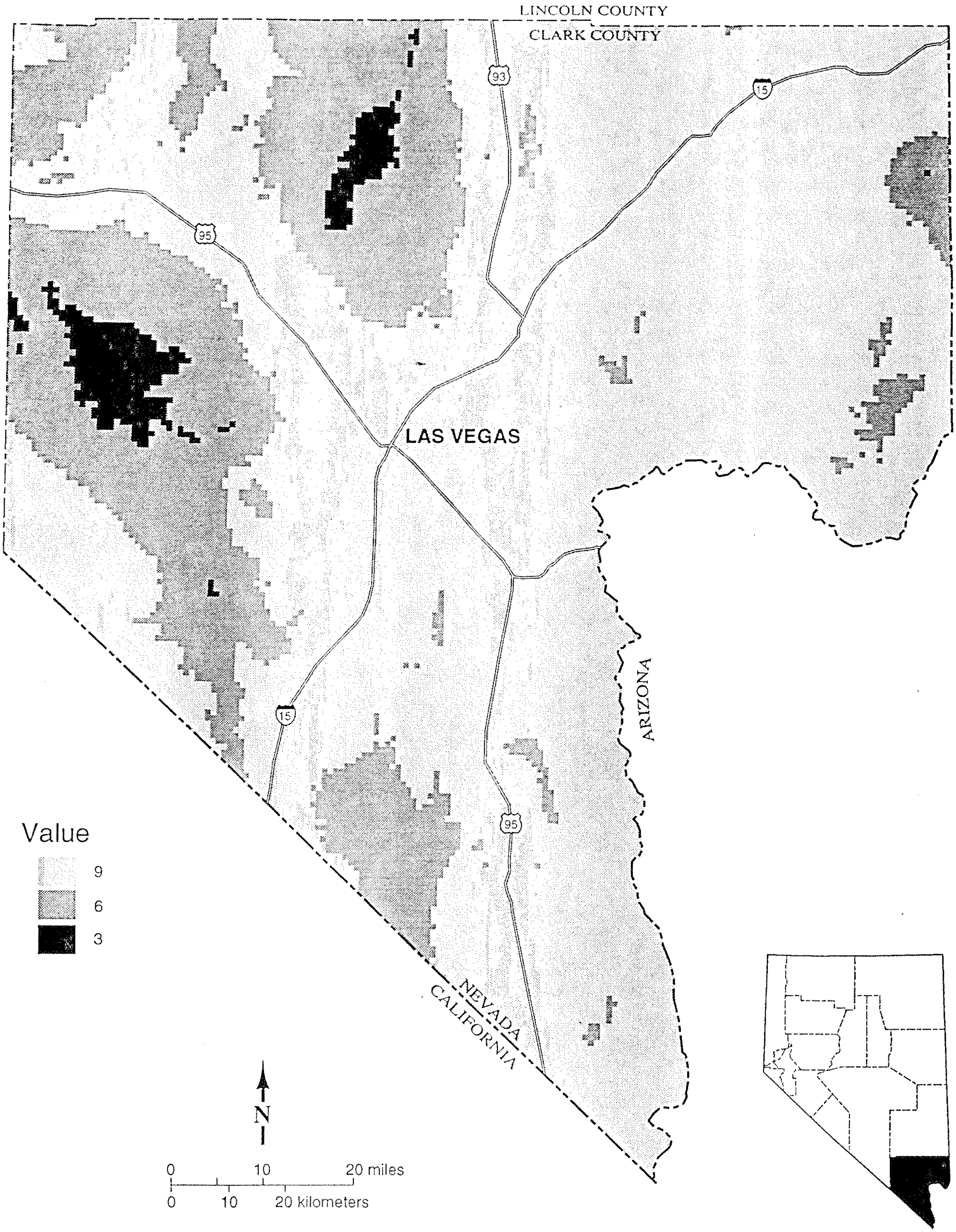


Figure 6. Weighted grid map for groundwater in Clark County based on values in Table 4.

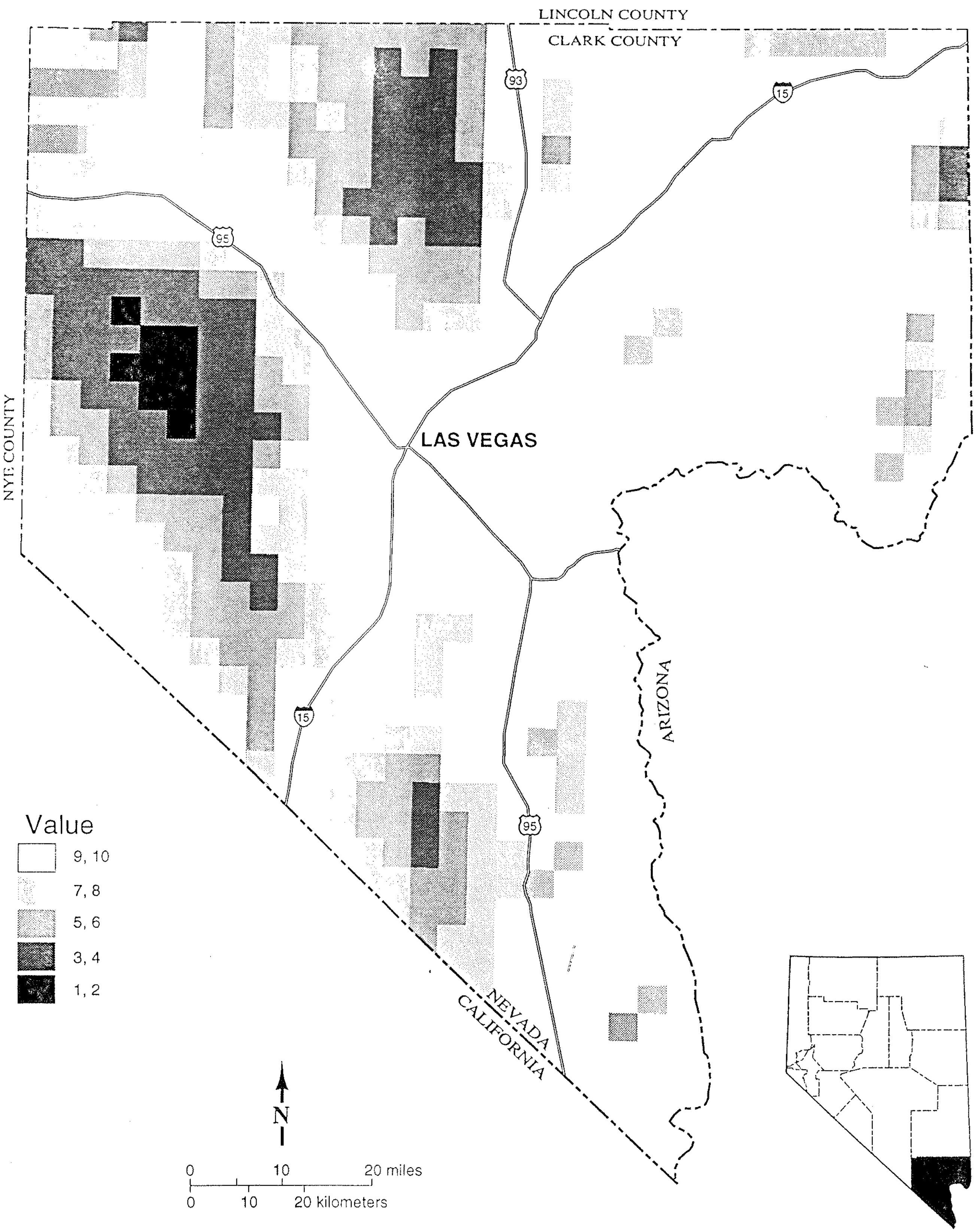


Figure 7. Weighted grid map for precipitation minus evaporation in Clark County based on values in Table 4. Precipitation is reported in 3 arc second grids in the PRISM data, and hence, grid sizes in this figure are larger than 1 km grid spacing depicted in other figures in this report.

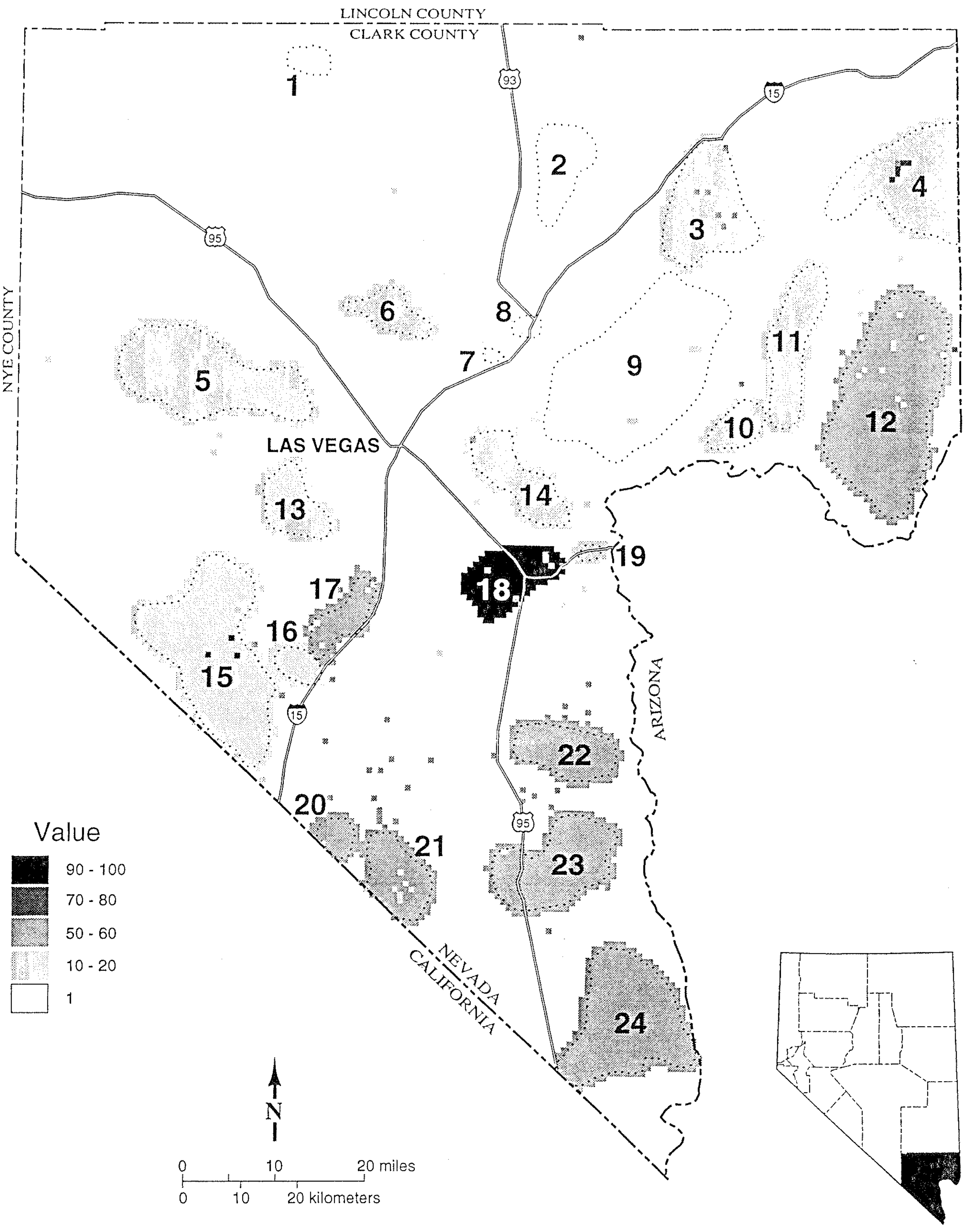


Figure 8. Map showing mining districts in Clark County based on values in Table 1. The dotted polygon outlines show locations of known mining districts. See Table 3 for identification of the mining districts.

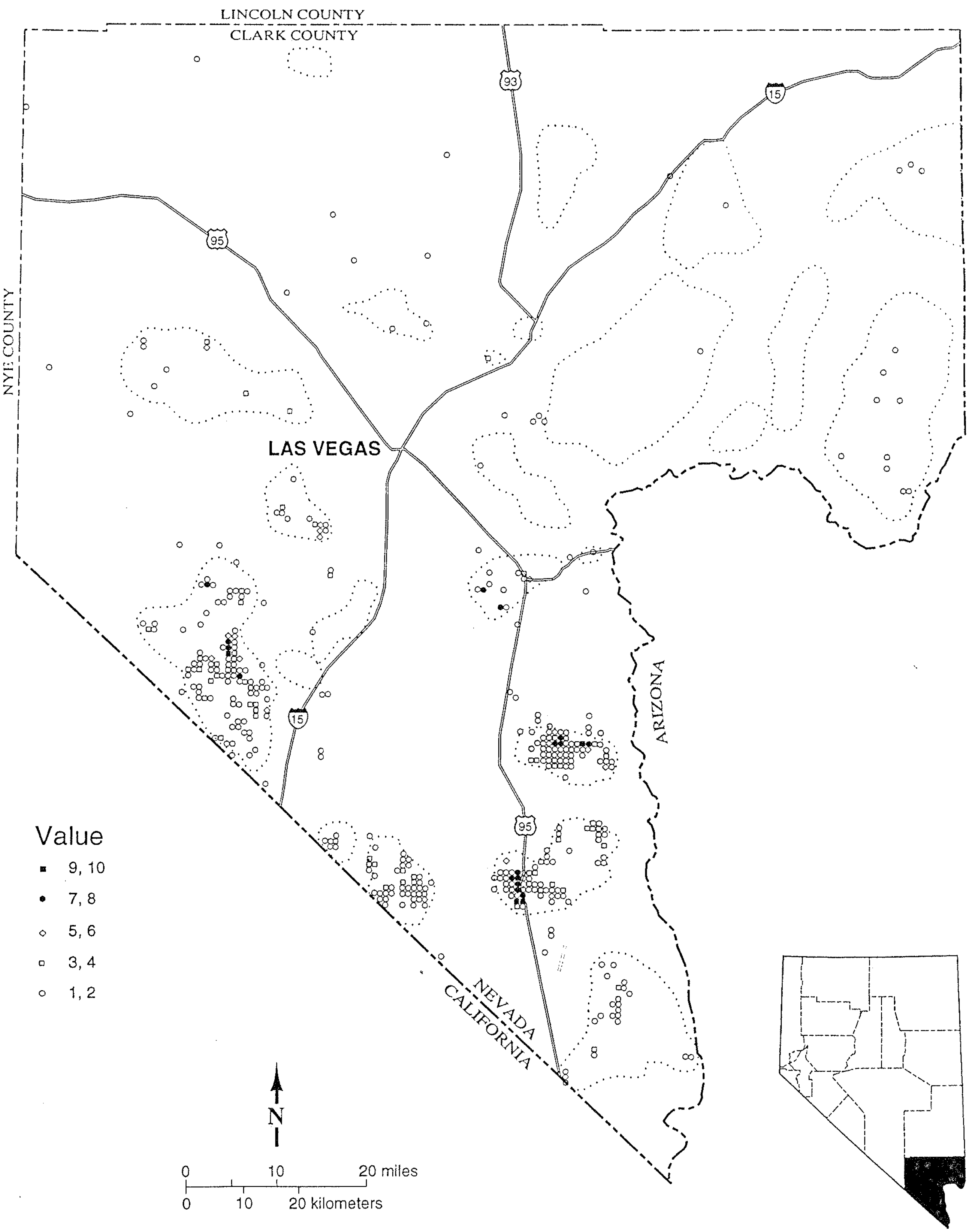


Figure 9. Final ranking of grids in Clark County based on physical hazards. The dotted polygon outlines show locations of known mining districts.

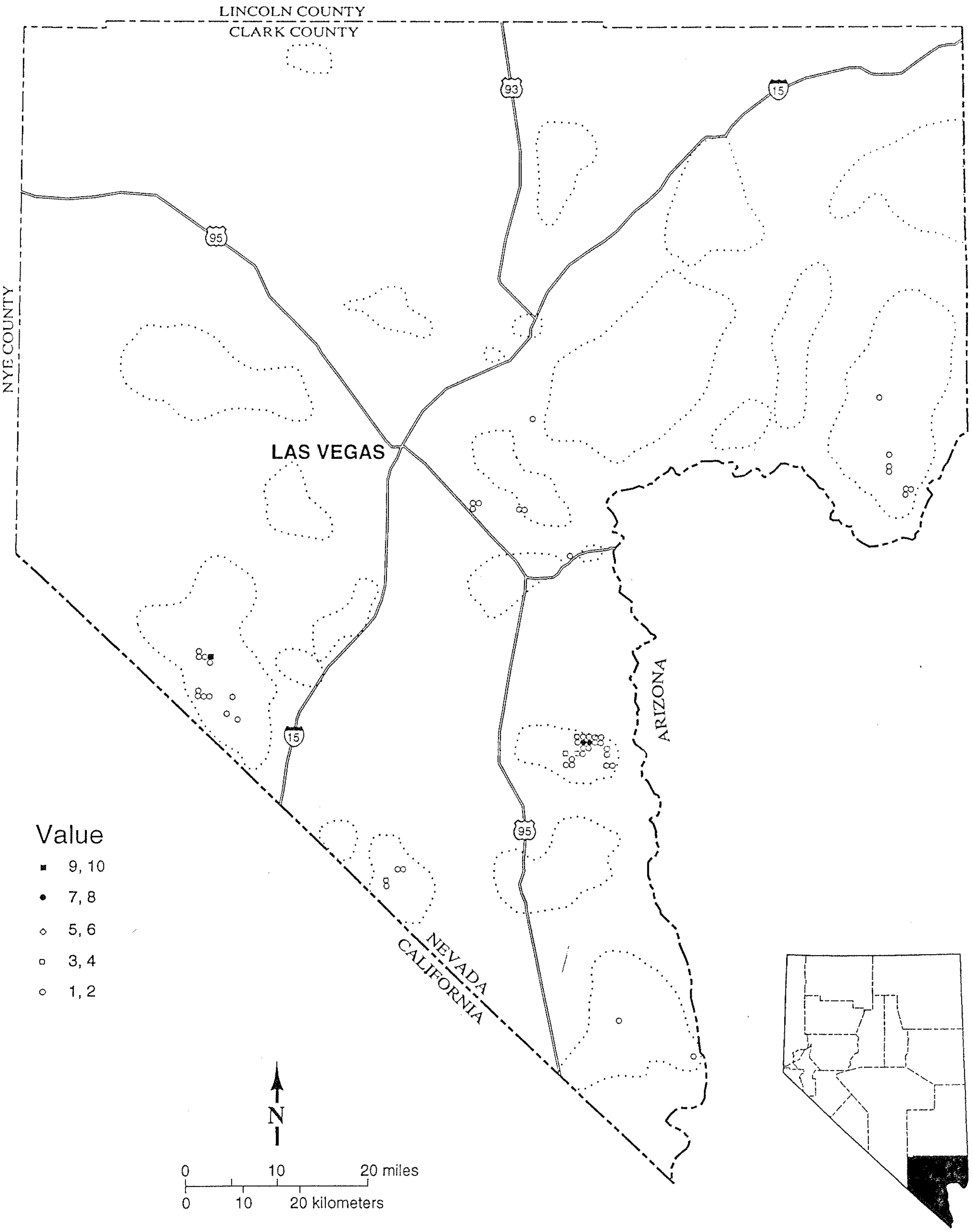


Figure 10. Final ranking of grids in Clark County based on surface water risks. The polygon outlines show locations of known mining districts.

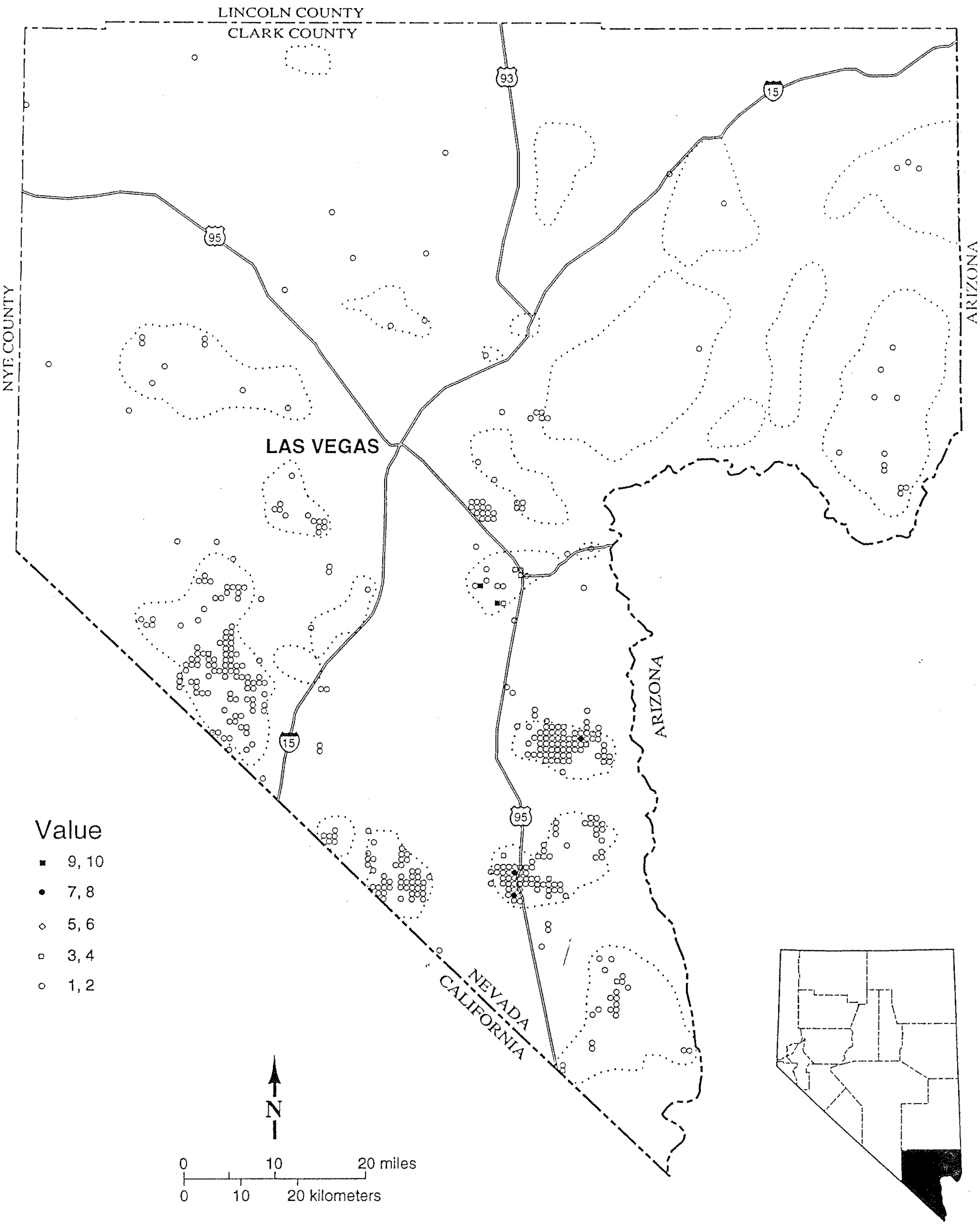


Figure 11. Final ranking of grids in Clark County based on groundwater risks. The dotted polygon outlines show locations of known mining districts.

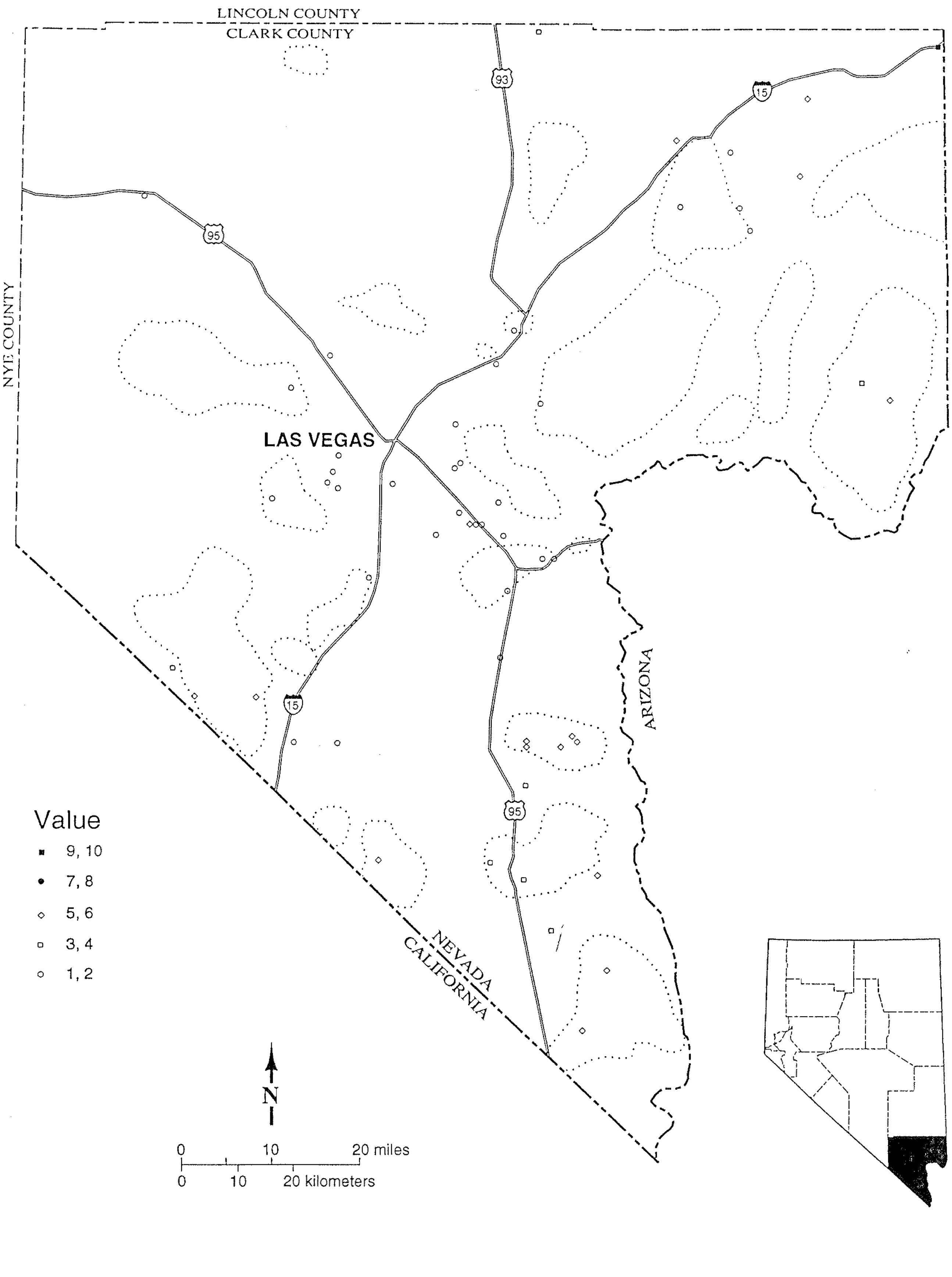


Figure 12. Final ranking of grids in Clark County based on mill type present in the grids. The dotted polygon outlines show locations of known mining districts.

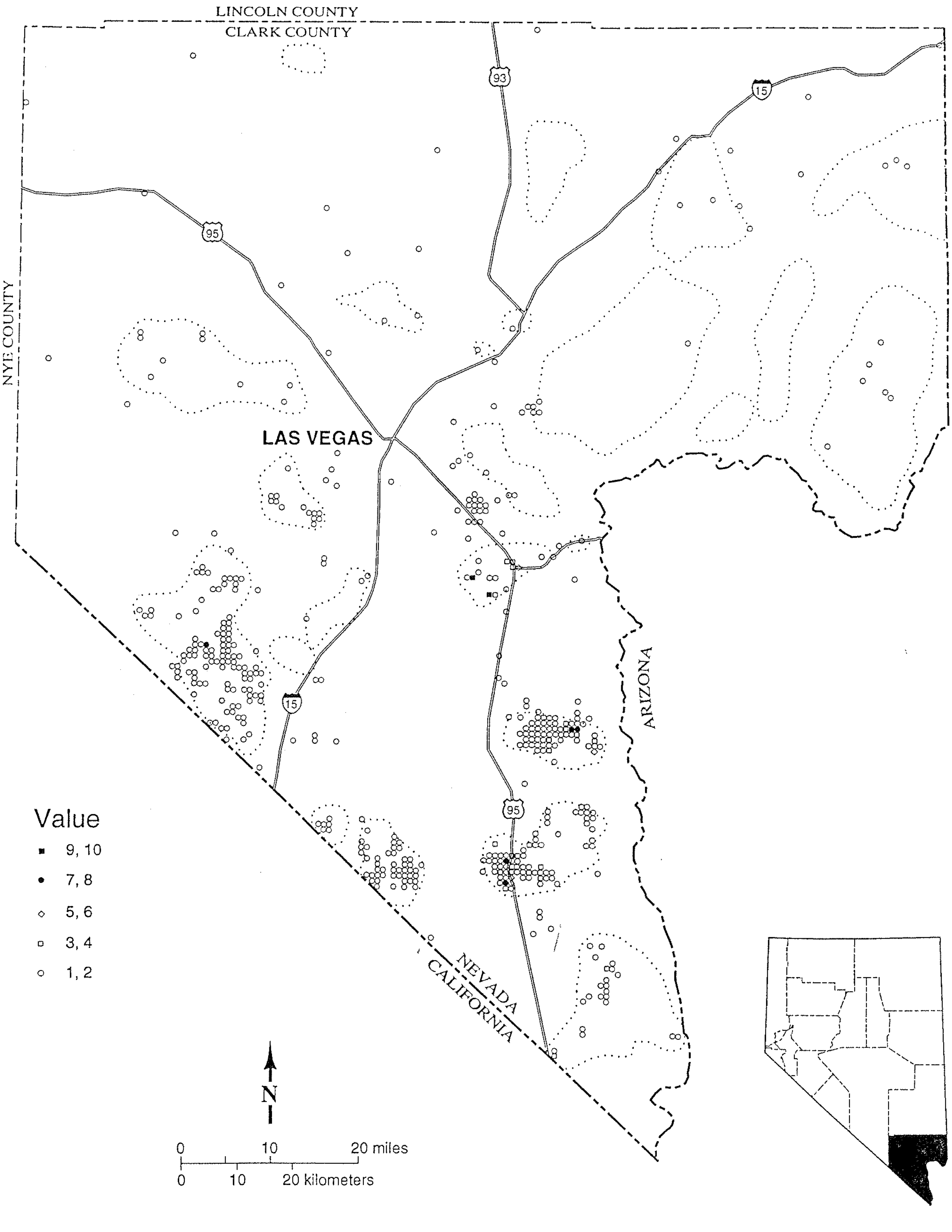


Figure 13. Final ranking of grids in Clark County based on the total ranking of the grid from equation 25. The dotted polygon outlines show locations of known mining districts.

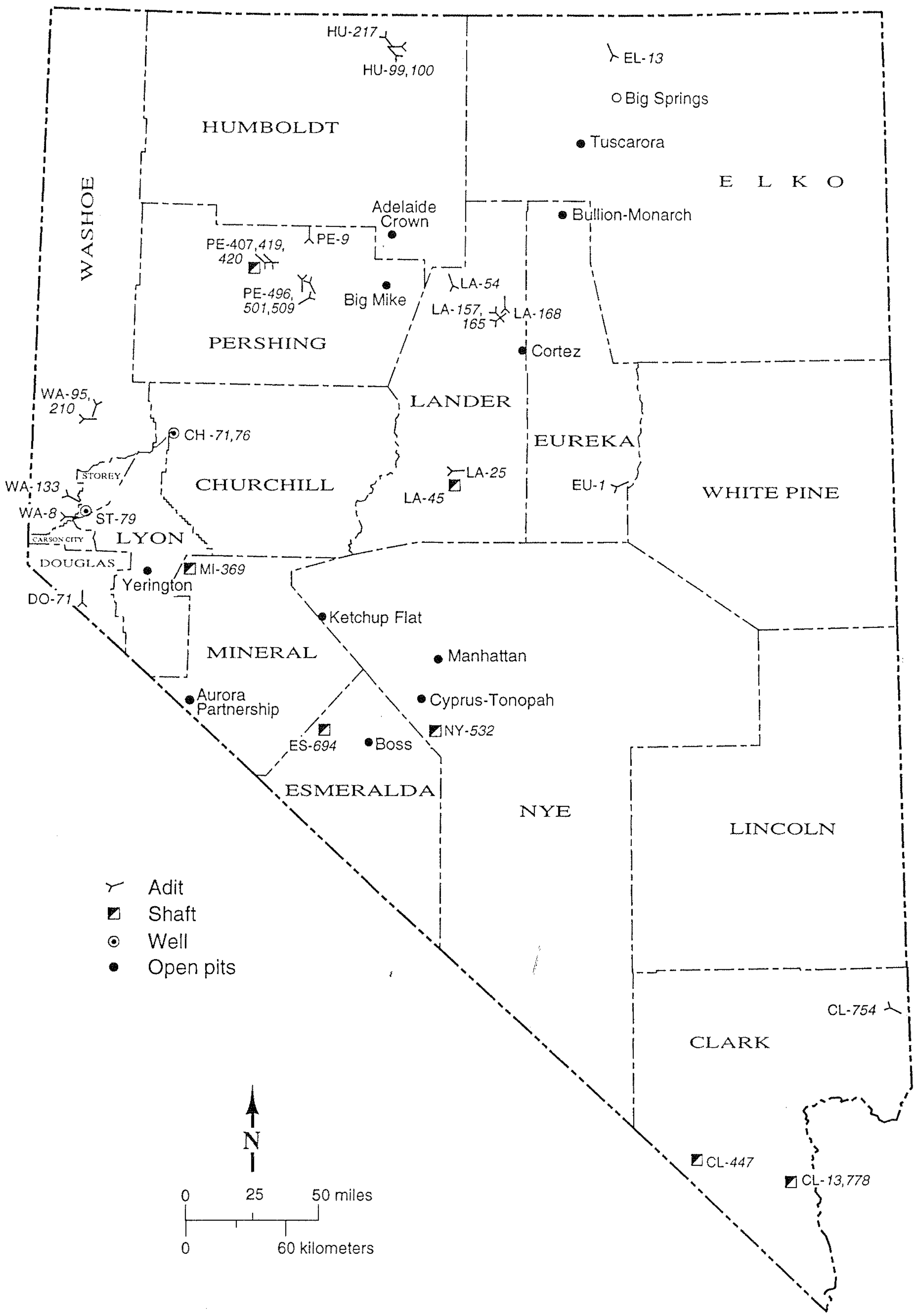


Figure 14. Sample locations for waters collected in 1995 (Price et al., 1995).

Table 1. Deposit classifications and their weightings for mine types in Clark County (in bold).

Nevada Mineral Deposit types

	Ranking	Type	Example	Potential associated trace elements	Pyrite/ Sulfide	Host Rocks Absorptive or Buffering	General Description	Remarks
1	70	**Mafic intrusive Ni-Cu-PGE**	Key West mine, Clark County	Ni, Cu, PGE, Co, Cr, Mg, S	A/A	Low-moderate	Primary magmatic or hydrothermal metal accumulations associated with mafic to ultramafic intrusion.	
2	10	Tungsten skarn	Nevada-Massachusetts mine, Pershing County	W, Mo, Zn, Cu, Sn, Bi, Be, As	M/M	High; carbonate host	Scheelite or powellite in contact-metamorphic carbonate adjacent to, or near, felsic intrusive rock.	
3	10	**Tungsten quartz vein**	Silver Dyke mine, Mineral County	W, Mo, Sn, Bi, As, Cu, Pb, Zn, Be, F	M/M	Low-moderate	Scheelite or wolframite-group minerals in veins in ss, shale, or metamorphosed equivalent adjacent to felsic intrusive rocks.	
4	30	Climax molybdenum	Mount Hope deposit, Eureka County	Mo, Sn, W, Rb > Pb, Zn, F, U	M/M	Low	Shell-like orebodies of disseminated and stockwork vein molybdenite associated with granite porphyry.	
5	70	Porphyry copper - molybdenum	Robinson district, White Pine County	Cu, Mo, Au, Ag, W, B > Pb, Zn, As, Sb, Se, Te, Mn, Co, Bi, S	A/A	Low	Disseminated copper sulfide in or near felsic, generally porphyritic, intrusive rock.	May have associated base-metal skarn or polymetallic vein deposits.
6	50	**Polymetallic vein**	Tybo district, Nye County	Zn, Cu, Pb, As, Au, Ag, Mn, Ba	A / A	Low	Base-metal bearing veins that are commonly associated with intrusive rock; trace element content variable.	Ag-Pb-Zn deposits that could be combined with other types.
7	20	**Base metal skarn and replacement**	Pioche district, Lincoln County	Pb, Zn, Cu, Mn, Co, Au, Ag, As, Sb, Bi, Sn	A/A	High; carbonate host	Base-metal sulfides in sedimentary rock, generally carbonates, with or without associated intrusive rock.	
8	100	Copper-zinc-lead-silver massive sulfide	Rio Tinto mine, Elko County	Cu, Zn, Pb, Ag, Au, Ba, As, Se, Sn, Bi	A / A	Low-moderate	Sedimentary or volcanic rock-hosted, generally strata-bound, sulfide mineral accumulations.	
9	8	**Epithermal manganese**	Three Kids mine, Clark County	Mn, Fe, Pb, Ag, Au, Cu, W	M/M	Low to high in carbonate host	Strata-bound, vein, or replacement deposits of manganese oxide.	Includes USGS replacement manganese type
10	10	Quartz-adularia precious metal	Round Mountain mine, Nye County	Au, Ag, As, Sb, Hg, Tl, Cu, Pb, Zn, Mn, Te, W, Se	M/M	Low to high, depending on calcite content	Epithermal vein deposits, generally in or associated with volcanic rock; low to moderate non-precious heavy metals.	Includes USGS Comstock and distal disseminated types
11	100	**Quartz-alunite precious metal**	Goldfield district, Esmeralda County	Au, As, Cu, Te, W, Bi; base metals at depth	M/M	Low to very low	Epithermal deposits, generally in or associated with volcanic rock; high non-precious heavy metals (e.g., As).	
12	30	Carlin gold	Carlin mine, Eureka County	Au, As, Ag, Sb, Hg, W, Tl ± Mo, F	M/M	Moderate-high	Sedimentary rock-hosted disseminated gold; generally no known igneous association; high non-precious heavy metals (e.g., As, Hg).	Low Ag
13	50	Precious-metal skarn	McCoy mine, Lander County	Au, Ag, As, Bi, Te, Pb, Zn, Cr, Ni, Co	A/A	Moderate to high; carbonate host	Pyrite- or pyrhottite-rich silver-gold deposits in contact metamophosed rock, associated intrusive rock.	
14	1	**Placer gold**	Manhattan district, Nye County	Au, Ag, Fe, Ti; low Hg, Sb, Cu	N/N	Low	Gold in recent to ancient alluvium. Low non-precious heavy-metal content.	

Table 1. Deposit classifications and their weightings for mine types in Clark County (in bold).

15	40	Sediment hosted silver	Candelaria mine, Mineral County	Ag, Pb, Mn, Zn, Cu, Sb, As, Hg, Te	M/M	Low	Sedimentary rock-hosted silver; generally no known igneous association.	
16	90	Epithermal mercury and sulfur	McDermitt mine, Humboldt County	Hg, S, As, Se, Sb, Tl, Pb, Bi, Te, Cl, Br	M/M	Low-moderate	Cinnibar and(or) sulfur in vein-type, irregular, or stratiform deposits in volcanic or sedimentary rocks.	
17	60	**Uranium**	Moonlight Mine, Humboldt County	U, C, As, Sb, F, Mo, W, Hg, V, Se, Ag, Cu	M/T	Low-moderate	Vein-type deposits in various settings, mainly volcanic; deposits in continental sedimentary rock ± organics.	
18	5	Igneous rock-hosted iron	Buena Vista mine, Churchill County	Fe, P	N/N	Low	Iron oxide vein or replacement deposits in igneous and metamorphosed igneous rock.	
19	10	Skarn and replacement iron	Minnesota mine, Douglas county	Fe, Cu, Co, Au	M/M	High-moderate; carbonate host	Iron oxide ± iron sulfide in metasedimentary rocks with or without associated intrusive igneous rocks.	
20	8	Bedded barite	Rossi mine, Elko County	Ba; local Zn, Pb, Cu, C	T/T	Moderate	Crudely stratiform deposits in Paleozoic sedimentary rocks, little or no sulfide or heavy metals.	Traces of heavy metals in minor gossan or sulfide occurrences in some mines
21	10	**Fluorspar**	Daisy mine, Nye County	Ba, As, Sb, Ag, Au, Hg, Tl, Pb, Zn, Cu, W	M/T or N/N	High; carbonate host	Vein and replacement deposits in various settings, mainly in limestone; may have associated heavy metals.	Most deposits have low heavy-metal content
22	5	**Pegmatite minerals and fluorite-Be deposits**	Wheeler Peak mine, White Pine County	Be, F, W, Li, Rb, Cs, Nb, Sn, W	M/T or N/N	Low	Mica, beryl, feldspar and other minerals generally in dikes or veins; little or no sulfide; generally low heavy metals.	
23	8	**Saline mineral**	Blue Diamond mine, Clark County	Na, B, Li, Sr, Cl	N/N	High-moderate	Ancient to recent deposits of gypsum, halite, borates in sedimentary rocks; generally strata-bound; little or no sulfide or heavy metals.	Includes brine and playa deposits
24	1	**Industrial mineral used in absorption, filtration, insulation, etc.**	Colado mine, Pershing County		T/N or N/N	Moderate	Clay, diatomite, perlite, vermiculite, talc, and zeolite deposits in various settings; little or no sulfide or heavy metals.	
25	1	**Industrial mineral for construction, glass, and chemical industries**	Pilot Peak limestone quarry, Elko County		N/N	Low to high	Limestone, dolomite, magnesite, silica sand, stone, etc. deposits in various settings; little or no sulfide or heavy metals.	
26	20	Oil shale, Coal, and Phosphorite	Elko district, Elko County	S, traces of heavy metals	T/N or N/N	Variable	Organic-rich stratabound deposits in sedimentary rocks; may contain sulfide and heavy metals.	

A=abundant, M=moderate, T=trace, N=None

Table 2. List of weightings used in the numerical classification scheme for Clark County for each of the relevant variables.

	Rankings			1 is low, 10 is a high rank						
	1	2	3	4	5	6	7	8	9	10
January										
Precip - Evap (PE)	>62	>52 - 62	>42 - 52	>32 - 42	>22 - 32	>12 - 22	>2 - 12	>-8 - 2	>-18 to -8	-28 to -18
Precip - Evap (PE')	-28 to -18	>-18 to -8	>-8 - 2	>2 - 12	>12 - 22	>22 - 32	>32 - 42	>42 - 52	>52 - 62	>62
Depth to water (ft)										
Elevation (ft)			>7500 - 11342			4000 - 7500			<4000	
Dist to surf water (ft)	>3000	>2600 - 3000	>2250 - 2600	>1900 - 2250	>1600 - 1900	>1300 - 1600	>950 - 1300	>500 - 950	100 - 500	<100
# shafts	1	2	3	4	5	6	7	8	9	>9
# pits*	0			1			2			3
# adits	1	2	3	4	5	6	7	8	9	>9
Area of tailings	>0 - <10%	10 - 20%	>20 - 30%	>30 - 40%	>40 - 50%	>50 - 60%	>60 - 70%	>70 - 80%	>80 - 90%	>90%
Area of tailings pond	>0 - <10%	10 - 20%	>20 - 30%	>30 - 40%	>40 - 50%	>50 - 60%	>60 - 70%	>70 - 80%	>80 - 90%	>90%
Area of Mine dump	>0 - <10%	10 - 20%	>20 - 30%	>30 - 40%	>40 - 50%	>50 - 60%	>60 - 70%	>70 - 80%	>80 - 90%	>90%
Mill Type	See section on Mills and Smelters									
Deposit Class.	See Table 1									

* exclusive of sand, gravel, borrow pits, and rock quarries.

Table 3. Mining districts and commodities for the large numbers noted in Figure 8. Data from Tingley, 1992.

Figure 8 Number	Mining District	Commodities
1	Slate	building stone
2	Arrow Canyon Range	silica, building stone
3	Moapa	gypsum, magnesite, silica, U
4	Bunkerville	Cu, Au, Ag, W, Ni, Pt, Pd, Co, Be, mica, gypsum, U, Ti
5	Charleston	Pb, Zn, Ag, gypsum
6	Gass Peak	Zn, Ag, Pb, Au, U
7	Dike	Pb
8	Apex	limestone
9	Muddy Mountain	borates, clay, gypsum, magnesite, sodium sulfate
10	Black Mountains	Fe, Mn
11	Saint Thomas	sodium chloride, glauberite, silica sand, magnesite
12	Gold Butte	Au, Cu, Pb, Zn, Ag, W, U, Be, Th, Ti, mica, magnesite, brucite
13	Arden	gypsum, silica sand
14	Las Vegas	Mn, Pb, Zn, Cu, gypsum
15	Goodsprings	Zn, Pb, Ag, Au, Cu, Pt, Pd, V, Co, Mo, U, Sb, Ti, perlite
16	Sutor	U, V
17	Sloan	limestone, dolomite, silica sand, U, V
18	Alunite	Au, W, alunite
19	McClanahan	Au, Ag, Cu, turquoise, alum
20	Sunset	Au, Pb, Ag, Cu, U
21	Crescent	Au, Ag, Pb, Cu, turquoise, Mo, V, Be, Th, U, perlite
22	Eldorado	Au, Ag, Pb, Zn, Cu, Hg, U, Be, Th
23	Searchlight	Au, Ag, Pb, Cu, Mo, turquoise, V, perlite
24	Newberry	Au, Ag, Cu, Sb, Th

Table 4. Range of values associated with each of the 10 separate subdivisions noted on Figures 9 through 13.

	Range of values				
Rank	Physical Hazards	Surface Water	Intermittent Surface Water	Groundwater	Total Risk
1	4 - 15	10 - 3990	1 - 256	9 - 8370	1 - 8527
2	16 - 30	3991 - 7980	245 - 512	8371 - 16,740	8528 - 17,054
3	31 - 45	7981 - 11,970	513 - 768	16,741 - 25,110	17,055 - 25,581
4	46 - 60	11,971 - 15,960	769 - 1024	25,111 - 33,480	25,582 - 34,108
5	61 - 75	15,961 - 19,950	1025 - 1280	33,481 - 41,850	34,109 - 42,635
6	75 - 90	19,951 - 23,940	1281 - 1536	41,851 - 50,220	42,636 - 51,162
7	91 - 105	23,941 - 27,930	1537 - 1792	50,221 - 58,590	51,163 - 59,689
8	106 - 120	27,931 - 31,920	1793 - 2048	58,591 - 66,960	59,690 - 68,216
9	121 - 135	31,921 - 35,910	2049 - 2304	66,961 - 75,330	68,217 - 76,743
10	136 - 152	35,911 - 39,900	2305 - 2560	75,331 - 83,700	76,744 - 85,270

Table 5. Frequency of cells with ranking values noted in the range in the 'grid value' columns.

Physical Hazards		Surface Water		Interm. Surface Water		Groundwater		Total Risk
Cell Value	Frequency	Cell Value	Frequency	Cell Value	Frequency	Cell Value	Frequency	Frequency
0 - 10	159	0 - 2000	29	0 - 200	250	0 - 4000	244	291
11 - 20	76	2001 - 4000	11	201 - 400	42	4001 - 8000	80	72
21 - 30	52	4001 - 6000	4	401 - 600	16	8001 - 12,000	39	43
31 - 40	41	6001 - 8000	3	601 - 800	7	12,001 - 16,000	17	20
41 - 50	22	8001 - 10,000	1	801 - 1000	5	16,001 - 20,000	8	8
51 - 60	8	10,001 - 12,000	3	1001 - 1200	6	20,001 - 24,000	6	9
61 - 70	8	12,001 - 14,000	0	1201 - 1400	2	24,001 - 28,000	10	8
71 - 80	11	14,000 - 16,000	0	1401 - 1600	4	28,001 - 32,000	4	5
81 - 90	4	16,001 - 18,000	0	1601 - 1800	1	32,001 - 36,000	3	2
91 - 100	7	18,001 - 20,000	0	1801 - 2000	1	36,001 - 40,000	4	6
101 - 110	5	20,001 - 22,000	0	2001 - 2200	0	40,001 - 44,000	2	2
111 - 120	3	12,001 - 14,000	0	2201 - 2400	0	44,001 - 48,000	2	2
121 - 130	2	24,000 - 26,000	0	2401 - 2600	1	48,001 - 52,000	3	2
131 - 140	2	26,001 - 28,000	2			52,001 - 56,000	0	0
141 - 150	0	28,001 - 30,000	0			56,001 - 60,000	0	0
151 - 160	2	30,001 - 32,000	0			60,001 - 64,000	1	2
		12,001 - 14,000	0			64,001 - 68,000	0	1
		34,000 - 36,000	0			68,001 - 72,000	0	0
		36,001 - 38,000	0			72,001 - 76,000	1	0
		38,001 - 40,000	1			76,001 - 80,000	0	2
						83,700 & 85,269	1	1

Table 6. Frequency of grid cells with each cell value,1 to 10.

Cell Value	Frequency of Cell Values for Individual Cells					
	Shaft	Adit	Pit	Tailings Pond	Tailings Pile	Rock Dump
1	121	129		7	27	3
2	47	50		1	1	1
3	27	31			1	
4	14	22	18	2		
5	12	7		3		
6	6	12				
7	5	8	4			
8	5	6		1		
9	4	5		1		
10	10	11	3	1		
Total # cells	251	281	25	16	29	4
# of cells with no feature:	20990	20960	21216	21225	21212	21237

Cell Value	Frequency of Cell Values for Individual Cells					
	PE	PE'	Surface Water	Intermittent Water	Ground-water	Mill Type
1	75	7011	187	560		32
2	150	6548	268	1102		
3	625	1744	241	1166	492	
4	1245	1233	251	1563		7
5	1315	1295	227	1628		
6	1295	1315	269	1847	4989	16
7	1233	1245	312	2523		
8	1744	625	375	3396		
9	6548	150	412	3323	15760	1
10	7011	75	110	801		
Total # cells	21241	21241	2652	17909	21241	56
# of cells with no feature:	0	0	18589	3332	0	21185

Cell Value	Deposit Classification
1	16251
5	381
6	46
8	942
10	5
20	1212
50	1573
60	369
70	9
100	152

Total # cells for Deposit: 20940

cells with no feature: 301

Table 7. Distribution of rankings for the highest ranked grids (no mills occur in any of these grids).

Mining District	Cell #	Rank Value	Cell Value	Physical Rank	Groundwater Rank	Surface Water Rank	Intermittent Water Rank
Alunite	130	85269	10	114	83700		1455
	146	78256	10	96	75600		2560
	122	50533	6	66	48600		1867
	119	29150	4	38	27900		1212
	147	27592	4	30	27000		562
	121	25241	3	30	24300		911
	118	20003	3	28	19800		175
	124	12040	2	18	11700		322
Eldorado	276	79180	10	140	50400	26850	1790
	277	63797	9	106	36450	26100	1141
CL-13	258	44655	6	105	44550		
	271	43770	6	120	43650		
CL-778	272	36394	4	94	35100		1200
	248	31126	4	76	31050		
Goodsprings	170	67280	10	80	27300	39900	
CL-447	173	15982	2	64	15120		798
	230	13248	2	50	12780		418
	166	12872	2	152	12720		
	236	12250	2	40	11880	330	
	228	10936	2	52	10440		444
	196	9822	2	102	9720		
Searchlight	442	61977	10	140	60300		1537
	383	51998	9	128	50400		1470
	443	47216	6	124	45900		1192
	355	31570	4	70	31500		
	372	29600	4	80	28800		720
	433	28029	4	82	27450		497
	394	27636	4	74	26550		1012

Table 8. Final ranking of cells with the highest values in each of the mining districts.

Mining District	Cell #	Rank Value	Cell Value
Alunite	130	85269	**10**
	146	78256	**10**
	122	50533	6
	119	29150	4
	147	27592	4
	121	25241	3
	124	12040	2
	118	2003	3
Apex		7641	1
Arden		616 - 7449	1
Bunkerville		159 - 2570	1
Charleston		1 - 7549	1
Crescent	367	15932	2
	399	15343	2
	377	12415	2
	387	9894	2
	419	9688	2
	427	8814	2
Dike		7641	1
Eldorado	276	79180	**10**
	277	63797	9
	258	44655	6
	271	43770	6
Gass Peak		1994 - 2847	1
Gold Butte		1 - 8901	1
Goodsprings	170	67280	**10**
	173	15982	2
	230	13248	2
	166	12872	2
	236	12250	2
	228	10936	2
	196	9822	2

Mining District	Cell #	Rank	Cell Value
Las Vegas		75 - 293	1
Moapa		1 - 360	1
Muddy Mountain		1 - 514	1
Newberry	478	27072	4
	461	25277	3
	473	16516	2
	458	9372	2
Searchlight	442	61977	**10**
	383	51998	9
	443	47216	6
	355	31570	4
	372	29600	4
	433	28029	4
	394	27636	4
Sloan		1 - 280	1
Sutor		None	
Sunset		139 - 8374	1

Table 9. Rankings of selected cells in Clark County, including water and rock chemistry at these sites.

	Cell #	Rank	pH	Hardness	TDS	SO4	As	Pb	Mn	Zn	SC
West of Moapa District											
Rocks	8	28					6		67	72	
Spring	8	28	8.15	231	695	8		0.01		0.24	320
Spring	22	103			242						
West of Las Vegas District											
Rocks	76	195					500-1400	20000	5000	200-690	
Well?	95	370	7.46		11914	2900		0.03		0.028	6630
			7.35								15100
Spring	81	466	7.3	3148			0.038				8409
Well?	96	466	7.5	2681	3826	2200		0.04		0.028	6694
			7.6	2006							6973
			7.7	1640							4661
Well?	89	833	7.73		7327	4063		0.03		0.02	6940
			7.63								9020
Well?	73	3,312	7.43	878	1336	1040					3860
			7.37		2003	1859					5370
Charleston District											
Spring	37	624		182	356	6	0.001	0.011		0.02	
Well	30	1,160	7.38	230	355	11		0.01		0.41	
Rocks	30						9	10000	294	15290	
Bunkerville District											
CL-754	9	2,156	7.88		605	84	<0.005	<0.5	0.033	<0.05	
Gold Butte District											
Rocks	34	2,072					150	100	70	2000	
Rocks	56	3,910					20	2000	200	200	

Table 9, continued

	Cell #	Rank	pH	Hardness	TDS	SO4	As	Pb	Mn	Zn	SC
Goodsprings District											
CL-447	172,173	3,942	7.36		8531	5340	<0.005	<0.5	0.54	<0.05	
Rx nearby		15,982					1,000	20000	200	2000	
Newberry District											
River	475	4,585	7.9	297	180?		0.002	0.005			920
Rocks	475	4,585						150	1000	100	
River	476	7,152	7.9	297	180?		0.002	0.005			920
Rocks	476	7,152					30	150	300	100	
Searchlight District											
Rocks	374	14,620						150	2000	35	
Rocks	430	42,596					10	2000	700	750	
Rocks	443	47,216					10	15000	200	800	
Eldorado District											
CL-13	258	44,655	7.14		2613	2090	<0.005	<0.2	1.9	<0.05	
Rx nearby							10	20	150	80	Nearby
Well?	275	21,650	7.8	390	654	290					925
CL-778	272	36,394	7.25		2556	1990	<0.005	<0.5	0.022	<0.05	
Rx nearby							10	20	150	80	Nearby
Well?	321	38,251	6.9	900	1546	900	0.02				1960
Rocks	321						200	1500	500	600	

Table 10. Calculated ranking of sites throughout the state of Nevada using data pertinent to mining excavations.

	Highest Weighted Deposit Types								
	CL-754	**PE-419**	**PE-420**	**HU-217**	**WA-133**	**HU-100**	**HU-99**	**WA-95**	**Rio Tinto**
	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight
S								1	1
A	1	1	1	1	1	1	1	1	1
P									
T									
Pd									
D									
DC	70	70	70	70	100	70	70	100	100
GW	6	6	6	6	6	6	6	6	6
SW	0	1	1	1	1	1	1	1	1
ISW	3	5	5	4	1	8	10	9	0
PE	6	6	6	4	6	3	3	6	4
PE'	5	5	5	7	5	8	8	5	7
SW rank	0	350	350	490	500	560	560	875	1225
ISW rank	53	88	88	98	25	224	280	394	0
GW rank	2100	2100	2100	2940	3000	3360	3360	6000	8400
Phys. rank	4	8	8	4	8	4	4	18	35
Total	2157	2546	2546	3532	3533	4148	4204	7287	9660
pH	7.88	3.94	6.24	**2.77**	**2.95**	**3.76**	**2.8**	**2.41**	6.3
TDS	605	216	305	**2110**	**2800**	<200	620	**6480**	467
Fe	0.07	**5.3**	**0.62**	**342.00**	**191.00**	**0.96**	**107.00**	**1380.00**	**1.4**
Mn	0.033	**2.4**	**4.6**	**27.00**	**4.40**	**0.20**	**0.12**	**19.00**	**1.5**
As	<0.005	<0.005	<0.005	**0.15**	0.01	<0.005	**0.83**	**16**	<0.005

Numbers in bold indicate values which exceed Nevada drinking water standards.

Table 10, continued

Intermediately Weighted Deposit Types												
EU-1	**CL-447**	**LA-168**	**WA-210**	**MI-369**	**NY-532**	**PE-407**	**PE-09**	**LA-25**	**LA-157**	**PE-509**	**LA-165**	**EL-13**
Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight
	1			1	1	1	1	1		1		1
1	1		1	1	1	1	1	1	1	1	1	1
		1										
20	20	50	50	50	50	50	50	50	50	50	50	50
6	6	6	8	6	6	6	6	6	6	6	6	6
1	0	1	1	1	1	1	1	1	8	1	9	1
9	8	6	8	1	6	8	9			6	9	7
5	5	5	6	7	6	6	6	5	5	5	5	4
6	6	6	5	4	5	5	5	6	6	6	6	7
120	0	188	250	350	438	438	438	525	2400	525	2700	613
54	84	56	100	18	131	175	197	0	0	158	135	214
720	1440	1500	2000	2400	3000	3000	3000	3600	1800	3600	1800	4200
4	96	21	8	34	44	32	54	54	8	26	7	32
898	1620	1765	2358	2802	3613	3645	3688	4179	4208	4309	4642	5059
7.17	7.36	7.18	**4.05**	7.41	7.55	7.39	7.45	6.77	**3.77**	7.38	7.21	7.47
498	**8530**	688	883	542	447	643	**1289**	611	761	766	910	362
3.7	<0.05	0.13	**21**	0.07	<0.05	<0.05	<0.05	<0.05	**4.9**	**0.84**	<0.05	<0.05
0.014	**0.54**	**2.4**	**12**	**0.43**	**2.1**	**1.1**	**0.45**	**2**	**1.6**	**0.13**	0.008	0.011
22	<0.005	**0.54**	<0.005	**13**	<0.005	<0.005	0.005	<0.005	<0.005	<0.005	<0.005	<0.005

Numbers in bold indicate values which exceed Nevada drinking water standards.

Table 10, continued

Intermediately Weighted Deposit Types						Lowest Weighted Deposit Types					
PE-496	PE-501	CL-13	LA-54	CL-778	LA-45	ES-694	CH-71	CH-76	DO-71	ST-79	WA-8
Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight	Weight
		1	1	1	1	1	1	1		1	1
1	1	1	1	1					1		1
		1		1						1	
1	1			1	1				1		
							1	1	1		
1	1										
50	50	50	50	50	50	10	8	8	10	10	10
6	6	9	6	9	6	6	9	9	6	6	9
1	1	0	10	0	9	1	1	1	1	9	9
10	10	0	7	8		10	1	1	1	9	9
5	5	8	6	8	5	8	7	7	6	6	6
6	6	3	5	3	6	3	4	4	5	5	5
										5	
840	840	0	4375	0	4725	23	66	66	145	743	788
420	420	0	153	285	0	11	3	3	7	37	39
5040	5040	6300	3000	7650	3600	180	792	792	960	660	900
16	16	73	46	137	50	20	20	50	4	17	172
6316	6316	6373	7574	8072	8375	234	881	911	1116	1457	1899
7.68	7.83	7	7.04	7.25	7.69	7.5	7.49	7.27	7.32	7.03	7.56
504	587	**2610**	711	**2556**	**1151**	**2789**	**7594**	**7631**	340	946	340
<0.05	<0.05	0.19	<0.05	<0.05	0.07	**0.56**	<0.05	<0.05	<0.05	0.13	<0.05
<0.002	<0.002	**1.90**	**0.88**	0.022	**0.65**	**0.45**	**0.32**	**0.23**	0.02	**1.6**	<0.002
<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.018	<0.005	<0.005	<0.005

Numbers in bold indicate values which exceed Nevada drinking water standards.