Synthesis of Water, Sediment, and Biological Data Using Hazard Quotients to Assess Ecosystem Health

By Susan E. Finger, Aïda M. Farag, David A. Nimick, Stanley E. Church, and
Tracy C. Sole

Chapter C of

Integrated Investigations of Environmental Effects of Historical Mining in the Basin and Boulder Mining Districts, Boulder River Watershed, Jefferson County, Montana

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Chapter C

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Abstract

The level of effort expended in the Boulder River watershed to assess the effects of trace elements on aquatic life is not feasible for land- and resource-management agencies when faced with evaluating risks associated with thousands of potential inactive historical mine sites. However, the comprehensive data set for the Boulder River watershed offered the opportunity to estimate potential ecological effects from measured geologic, geochemical, and hydrological conditions and to validate these estimates by comparing them with measured biological responses. Hazard quotients calculated with chronic water-quality criteria and with sediment probable-effects concentrations generally agreed with measurements of biology to designate the primary areas of potential hazard in the Boulder River watershed. Sampling sites that potentially represent high hazards to aquatic life included the Bullion Mine tributary, Jack Creek, Uncle Sam Gulch, Cataract Creek downstream from Uncle Sam Gulch, lower Cataract Creek (upstream from the Boulder River), High Ore Creek downstream from the Comet mine, and lower High Ore Creek (upstream from the Boulder River). Fish were absent from all of these sites except lower Cataract Creek, and poor survival during 96-hour survival experiments suggested that trout would be unable to survive in these stream reaches. Adult fish were present in lower Cataract Creek, but the biomass, density, and individual health of trout were adversely affected, suggesting that chronic effects on the fishery in Cataract Creek existed. The only exceptions to the agreement between hazard quotients for water and sediment were in the Bullion Mine tributary and Jack Creek, where the lower pH of the water reduced the ability of trace elements to sorb to colloids and streambed sediment. Therefore, consideration of pH is critical for the interpretation of water and sediment chemistry from regions of historical mining activity. Remediation of the major inactive mine sites in the basins upstream from the primary areas of potential hazard could include removal of mine wastes located on valley floors and reduction of trace-element loading from draining adits. Our hazard-quotient analyses suggest that such remediation could result in substantial improvement of ecological health in the watershed.

Introduction

The watershed approach provides an effective means to evaluate the overall status of ecological resources in an area affected by historical mining and helps focus remediation and restoration strategies on regions that will most benefit from recovery of the watershed. Such a large-scale approach can entail the collection of extensive information on geology and geochemistry, hydrology and water chemistry, and ecological structure, health, and organization within the watershed of concern. During the assessment of the Boulder River watershed, mines were inventoried, geologic conditions were defined, aquatic habitat was assessed, hundreds of water and sediment samples were chemically analyzed, toxicity tests were conducted, fish tissues and indicators of physiological malfunction were analyzed and assessed, invertebrates and biofilm were examined, and hydrological regimes were defined. This level of effort is not feasible for land- and resource-management agencies to undertake routinely when faced with evaluating risks associated with thousands of potential inactive historical mine sites. However, this comprehensive data set offers the opportunity to use geologic, geochemical, and hydrological conditions measured throughout the watershed to estimate potential ecological effects on the aquatic communities and to validate these estimates by comparing them with measured biological responses. Although the focus of this volume is on the health of the aquatic community, a similar watershed-level approach could be used to evaluate the potential health of the terrestrial flora and fauna, or to evaluate the potential problems that might be encountered in attempts to revegetate the riparian corridor. Standard methods are available for measuring effects on the survival, growth, and reproductive health of terrestrial organisms (USEPA, 1992). Similarly, standard procedures to evaluate toxicity of soils to plants could be combined with information on sediment geochemistry to establish conditions in the flood-plain and riparian corridor (Linder and others, 1993).

Ecological risk assessments evaluate the potential that adverse effects may occur as the result of exposure to one or more stressors. These assessments provide a framework for organizing and evaluating data and offer an approach for environmental managers to consider available scientific information in determining a course of action. The ecological risk assessment approach was developed to address anthropogenic changes that have potentially undesirable outcomes such as adverse effects on an ecosystem. Therefore, this general approach is appropriate and useful in evaluation of the effects of inactive mine sites on ecological health. The level of complexity of a risk assessment may vary from highly quantitative to a qualitative process depending on the objectives of the project. The end result should provide a relative means to rank the potential for adverse effects in the environment at the individual, population, or community level.

Purpose and Scope

The purpose of this chapter is to present an integrated assessment of environmental conditions in the Boulder River watershed and rank those conditions based on their potential to influence the health and recovery of the aquatic community. Information from a range of geologic, geochemical, hydrological, and biological studies is evaluated within an ecological risk assessment framework.

Scientific information collected during our studies in the Boulder River watershed, standard U.S. Environmental Protection Agency assessment methods, and information from the scientific literature are combined to

- Identify stressors that influence ecosystem health
- Identify pathways of exposure
- Calculate hazard quotients for ranking severity of effects
- Compare the ranking to measured biological responses.

Ecosystem Stressors

Historical mining activity in the Boulder River watershed significantly affected the physical and biological nature of the region. Fish were absent from some areas in the watershed directly downstream of draining mine adits, but populations of brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), and cutthroat trout (*Oncorhynchus clarki*) occurred further downstream in tributaries and in the Boulder River (fig. 1). In addition, native populations of westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) existed upstream of the Comet mine in the High Ore Creek basin (Farag and others, this volume, Chapter D10). Although current information suggests that both fish and invertebrate populations are adversely affected in the Boulder River watershed, absence of physical habitat does not appear to be a major limiting factor. The persistence of an aquatic community in some parts of the watershed provides a basis for future ecosystem restoration.

Contaminants in surface water and streambed sediment are major stressors on the aquatic ecosystem in the Boulder River watershed. Specifically, copper, lead, zinc, arsenic, cadmium, silver, and antimony are the major contaminants in the watershed. Elevated concentrations of these trace elements can be linked directly to historical mining at the Buckeye and Enterprise mines in upper Basin Creek, the Bullion mine on a tributary of Jack Creek, the area of Cataract Creek upstream from Uncle Sam Gulch, the Crystal mine in upper Uncle Sam Gulch, and the Comet mine in upper High Ore Creek (Martin, this volume, Chapter D3). Although some trace elements, such as copper and zinc, are essential to normal growth and development of aquatic life, excess concentrations of trace elements are associated with abnormal reproduction, growth, and development (Rand and Petrocelli, 1985). Our characterization of the Boulder River watershed documented concentrations of a range of trace elements in water, sediment, colloids, biofilm, benthic macroinvertebrates, and trout. This approach provided the information necessary to characterize exposure pathways and to document the extent and severity of contamination in the watershed as a result of the exposure of aquatic life to their environment.

In streambed sediment from the sites just described, concentrations of trace elements associated with ore deposits were substantially higher than concentrations in premining streambed sediment (Church, Unruh, and others, this volume, Chapter D8). Similarly, the Bullion, Crystal, and Comet mines also produced most of the dissolved trace-element load to the watershed. Cadmium, copper, and zinc concentrations were most commonly elevated in stream water downstream from these sites (Nimick and Cleasby, this volume, Chapter D5). However, pH of most streams was near neutral. In contrast to many regions where inactive mines occur, the mineralogical and textural character of the bedrock in the Boulder River watershed exhibits a widespread acid-neutralizing capacity, thus minimizing the presence of acid water drainage in the basin (O'Neill and others, this volume, Chapter D1).

The contributions of streambed sediment from Basin and Cataract Creeks to the Boulder River were similar, but the impact of the contamination in streambed sediment from High Ore Creek dominated the concentrations of trace elements in streambed sediment of the Boulder River from High Ore Creek downstream to the Jefferson River (Church, Unruh, and others, this volume). In contrast, surface water from Cataract Creek contributed larger trace element loads to the Boulder River than either Basin Creek or High Ore Creek (Nimick and Cleasby, this volume). The major source of metal loading to Cataract Creek was the discharge to Uncle Sam Gulch from the Crystal mine adit. For example, about 75 percent of the zinc load to Cataract Creek came from Uncle Sam Gulch (Kimball and others, this volume, Chapter D6). The relative importance of streambed sediment from High Ore Creek contrasted with the importance of surface-water loading from Cataract Creek highlights the fact that both water and sediment quality must be considered when the potential for biological effects in an ecosystem is evaluated.

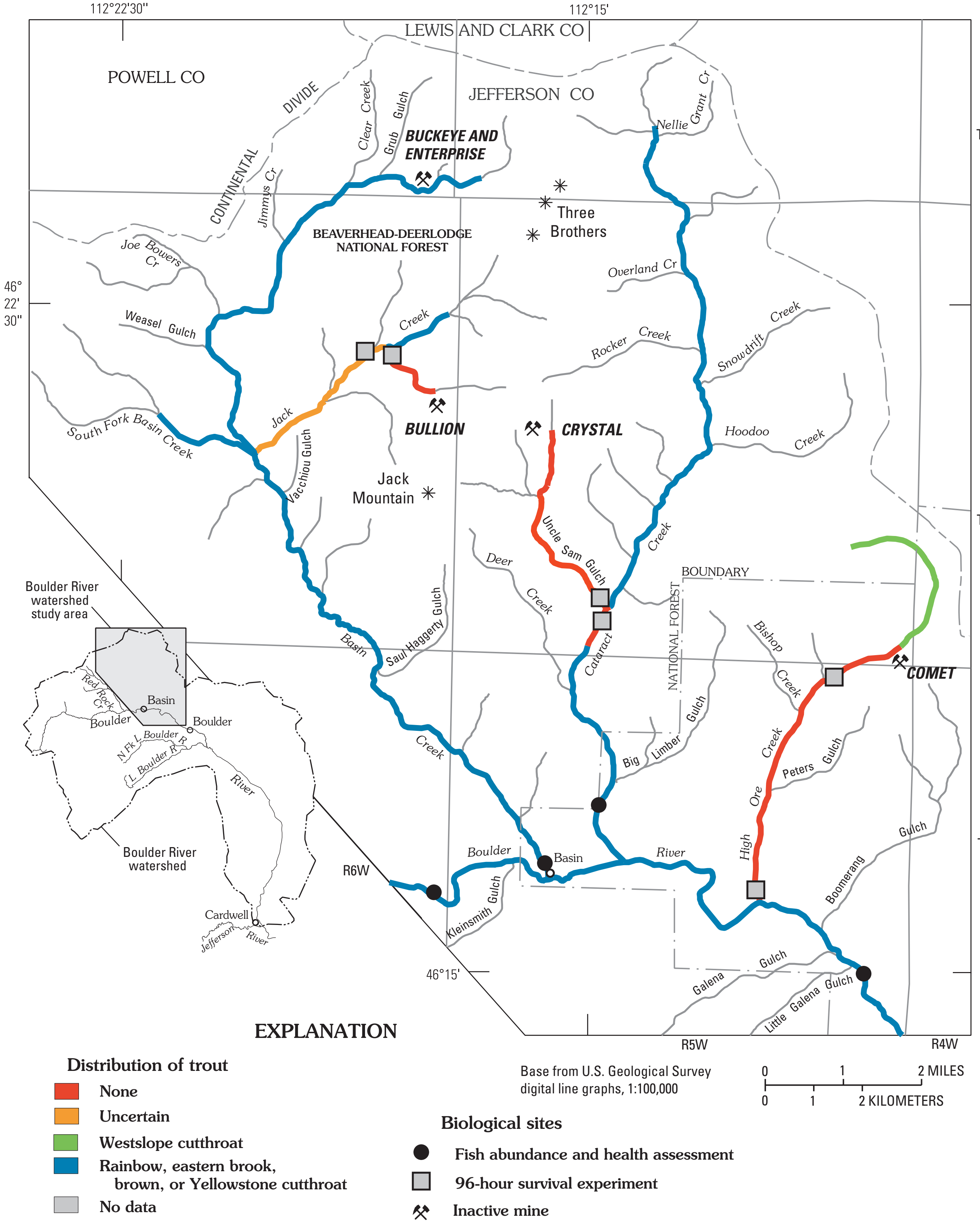

Figure 1. Estimated distribution of trout prior to large-scale remediation work in Boulder River watershed study area.

Exposure Pathways

In biological studies, Farag and others (this volume) suggest that the accumulation of trace elements in tissues of benthic macroinvertebrates and fish in the Boulder River watershed occurs through two pathways and is associated with adverse effects on the overall health of the watershed. Accumulation of trace elements in fish tissue results from direct exposure through water and sediment and indirect exposure through dietary pathways. Thus, the exposure pathways to trout include biofilm, benthic macroinvertebrates, water, colloids, and sediment.

Streambed sediment and surface water provide major pathways for transport and distribution of contaminants through the watershed and for direct exposure of the biological community. Exposure of an organism is dependent on the concentration of the trace elements in both the water and sediment pathways. Accumulation of trace elements and resulting toxicological responses are determined by both concentration and duration of exposure. Chemical data for individual water-quality samples reflect an instantaneous measure of conditions at a single point in time. Trace-element concentrations in streams may vary widely depending on time of day, streamflow, ground-water inflow, and season. Trace-element concentrations in streambed sediment have less temporal variability than concentrations in water because streambed sediment integrates contaminant conditions over an extended period of time. This integration occurs because coatings on sediment grains, particles, and colloidal material sorb trace elements from the water column. This geochemical reaction reduces the dissolved trace-element concentrations in water and increases concentrations in streambed material.

Iron and aluminum colloids, defined as particles between 0.001 and 0.45 µm (micrometers) in size, are transported downstream suspended in the water column. Because the association of colloids and trace elements is dynamic, trace elements may sorb and desorb frequently during downstream transport. These colloids may be trapped by biofilm on rock surfaces and may accumulate trace elements when they become available. Both colloids and biofilm (also referred to as *aufwuchs*) appear to play an important role in the movement of trace elements through the food chain. Farag and others (this volume) observed significant correlation between concentrations of arsenic, copper, lead, and zinc in colloids and biofilm, which indicates a possible relation between trace elements in the two components.

These exposure pathways are important in the Boulder River watershed because they provide multiple encounters between aquatic life and elevated concentrations of trace elements. As a result of these exposures, survival of trout may be limited in parts of the Basin and Cataract Creek basins and in High Ore Creek downstream from the Comet mine. Furthermore, the number of trout present and the health of individual fish are also affected in lower Cataract Creek.

Ranking Stream Reaches Using Hazard Quotients

Assessment of environmental hazards from trace-element exposure can be definitively accomplished by direct measurement of biological effects. To measure biological effects at all points in a stream system is usually impractical; therefore, ecological risk assessment methods have been developed to estimate environmental hazards associated with contaminant exposure. One of the basic strategies used to perform these types of assessments is to compare the environmental concentration of trace elements with a measured biological effect or no-effect level. Thus, estimates of trace-element concentrations in water or sediment may be compared to results from toxicological criteria, regulatory standards and guidelines, or individual threshold values that encompass the concentration-response relationship between a trace element and an organism. This is known as the quotient approach to hazard assessment (Urban and Cook, 1986). If the environmental concentration of a contaminant in an aquatic ecosystem exceeds an effect concentration, then a hazard exists. Similarly, if the environmental concentration is far below the no-effect level, then one may assume the hazard is minimal or not a threat.

Potential hazards in the Boulder River watershed were determined by use of hazard quotients to compare relative risks among reaches. For the assessment, we calculated hazard quotients (HQ) for individual trace elements in water or sediment by dividing the trace-element concentration for an environmental sample either by the U.S. Environmental Protection Agency (USEPA) chronic water quality criteria or by the sediment guideline for probable-effects concentration. If the $HQ < 0.1$, no adverse effect is expected. If $0.1 < HQ < 1$, the hazard is low, but potential for adverse effects should be considered; and if $1.0 > HQ < 10$, some adverse effect or moderate hazard is probable. If $HQ > 10$, high hazard is anticipated.

Hazard quotients were developed for water and streambed sediment from the Boulder River watershed study area. Based on the analysis of exposure pathways presented by Farag and others (this volume) and summarized in the preceding section, cadmium, copper, and zinc were the key metals that appear to cause toxicity in the watershed. In addition, arsenic and lead were measured in fish tissues and may contribute to hazards present in the watershed. For example, arsenic may contribute to morphological changes observed in skin of fish held in High Ore Creek (Farag and others, this volume).

Because water and streambed sediment were collected over a multi-year period during various hydrologic and geochemical conditions in the study area, we chose a subset of the data representing conditions most toxic to aquatic life for calculation of hazard quotients. These conditions coincide with low flow, which occurs from late summer through early spring (Church, Nimick, and others, this volume, Chapter B). In addition, only data collected prior to large-scale remediation efforts (which began in 1997 in the watershed) were selected.

We constructed ribbon maps to depict individual hazard quotients for cadmium, copper, and zinc in water (figs. 2–4) and for cadmium, copper, lead, and zinc streambed sediment (figs. 6–9). Streams were color-coded upstream and downstream from the sample sites with calculated hazard quotients. The color codes were based on our knowledge of metal sources, metal attenuation, and expected dilution effects of tributaries. Because so many hazard quotients exceeded a value of 1 for the Boulder River watershed, the HQ interval between 1 and 10 was divided into three categories to facilitate ranking of reaches. Note that the multiple colors, and hence, multiple intervals, were not chosen for biological relevance (that is, hazard quotients greater than 1 generally indicate that hazards may exist for biota), but were chosen to delineate reaches where restoration might provide the most significant benefits.

Hazard quotients are most useful in determination of either high or low risks and for relative comparisons of the potential for adverse effects among stream reaches. Hazard quotients estimate the hazard associated with individual rather than multiple trace elements and therefore do not account for additive, antagonistic, or synergistic interactions commonly associated with chemical mixtures. Hazard quotients based on measurements of environmental concentrations and measured biological effect or no-effect levels should not be used to evaluate hazards associated with elements that biomagnify such as selenium and mercury.

To address the issue of interactions of multiple contaminants in an aquatic system, Sprague and Ramsey (1965) suggested that the strength of a contaminant could be expressed as a fraction of its lethal concentration using a ratio identical to that now used in calculating hazard quotients. They referred to these values as toxic units. Sprague (1970) further suggested that the toxic unit for each element in a mixture could be calculated and these values summed to estimate the overall toxicity of the mixture. This approach assumes that elements exhibit the same modes of action and that the toxicity of mixtures is strictly additive. Nonetheless, it provides a reasonable and now commonly used approach for evaluating mixture toxicity. Furthermore, a compilation of results for 76 studies that assessed the toxicity of mixtures including elements such as copper, zinc, cadmium, mercury, nickel, and chromium demonstrated that the toxic unit approach closely approximated the toxicity of the mixture in 87 percent of the cases. Lloyd (1982) concluded that although antagonistic and synergistic interactions definitely occur, the joint action of toxic mixtures of common trace elements is likely to be additive.

We constructed maps that show the summation of hazard quotients by site in an effort to exhibit the potential hazard from a combination of trace elements in water or sediment. These maps summed the individual hazard quotients for cadmium, copper, and zinc in water (fig. 5) and in sediment (fig. 10). It should be noted that the sum of the hazard quotients in many places was greater than 30 in water (fig. 5). Therefore, the color designations in the mixture hazard quotient maps reflect greater hazard quotients than those depicted in the maps for individual trace elements.

Water

For water, aquatic-life water-quality criteria established by the USEPA (1999, 2001) are suitable criteria for the “no adverse effect” concentration used in the denominator of the hazard quotient formula. These criteria are an estimate of the concentration of a trace element in surface water to which an aquatic community can be exposed briefly (acute criteria) or indefinitely (chronic criteria) without experiencing an adverse effect. Chronic criteria, which are determined from controlled laboratory experiments with a number of freshwater species, were used to calculate hazard quotients. Thus, a hazard quotient calculated using the chronic criteria (HQ_C) provides an assessment of potential chronic toxicity incorporating effects such as impairment of growth and reproductive success. These are the types of effects that likely occurred at sites such as lower Cataract Creek (Farag and others, this volume). Hazard quotients calculated with acute criteria revealed a pattern of degraded reaches similar to those identified by the HQ_C values. As a result, the hazard quotients computed using acute criteria are not presented.

We calculated the HQ_C for waterborne elemental concentrations using the ratio of the environmental concentration in a filtered (0.45-µm) water sample to the USEPA chronic water-quality criterion.

$$HQ_C = \text{Elemental Concentration / USEPA Chronic Water-Quality Criterion} \qquad (1)$$

Chronic aquatic-life water-quality criteria (table 1) were calculated as defined by U.S. Environmental Protection Agency (USEPA, 1999, 2001). The criteria are dependent on hardness (as mg/L $CaCO_3$), which was calculated from measured concentrations of dissolved calcium and magnesium (in mg/L) using the following equation:

$$\text{Hardness} = ((Ca/40.08)+(Mg/24.31))*100 \qquad (2)$$

A single sample collected during low flow, which would represent the most toxic conditions to aquatic life, was selected for each water-quality sampling site. Approximately 50 percent of the sites in the watershed were sampled in September 1997, and these data were used in the HQ_C calculations. For the sites not sampled during September 1997, data from a sample collected during September or October in 1996, 1998, or 2000 were used, because streamflow conditions were similar to the September 1997 flows. However, only October 1996 data were used for High Ore Creek and the Boulder River downstream of High Ore Creek, because remediation had started in the High Ore Creek basin in September 1997. Maps showing hazard quotients for cadmium, copper, and zinc in water are in figures 2–4, and the sum of the three calculated hazard quotient values is in figure 5.

Table 1. Chronic aquatic-life water-quality criteria for cadmium, copper, and zinc.[1]

Cadmium:

$$\mathrm{Cd}_{\mathrm{chronic}} = (e^{(0.7852[\ln(\mathrm{hardness})] - 2.715)}) * [(1.101672\text{-}\ln(\mathrm{hardness}) * (0.041833)]$$

Copper:

$$\mathrm{Cu}_{\mathrm{chronic}} = (e^{(0.8545[\ln(\mathrm{hardness})] - 1.702)}) * 0.960$$

Zinc:

$$\mathrm{Zn}_{\mathrm{chronic}} = (e^{(0.8473[\ln(\mathrm{hardness})] = 0.884)}) * 0.986$$

[1] U.S. Environmental Protection Agency (USEPA, 1999, 2001).

Streambed Sediment

For streambed sediment, the probable-effect concentration was used in the denominator of the hazard quotient formula. The probable-effect concentration is the concentration of a trace element above which harmful effects on sediment-dwelling organisms are expected to occur frequently (MacDonald and others, 2000). These consensus-based concentrations are reliable and predictive of sediment toxicity based on evaluation of samples on both a national and a regional basis.

We calculated the HQ_S for sediment elemental concentrations using the ratio of the environmental concentration in a total digest of a sediment sample to the probable-effect concentration.

$$\mathrm{HQ}_S = \text{Total Elemental Concentration / Probable Effects Concentration} \qquad (3)$$

The consensus-based probable-effect concentrations used in calculating these quotients were 4.98 µg/g cadmium, 149 µg/g copper, 128 µg/g lead, and 459 µg/g zinc (MacDonald and others, 2000). Maps showing the hazard quotients for cadmium, copper, lead, and zinc in sediment are in figures 6–9, and the sum of the calculated hazard-quotient values for cadmium, copper, and zinc in sediment is in figure 10.

As was observed for water, the concentrations of trace elements in sediment were generally higher during low-flow than during high-flow conditions. These higher concentrations likely occur during the fall each year, so the 1996 data were used for environmental concentrations. Some sites were not sampled in 1996, and for these sites, 1997 or 1998 data were used. Streambed-sediment samples were analyzed for leachable and total trace-element concentrations; the total concentrations were used to calculate hazard quotients.

Comparisons of Hazard Quotients and Biological Effects

The hazard-quotient maps indicate that areas of potential hazard to biota exist in Basin Creek, Cataract Creek, and High Ore Creek, the three main tributaries in the Boulder River watershed. Both chronic water and sediment hazard quotients show that the hazard potential is most widespread and extreme in Uncle Sam Gulch, lower Cataract Creek, and High Ore Creek.

The combined hazard quotients for chronic effects of surface water indicate highest concern for adverse effects on the biological community to be in Uncle Sam Gulch, Cataract Creek downstream from Uncle Sam Gulch, the Bullion Mine tributary, Jack Creek downstream from the Bullion Mine tributary, High Ore Creek downstream from the Comet mine, and, to a slightly lesser extent, lower High Ore Creek. The individual chronic hazard quotients are greater than 10 for cadmium, copper, and zinc in water in sections of Jack Creek, the Bullion Mine tributary, and Uncle Sam Gulch, and for cadmium and zinc in High Ore Creek downstream of the Comet mine (figs. 2–4). Therefore, high hazard is anticipated in these reaches based on the concentrations of just one of these trace elements. As a result, these areas have combined chronic hazard quotients greater than 30, except lower High Ore Creek, which is 21–30 (fig. 5).

Chronic effects encompass nonlethal biological responses including reduced growth, reproductive impairment or failure, behavioral changes, or physiological malfunction. Any of these would result in reduced health at the individual or population level. In fact, fish health and biomass/density estimates (Farag and others, this volume) confirm that individual fish health and biomass/density were compromised at lower Cataract Creek. This is the same area that hazard quotients calculated with chronic water-quality criteria define as a potential high hazard for aquatic biota.

Comparisons of acute water-quality criteria to environmental concentrations in water demonstrate the same pattern of potential hazards as the chronic water-quality criteria (maps of hazard quotients calculated using acute criteria not presented). Acute criteria (and hazard quotients based on them) imply that significant mortality will result if aquatic life is exposed to water at sites in the Boulder River watershed just listed. These findings of potential hazard related to mortality agree with survival experiments performed by Farag and others (this volume). Westslope cutthroat trout held in Uncle Sam Gulch, Cataract Creek downstream from Uncle Sam

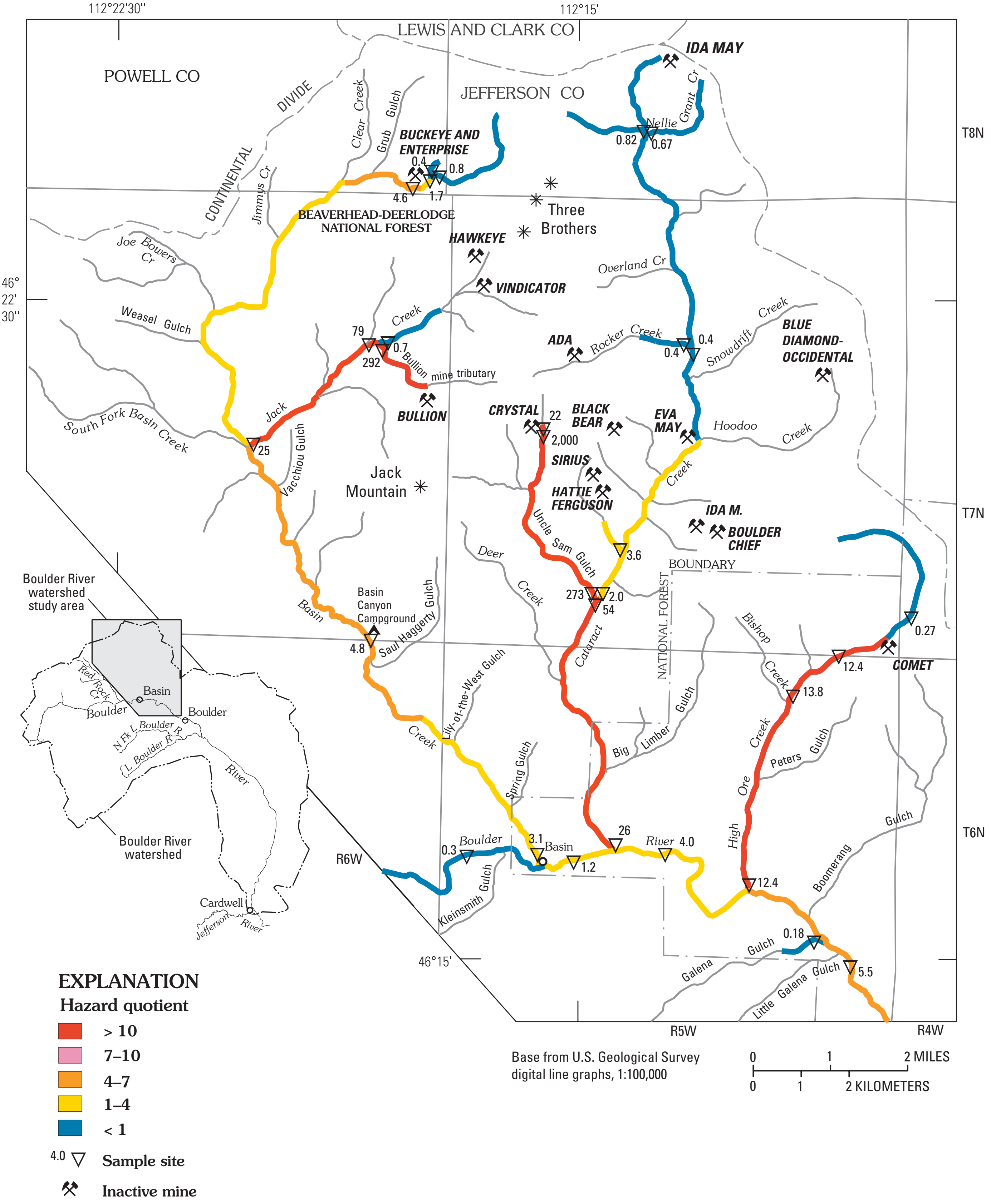

Figure 2. Cadmium chronic hazard quotients for water.

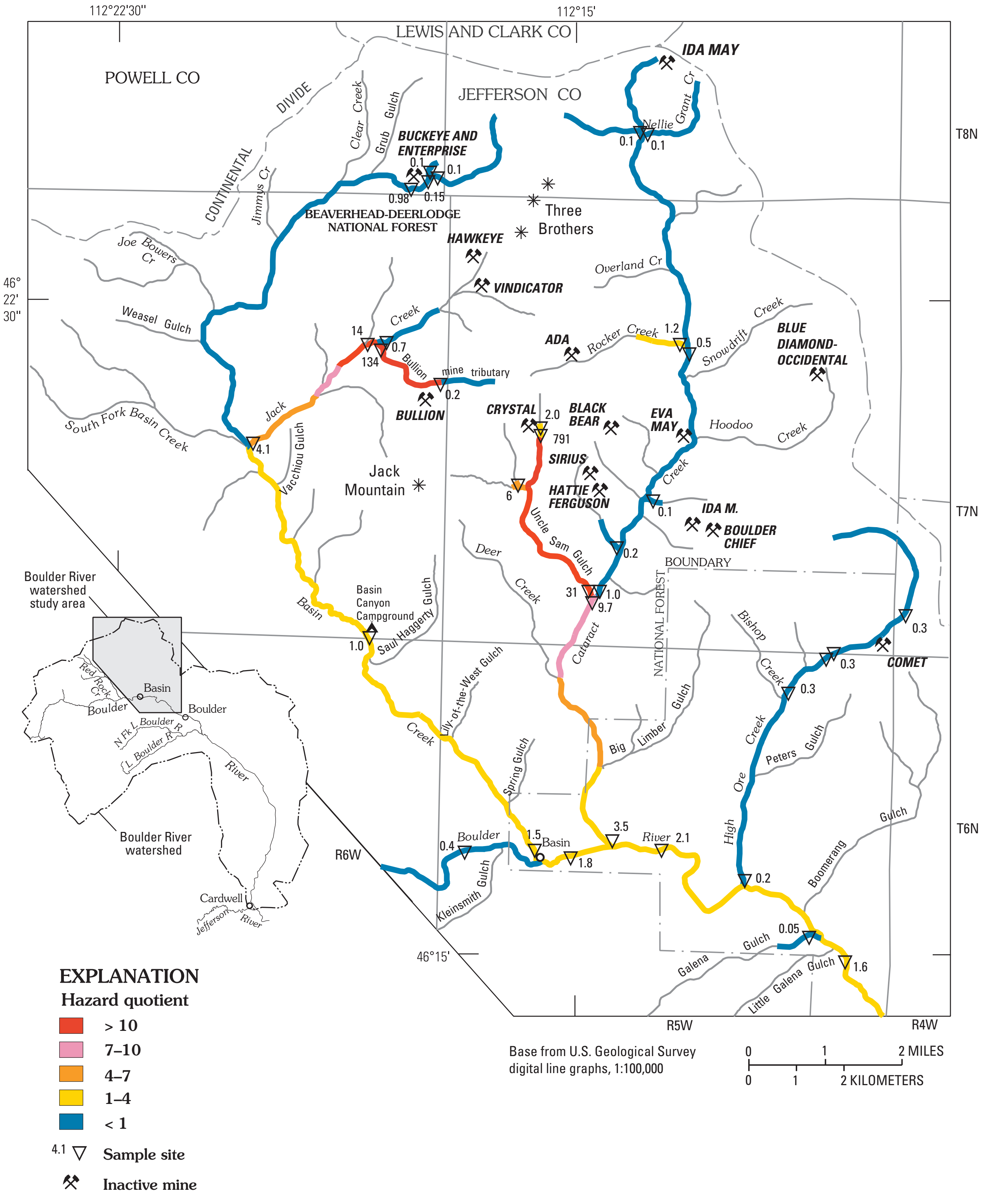

Figure 3. Copper chronic hazard quotients for water.

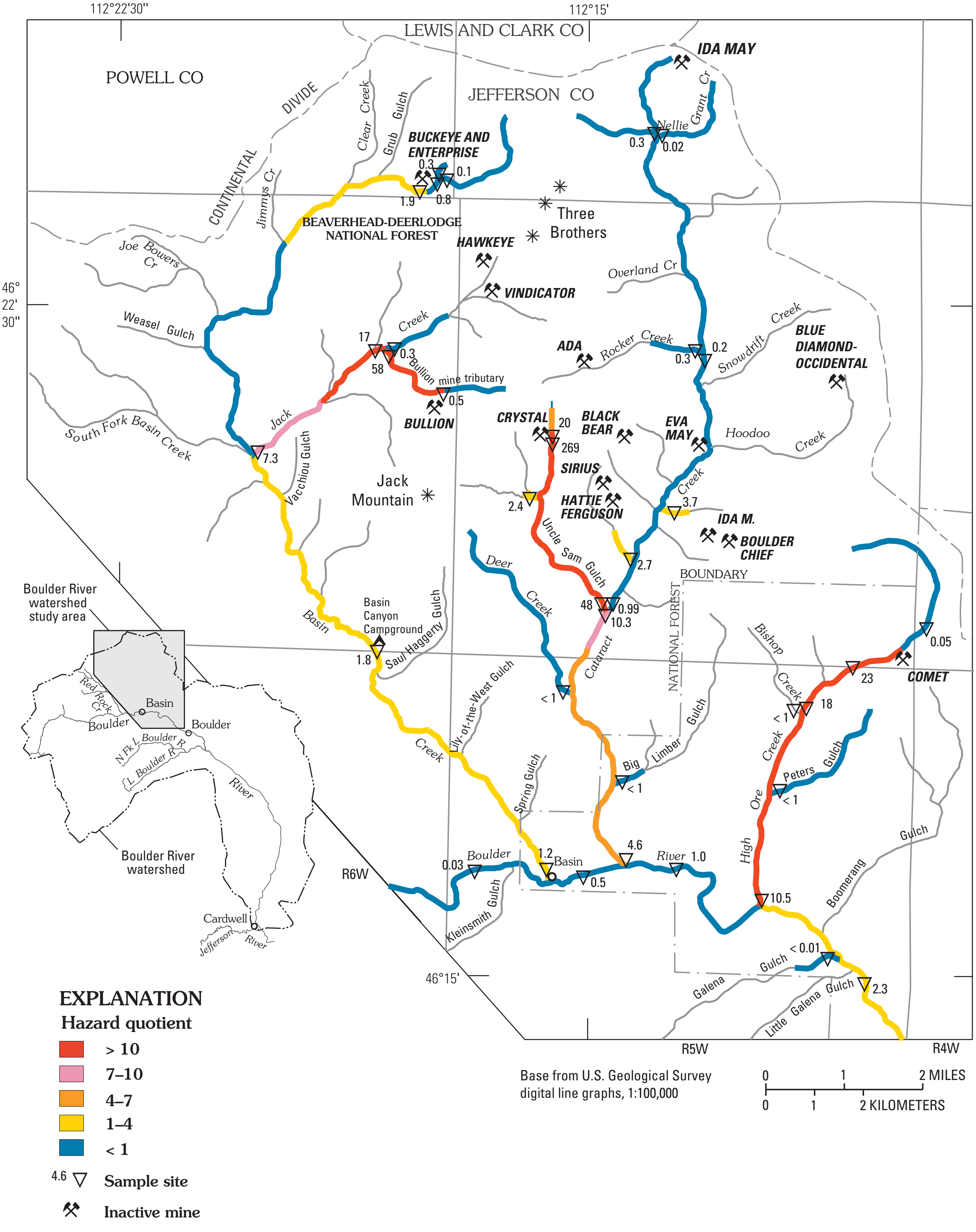

Figure 4. Zinc chronic hazard quotients for water.

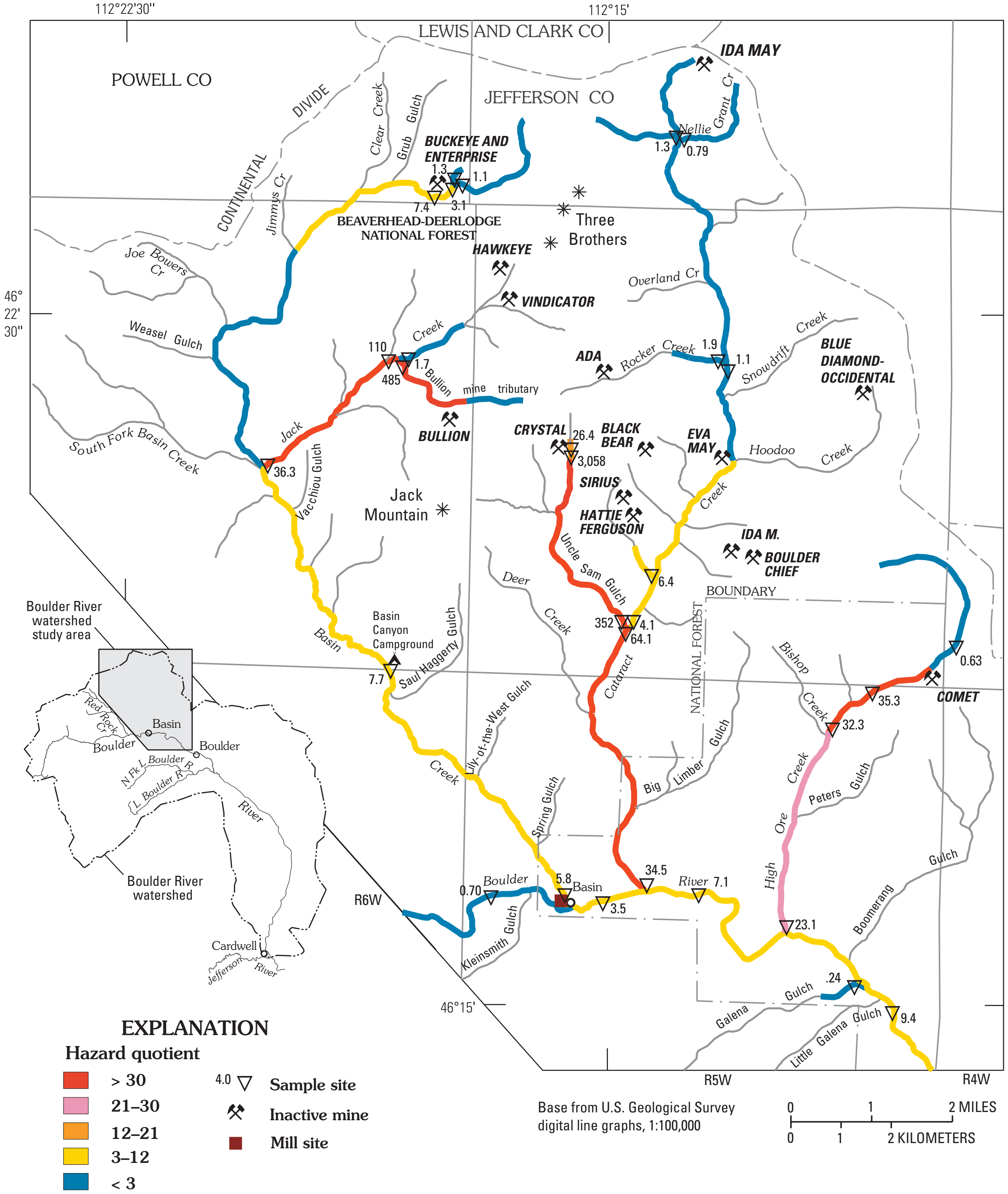

Figure 5. Estimated risk based on sum of chronic hazard quotients for water for cadmium, copper, and zinc. Mill site immediately upstream from confluence of Basin Creek with Boulder River shown for reference.

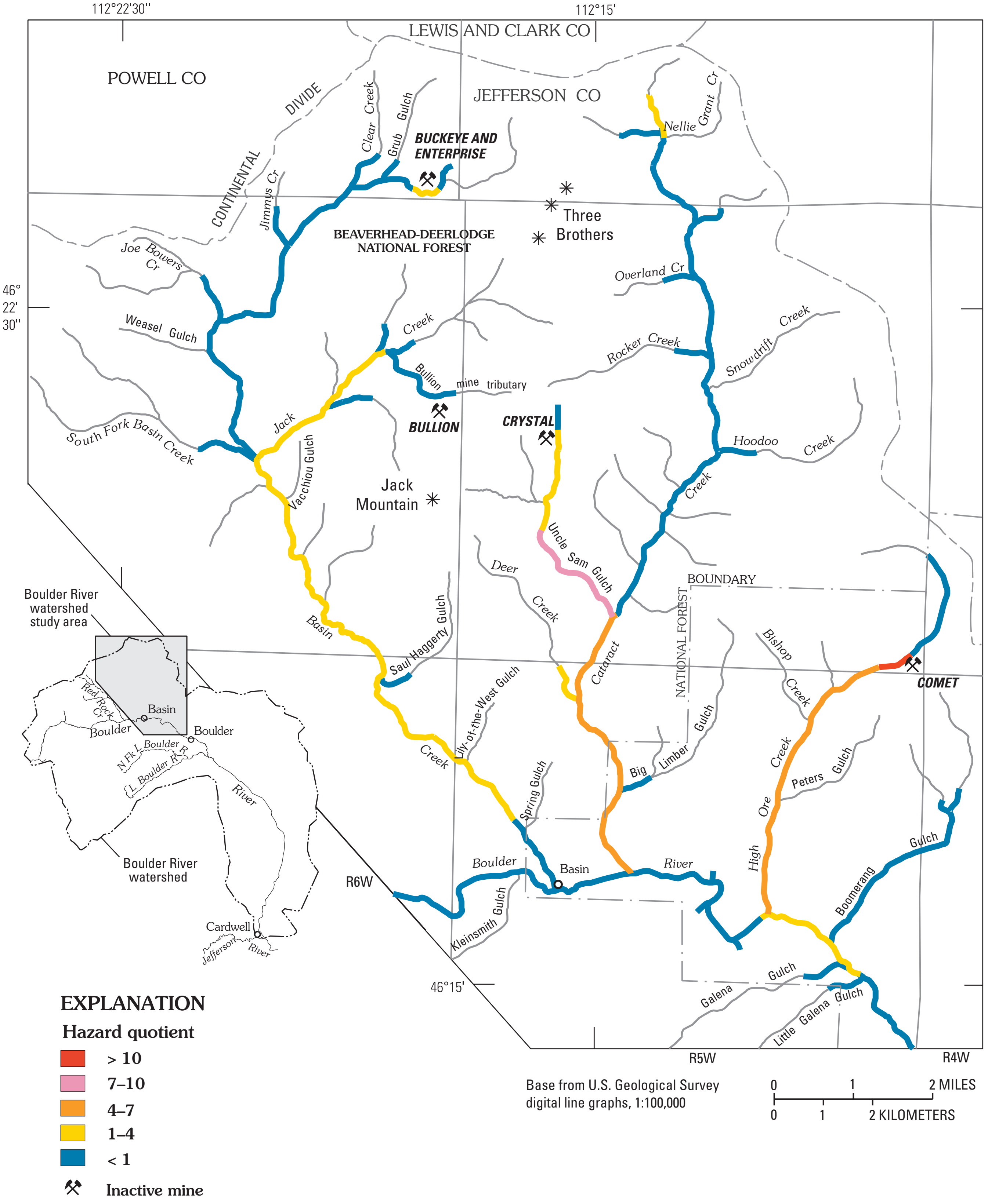

Figure 6. Cadmium hazard quotients for streambed sediment.

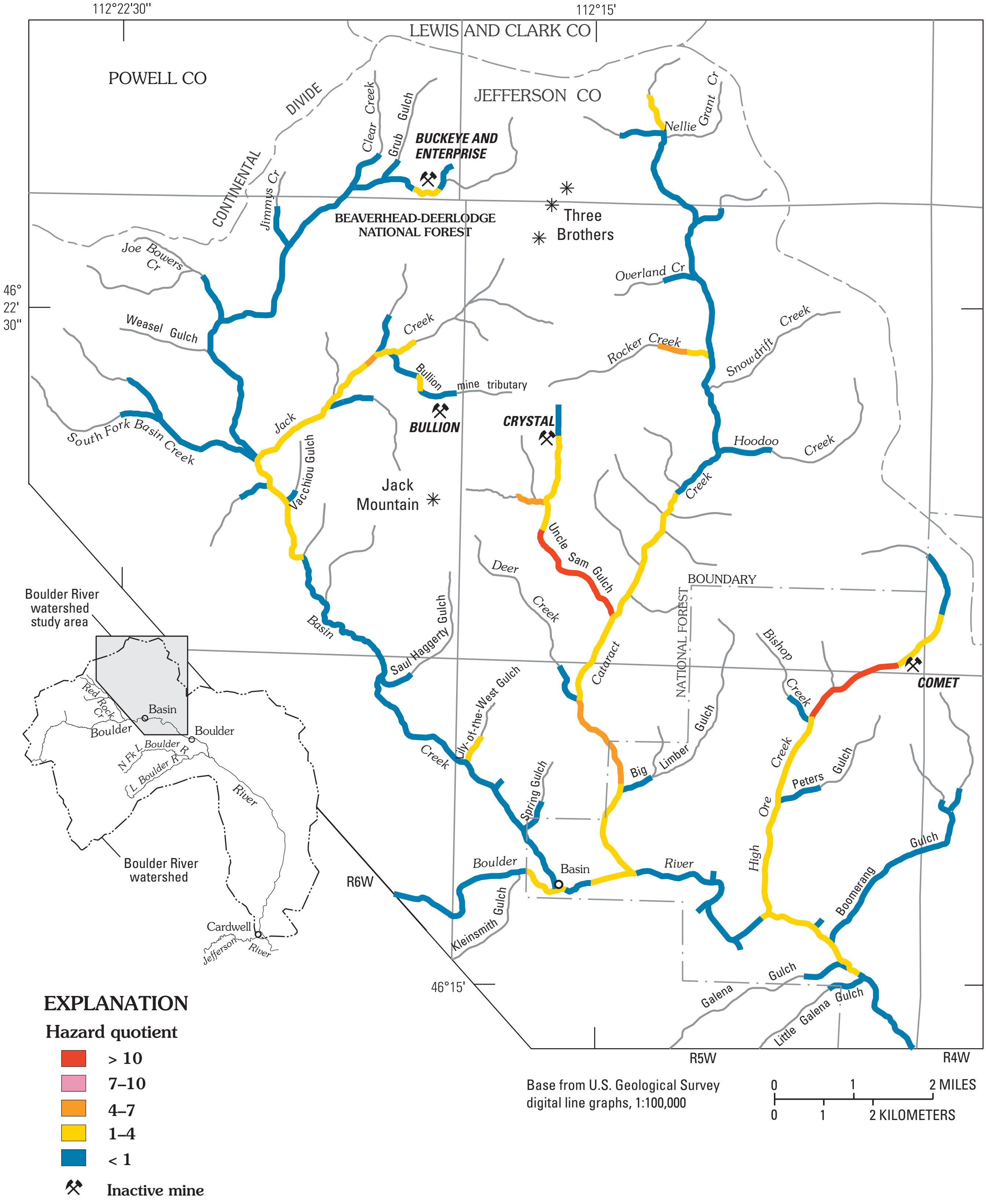

Figure 7. Copper hazard quotients for streambed sediment.

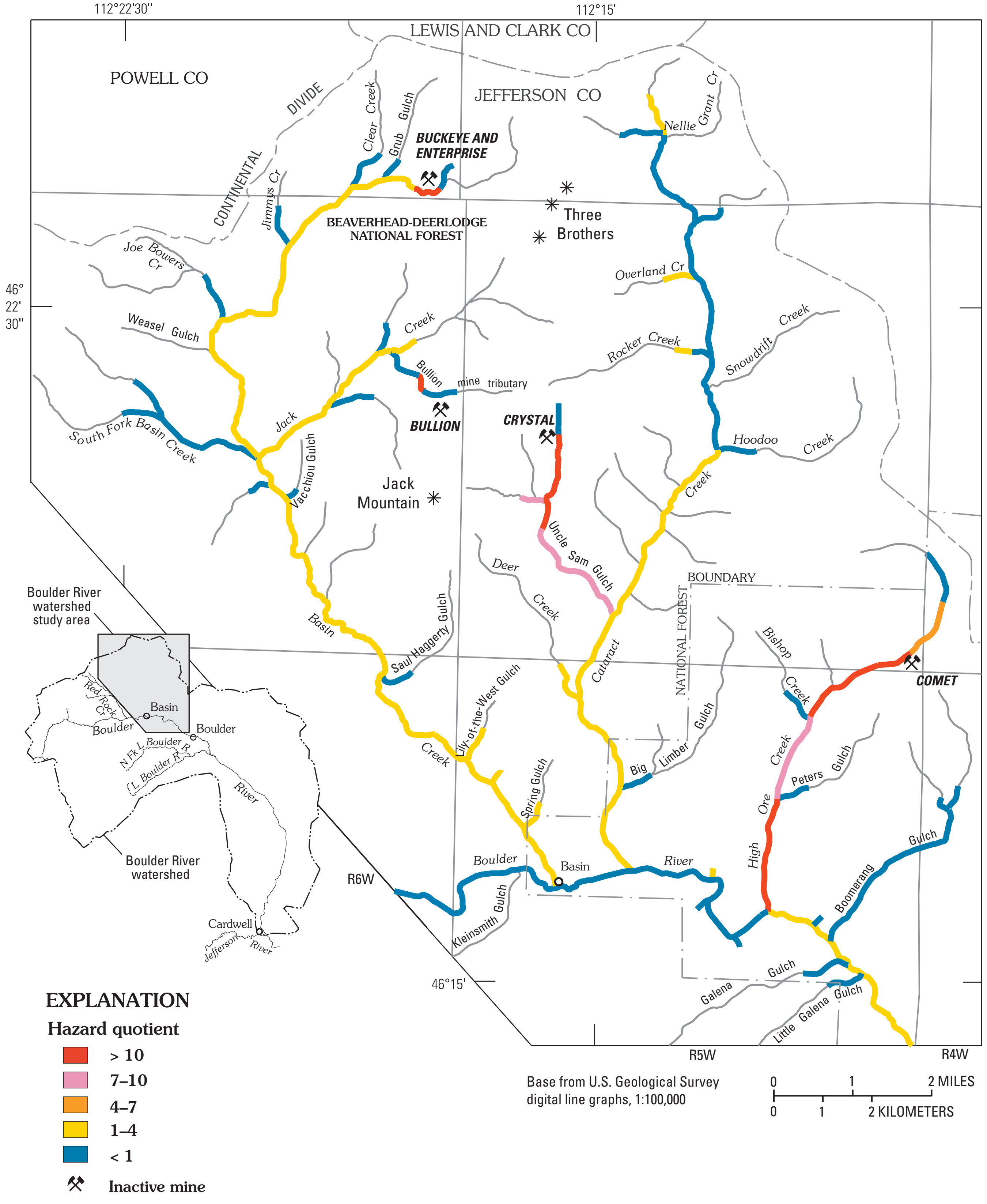

Figure 8. Lead hazard quotients for streambed sediment.

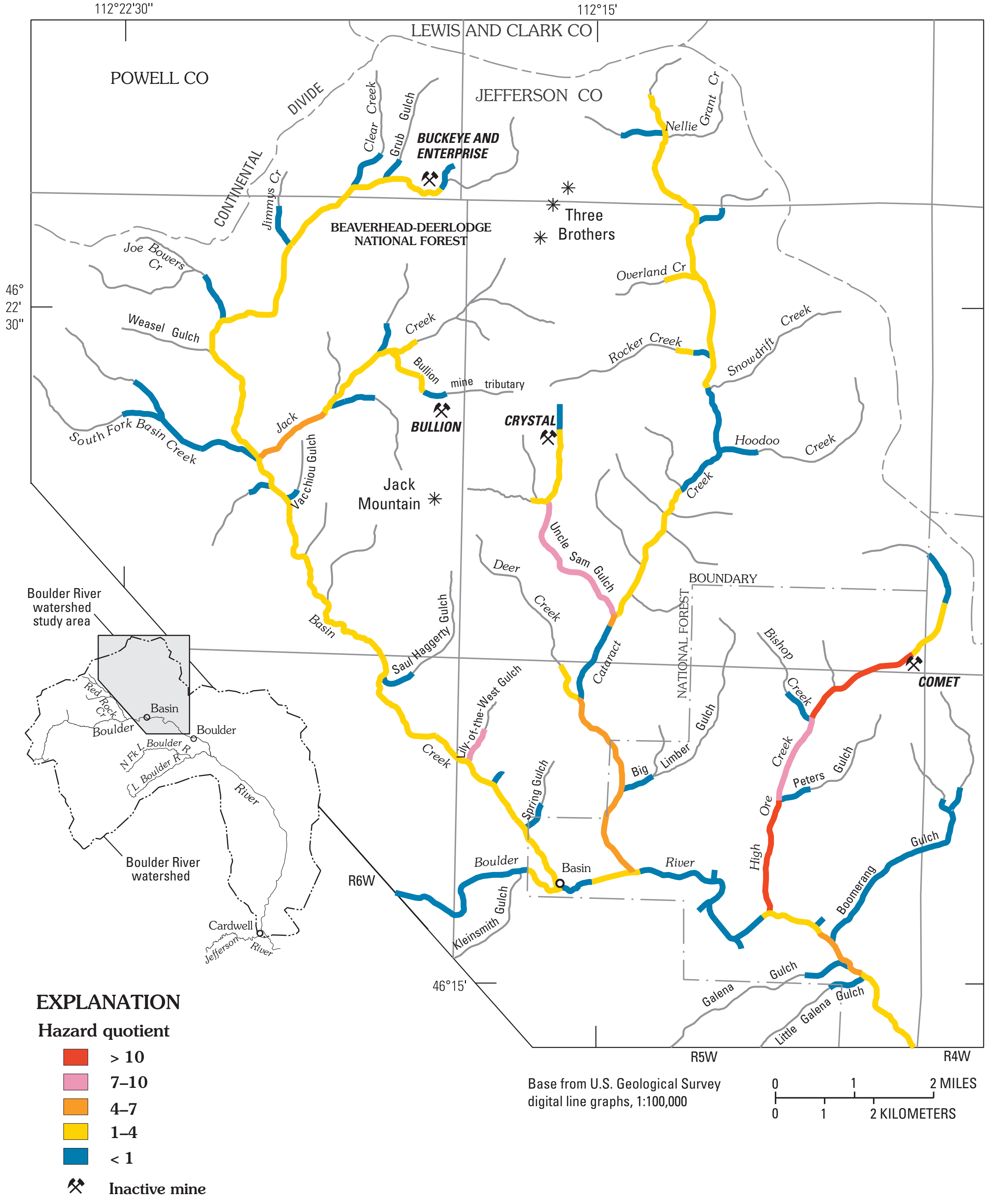

Figure 9. Zinc hazard quotients for streambed sediment.

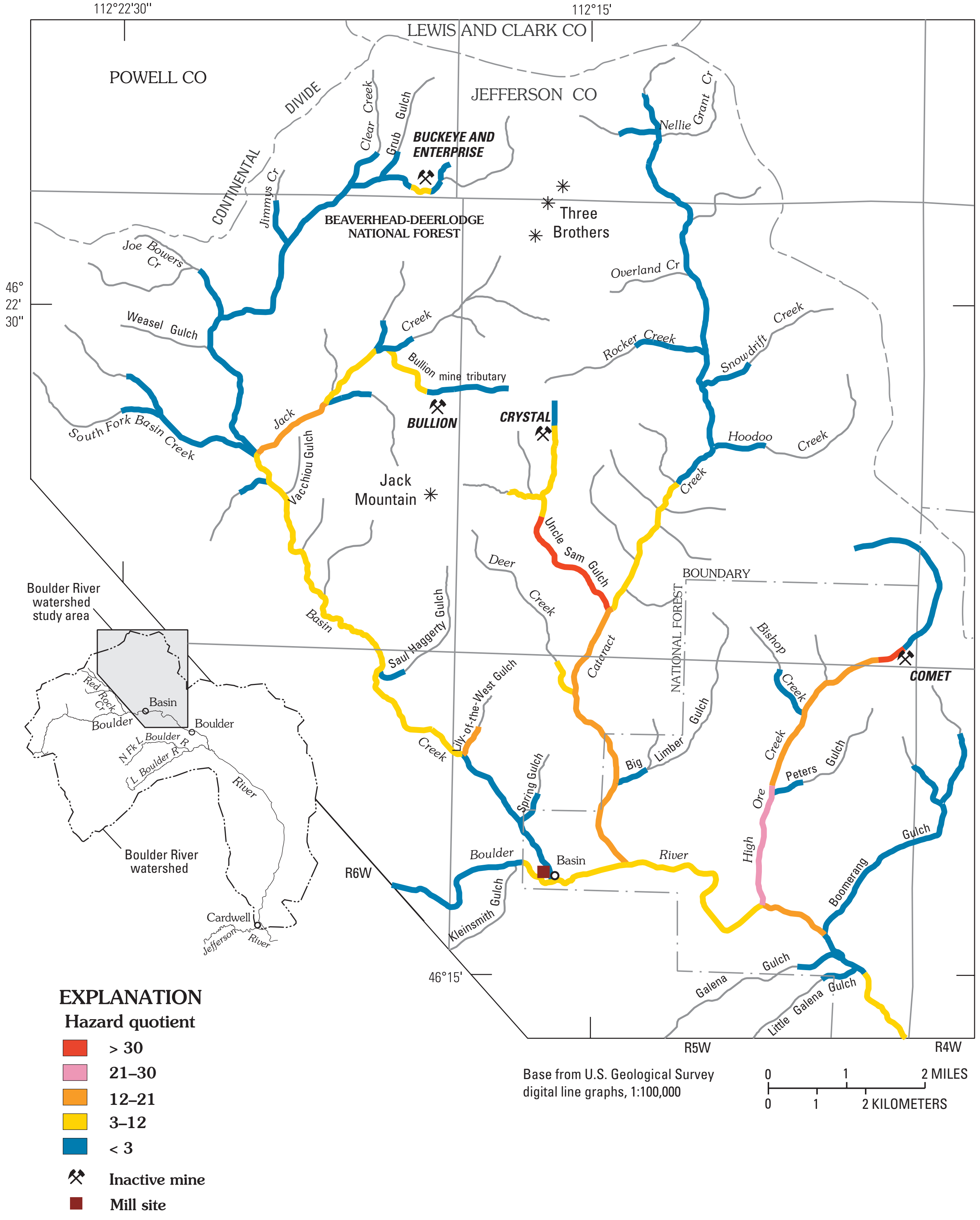

Figure 10. Estimated risk based on sum of hazard quotients for streambed sediment for cadmium, copper, and zinc. Mill site immediately upstream from confluence of Basin Creek with Boulder River shown for reference.

Gulch (but not as far downstream as lower Cataract Creek), the Bullion Mine tributary, Jack Creek downstream from the Bullion Mine tributary, High Ore Creek downstream from the Comet mine, and lower High Ore Creek experienced extensive mortality in the 96-hr survival experiments (Farag and others, this volume).

If the chronic and acute water-quality standards provide the same pattern of potential hazard in the Boulder River watershed, then why do we see any fish in lower Cataract Creek? If trace-element concentrations at this site exceed the acute water-quality criteria, would it not be rendered completely uninhabitable by fish? Two explanations exist for this contradiction. First, the acute criteria were established for multiple species of aquatic life and focus on the survival of larval and swim-up stages that are generally believed to be the most sensitive to contaminant exposure. Adult fish were observed and collected in lower Cataract Creek. It is possible that early life-stage fish would not survive at this site.

Second, acclimation and avoidance behavior may explain the presence of fish in lower Cataract Creek whereas they were not observed immediately downstream from Uncle Sam Gulch. Farag and others (this volume) discuss the likelihood that fish collected in lower Cataract Creek have acclimated to metals in the water at that site. Additionally, the authors document that the cost of this acclimation may be exhibited by reduced biomass/density and physiological changes interpreted in a decline in overall fish health.

Furthermore, anecdotal observations during the in-place 96-hr survival experiments provide evidence that an avoidance response occurs in sections of Cataract Creek. During the experiments, trout were observed in Cataract Creek upstream from Uncle Sam Gulch. These trout fed in a riffle located near the confluence and moved quickly back upstream if they were carried below the confluence. Several dead trout were also found downstream from the confluence with Uncle Sam Gulch. These observations are anecdotal and do not prove behavioral avoidance in this section of the stream, but they suggest the relevance of avoidance behavior in this area. It is possible that some fish in lower Cataract Creek overcame the avoidance response to respond to more immediate stressors such as the need for food (though amounts available may be less than at other sites with lesser concentrations of metals) and a lack of competition from other fish at that site.

Hazard-quotient maps for sediment (figs. 6–9) point to the same general areas of potential hazard as do the maps for water. Combined hazard quotients for sediment (fig. 10) indicate that the areas of highest concern for adverse effects on the biological community were in Uncle Sam Gulch and High Ore Creek downstream from the Comet mine, and to a lesser extent, High Ore Creek downstream from Peters Gulch. Additional areas of concern were Jack Creek downstream from an unnamed tributary draining the Jack Mountain area (figs. 9 and 10), Cataract Creek downstream from Uncle Sam Gulch, and High Ore Creek between Bishop Creek and Peters Gulch. For each of these reaches, one or more of the hazard quotients for cadmium, copper, lead, or zinc exceeded 10. In the case of High Ore Creek downstream from the Comet mine, the hazard quotient exceeded 10 for all four of these trace elements.

Although the hazard quotients calculated from the sediment data point to the same general areas of concern as those calculated from the water, the hazard quotients calculated from the sediment data for Jack Creek and the Bullion Mine tributary (hazard quotients are 3–21 with sediment data, fig. 10) were not as large as those calculated from water-quality data (hazard quotients > 30 with water data, fig. 5). Such differences may be attributed to the lower pH of surface water in the Bullion Mine tributary. If the pH of the water is slightly acidic, cadmium, copper, and zinc, but not lead and arsenic, remain in the water column rather than sorb onto colloidal particles. The pH of water in the Bullion Mine tributary was measured as low as 5.2 in August 1999 (Nimick and Cleasby, 2000). Therefore, the low pH of water at a site lowers the hazard quotients slightly in sediment versus water.

Evaluation of the ecological health of a stream is commonly based on the condition of its fisheries resources because fish represent the top of the food chain in streams and are considered an important resource to land managers and the public. Ecological health of a system is dependent on the chemical and physical conditions in the habitat. If hazard quotients are good estimators of ecological health, then biological conditions of individuals, populations, and communities should reflect interpretations similar to those derived from these simple ratio estimators.

The impaired health of the fish community in lower Cataract Creek corresponded to adverse effects suggested by the hazard quotient method of ranking. The HQ_C values for water suggested extreme hazard for aquatic life in Jack Creek, Bullion Mine tributary, Uncle Sam Gulch, and High Ore Creek downstream from the Comet mine. Fish survival was poor during 96-hr survival in-place experiments performed at these sites (Farag and others, this volume). These reaches should pose the most immediate concern for land managers. Also, the hazard quotients and the survival data may provide explanations about the presence or absence of fish species throughout the Boulder River watershed (fig. 1). Fish were not present in the Bullion Mine tributary, Uncle Sam Gulch, Cataract Creek downstream from Uncle Sam Gulch, and High Ore Creek downstream from the Comet mine. The combined hazard quotients for water agree with the 96-hr survival experiments and point to these reaches as areas of potential high hazard. Except for the Bullion Mine tributary and Jack Creek (as discussed previously), the sediment hazard quotients also indicate these as areas of potential high hazard. Therefore, biology measurements and hazard quotients calculated with water-quality criteria and sediment probable-effects concentrations provide a complete picture of the probable hazards that exist in the Boulder River watershed.

Furthermore, biomass of all species of trout was the smallest at the lower Cataract Creek site. The reduced fish population biomass and density cannot be explained by habitat differences alone (Farag and others, this volume). In addition, concentrations of most trace elements in the livers, gills, and whole-fish tissue of resident rainbow trout were the greatest in fish from the lower Cataract Creek site. The impairment of physiological function was also most pronounced in the rainbow trout from lower Cataract Creek. Similar effects on population biomass and density, tissue contamination, and physiological impairment were not detected at the lower Basin Creek site, nor did the quotient ranking indicate that they would occur. In addition, using total Ephemeroptera (mayflies), Plecoptera (stoneflies), and Tricoptera (caddis flies) taxa as indicators of macroinvertebrate health, Boyle and Gustina (2000) showed that macroinvertebrate communities in High Ore Creek, Jack Creek downstream from the Bullion Mine tributary, and Cataract Creek were the three sites most affected by historical mining in the Boulder River watershed.

Elevated trace-element concentrations were also measured in fish from lower Basin Creek and the Boulder River downstream from Galena Gulch (Farag and others, this volume). However, physiological changes and changes in biomass and density were not significant at those two sites. Therefore, the biological data suggest that these may be areas land-use managers should continue to monitor, but as shown by the hazard quotient for water and sediment, trace-element concentrations in these two areas do not represent the level of hazard noted in lower Cataract Creek. Some sections of the Boulder River have combined hazard quotients from 3 to 12 for water and sediment (figs. 5 and 10), which suggests that some moderate hazard is possible in both lower Basin Creek and the Boulder River downstream from the mill site immediately upstream from Basin Creek. The combined ranking of information for both chronic water-quality criteria and sediment probable-effects concentrations identified the six most biologically impaired sites: Bullion Mine tributary, Jack Creek, Uncle Sam Gulch, Cataract Creek downstream from Uncle Sam Gulch, High Ore Creek downstream from the Comet mine, and lower High Ore Creek (table 2). These sites, where acute effects on organism survival are anticipated, overlapped with sites where a high potential for chronic effects was estimated. We surmise that remediation efforts, including removal of mine wastes located on valley floors and reduction of trace-element loading from draining adits, of inactive mine sites in the basins draining to these six reaches will result in substantial improvement of ecological conditions in the watershed. Additionally, restoration efforts in the Cataract Creek basin are most likely to positively affect fish biomass, density, and individual health in lower Cataract Creek.

Summary

Hazard quotients calculated with chronic water-quality criteria and with sediment probable-effects concentrations generally agreed with measurements of biology to designate the primary areas of potential hazard in the Boulder River watershed (table 2). The sites where potential for high hazards to aquatic life exists included the Bullion Mine tributary, Jack Creek, Uncle Sam Gulch, Cataract Creek downstream from Uncle Sam Gulch, lower Cataract Creek (upstream from the Boulder River), High Ore Creek downstream from the Comet mine, and lower High Ore Creek (upstream from the Boulder River). Fish were absent from all of these sites except lower Cataract Creek, and poor survival during 96-hr survival experiments suggested that trout would be unable to survive in these locations. Adult fish were present in lower Cataract Creek, but the biomass, density, and individual health of trout were affected, which suggests that chronic effects on the fishery in Cataract Creek exist.

The only exception to the agreement between hazard quotients for water and sediment was in the Bullion Mine tributary and Jack Creek, where the lower pH of the water in the Bullion Mine tributary reduced the ability of trace elements to sorb to colloidal material in the sediment. Therefore, it is

Table 2. Comparisons of biological assessment endpoints with estimated risk based on hazard quotients.

[Hazard quotients calculated using chronic water-quality criteria (HQ_C) and sediment probable-effects concentrations (HQ_S). Endpoints not assessed are labeled N/A]

Site	HQ_C	HQ_S	Resident fish	Resident biomass/density effects	Resident fish health effects	Individual survival effects (96-hr tests)
Uncle Sam Gulch	High	High	Absent	N/A	N/A	Yes
Cataract Creek downstream from Uncle Sam Gulch.	High	High	Absent	N/A	N/A	Yes
High Ore Creek downstream from Comet mine.	High	High	Absent	N/A	N/A	Yes
Lower High Ore Creek	High	High	Absent	N/A	N/A	Yes
Lower Cataract Creek	High	High	Present	Yes	Yes	N/A
Bullion Mine tributary	High	Low	Absent	Yes	N/A	Yes
Jack Creek	High	Low	Absent	N/A	N/A	Yes
Upper Basin Creek	Low	Low	Present	N/A	N/A	N/A
Lower Basin Creek	Low	Low	Present	No	No	N/A
Boulder River	Low	Low	Present	No	No	N/A

critical that pH be monitored to interpret water and sediment chemistry.

As a result of hazard-quotient analyses, we estimate that remediation could result in substantial improvement of ecological conditions in the Boulder River watershed study area. These efforts could include removal of mine wastes located on the valley floors of these basins and reduction of trace-element loading from draining adits of the major inactive mine sites in the basins upstream from the primary areas of potential hazard. With remediation, the likelihood that aquatic life will survive at sites where survival was minimal during 96-hr survival experiments will be improved. Additionally, remediation efforts in the Cataract Creek basin are most likely to positively affect fish biomass/density and individual health in lower Cataract Creek.

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