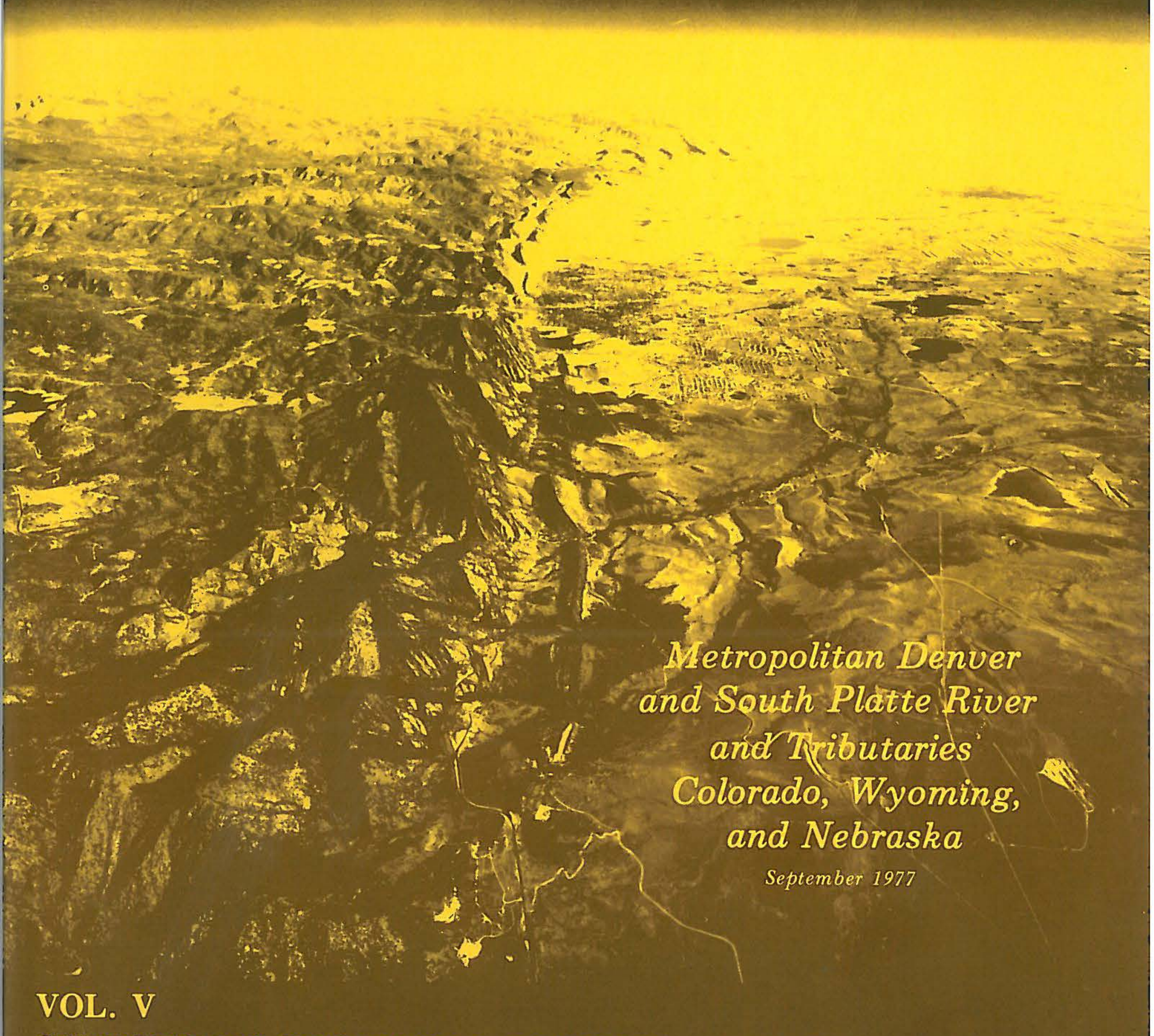
WATER AND RELATED LAND RESOURCES MANAGEMENT STUDY



Metropolitan Denver
and South Platte River
and Tributaries
Colorado, Wyoming,
and Nebraska
September 1977

VOL. V
SUPPORTING TECHNICAL REPORTS APPENDICES

APPENDIX F — USGS MINE DRAINAGE STUDY

Cover Photograph:
Infrared photo of Colorado Front Range, looking north toward Boulder.

Courtesy of:
High Altitude Remotesensing & Photography Denver, Colorado.

Preface

This portion of the Metropolitan Denver and South Platte River and Tributaries Report is one of sixteen individual documents which together comprise Volume V Supporting Technical Reports Appendices. These supporting reports have been completed at various times throughout the study process by the Omaha District, other Federal Agencies, and by Universities and architect-engineer firms under contract with the Omaha District. These supporting reports have been considered in developing the overall conclusions and recommendations contained in Volume I Summary Report, and a number of them were released to local interests prior to completion of the overall study in order to facilitate distribution of the requested planning material in a timely manner. Since some of the conclusions and recommendations in these supporting reports were based on preliminary data obtained early in the study investigation or reflect a single-purpose viewpoint, they may not necessarily agree with the final conclusions of the Omaha District Engineer contained in Volume I.

REVIEW REPORT FOR

Metropolitan Denver
and South Platte River
and Tributaries
Colorado, Wyoming,
and Nebraska

WATER AND RELATED LAND RESOURCES MANAGEMENT STUDY

Volume V

Supporting Technical Reports Appendices

Appendix F

USGS Mine Drainage Study

REVIEW REPORT FOR
WATER AND RELATED LAND RESOURCES MANAGEMENT STUDY
METROPOLITAN DENVER AND SOUTH PLATTE RIVER AND TRIBUTARIES
COLORADO, WYOMING, AND NEBRASKA

VOLUME I	SUMMARY REPORT
VOLUME II	BACKGROUND INFORMATION
VOLUME III A	WATER QUALITY PLAN FORMULATION
VOLUME III B	WATER SUPPLY PLAN FORMULATION
VOLUME III C	FLOOD CONTROL PLAN FORMULATION
VOLUME III D	RECREATION & FISH & WILDLIFE PLAN FORMULATION
VOLUME IV	PUBLIC INVOLVEMENT & COMMENTS
VOLUME V	SUPPORTING TECHNICAL REPORTS APPENDICES
	APPENDIX A - REVIEW OF CURRENT WATER QUALITY PLANS AND PLANNING ACTIVITIES
	APPENDIX B - FLOOD HAZARD IDENTIFICATION
	APPENDIX C - UNCERTAINTIES ASSOCIATED WITH WATER AND RELATED LAND RESOURCES PLANNING
	APPENDIX D - CHARACTERISTICS AND PROBLEMS OF THE WATER SUPPLY SYSTEM - MAIN REPORT AND APPENDIX
	APPENDIX E - MOUNTAIN AND EASTERN PLAINS WATER QUALITY STUDY
	APPENDIX F - USGS MINE DRAINAGE STUDY

APPENDIX G - CHEYENNE WATER QUALITY STUDY

APPENDIX H - HYDROLOGY

APPENDIX J - WATER SUPPLY MANAGEMENT ANALYSIS AND ALTERNATIVE DEVELOPMENT

- VOLUME 1 - MAIN REPORT - WATER SUPPLY - DEMAND ANALYSIS
- VOLUME 2 - TECHNICAL APPENDIX - WATER SUPPLY ANALYSIS
- VOLUME 3 - TECHNICAL APPENDIX - MUNICIPAL WATER DEMANDS
- VOLUME 4 - TECHNICAL APPENDIX - INDUSTRIAL WATER DEMANDS
- VOLUME 5 - TECHNICAL APPENDIX - ENERGY WATER DEMANDS
- VOLUME 6 - TECHNICAL APPENDIX - AGRICULTURAL WATER
- VOLUME 7 - TECHNICAL APPENDIX - USERS MANUAL FOR AN INPUT-OUTPUT WATER BALANCE COMPUTER PROGRAM

APPENDIX K - BUREAU OF OUTDOOR RECREATION REPORT

QUANTITY AND QUALITY OF DRAINAGE FROM THE ARGO TUNNEL AND OTHER SOURCES RELATED TO METAL MINING IN GILPIN, CLEAR CREEK, AND PARK COUNTIES, COLORADO

Prepared in cooperation with the
U.S. Army Corps of Engineers
Omaha District,
Omaha, Nebraska

September 1977

QUANTITY AND QUALITY OF DRAINAGE
FROM THE ARGO TUNNEL
AND OTHER SOURCES RELATED TO METAL MINING
IN GILPIN, CLEAR CREEK, AND PARK COUNTIES, COLORADO

By

Dennis A. Wentz
U.S. Geological Survey

Prepared in cooperation with the
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Omaha District,
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1977

CONTENTS

Page
Metric conversions. IV
Abstract. 1
Introduction. 2
    Background 2
        Geographic setting. 2
        Geology and ore deposits. 4
        Metal-mine drainage--processes and impacts on water resources 8
Sources of metal-mine drainage. 16
    Documented mining-related discharges 16
    Active metal-mining operations 22
Characteristics of drainage from the Argo Tunnel. 22
    Previous scientific studies. 22
    Monitoring program--1976 to 1977 25
        Discharge, water temperature, and specific conductance. . . 25
        Chemical quality. 31
    Controls on chemical quality 39
    Effects on downstream water use. 47
Management alternatives for mine-drainage abatement 49
Summary and conclusions 56
Acknowledgments 57
References. 58

ILLUSTRATIONS

Figures 1-7. Maps showing:
    1. Location of study area within Colorado 3
    2. Colorado mineral belt. 5
    3. Principal metal-mining districts 6
    4. Stream reaches affected adversely by metal-mine drainage. 12
    5. Documented sources of metal-mine drainage. . . 18
    6. Currently active (1975) metal-mining operations 21
    7. Location of the Argo Tunnel and relation to ore zonation 23
8-10. Graphs showing:
    8. Variation of selected trace elements in the Argo Tunnel drainage, January 24, 1973, through February 8, 1974 26
    9. Variation of discharge, water temperature, and specific conductance in the Argo Tunnel drainage, January 29, 1976, through March 18, 1977 29
    10. Variation of dissolved arsenic, cadmium, copper, iron, lead, manganese, and zinc in the Argo Tunnel drainage, March 11, 1976, through March 18, 1977 38

Page
Figure 11. Diagram showing hypothesized effect of the Argo Tunnel on ground-water flow. 41
12. Diagram showing relation of Argo Tunnel bore to altitude of land surface and to ore zonation. 42
13. Graph showing discharge for Clear Creek near or at Golden, minus Clear Creek near Lawson, January 1973 through February 1974 44

TABLES

Table 1. Summary of metallic mineral production. 7
2. Stream reaches affected adversely by metal-mine drainage. 11
3. Maximum standards and criteria for trace-element and cyanide concentrations and pH in waters for various uses exclusive of recreation and industry 13
4. Documented sources of metal-mine drainage 17
5. Currently active (1975) metal-mining operations 19
6. Comparison of recent chemical analyses of the Argo Tunnel drainage 24
7. Physical and chemical data for the Argo Tunnel drainage, March 11, 1976, through March 18, 1977 32
8. Precision of selected trace-element concentrations in the Argo Tunnel drainage, January 24, 1977. 37
9. Baseline concentrations of selected trace elements in the Argo Tunnel drainage. 40
10. Comparison of current and historical chemical analyses of the Argo Tunnel drainage 46
11. Management alternatives applicable to the abatement of mine drainage. 51

METRIC CONVERSIONS

English units in this report may be expressed as metric equivalents by use of the following conversion factors:

To convert English units	*Multiply by*	*To obtain metric units*
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
tons (short)	.9072	metric tons (t)

QUANTITY AND QUALITY OF DRAINAGE FROM THE ARGO TUNNEL AND OTHER SOURCES RELATED TO METAL MINING IN GILPIN, CLEAR CREEK, AND PARK COUNTIES, COLORADO

By Dennis A. Wentz
U.S. Geological Survey

ABSTRACT

Eighteen metal-mine drainage sources have been located in that part of Gilpin, Clear Creek, and Park Counties, Colo., lying within the Missouri River basin. At least 13 of these sources are known to contain high acidity and (or) trace-element concentrations or to contribute water to adversely affected streams. From January 1976 to March 1977, drainage from the Argo Tunnel in Idaho Springs--one of the major metal-mine drainage sources in the study area--exhibited variations in discharge from 0.35 to 0.55 cubic feet per second (0.010 to 0.016 cubic meters per second), a relatively constant temperature of 16° Celsius, and variations in specific conductance from 2,680 to 3,410 micromhos per centimeter at 25° Celsius (though a value of about 3,100 micromhos persisted throughout most of the period of record). High, but relatively constant, total concentrations (in micrograms per liter) of arsenic (100 to 180), cadmium (140 to 170), copper (5,000 to 6,600), iron (160,000 to 200,000), lead (less than 100 to 200), manganese (80,000 to 110,000), and zinc (40,000 to 49,000) were measured in the Argo Tunnel drainage from March 1976 to March 1977. Except for lead, the trace elements were mostly dissolved (82 percent or greater) and appear to represent baseline concentrations. Long-term degradation of water flowing from the Argo Tunnel is shown by increases of at least 2.5 to 8.0 times for dissolved solids, dissolved iron, calcium, magnesium, and sulfate since 1906. The acidity has changed from neutral in 1906 to a median pH value of 2.9 in 1976-77. Comparison of current Argo Tunnel data with those collected previously by other investigators indicates that spring chemical flushes containing higher than baseline trace-element concentrations occurred in 1973 and 1974, but not in 1975 or 1976, and probably not in 1972. The spring chemical flushes appear to be associated with increased infiltration from snowmelt in the catchment of the Argo Tunnel. Because of the wide ranges in mine-drainage quality and quantity expected for discharges from abandoned mines in the study area, each situation must be examined individually, and the management alternative chosen for mine-drainage abatement must be tailored to solve the particular mining and hydrologic problems at a given site.

INTRODUCTION

The U.S. Geological Survey has delineated 25 areas in Colorado where approximately 450 mi (720 km) of streams contain potentially toxic concentrations of trace elements[1] and acidity resulting from metal mining and related activities (Wentz, 1974). Deteriorated quality in these streams is caused by discharges from drainage tunnels, milling operations, and active and abandoned mines and tailings ponds, in addition to natural mineral seeps. Water flowing from any of these sources is referred to as mine drainage in this report, but no implication as to the quality of the water is to be construed. Subsequent studies (Moran and Wentz, 1974) have concentrated on the chemical and physical processes influencing trace-element transport in affected streams, but little effort has been directed specifically toward drainage sources.

In January 1976, the U.S. Geological Survey entered into a cooperative agreement with the U.S. Army Corps of Engineers to study the drainage from metal mines and tailings in that portion of Gilpin, Clear Creek, and Park Counties, Colo., contained within the Missouri River basin. Coal-mine drainage has not been considered, because it does not exist in the study area (Wentz, 1974). The general objectives of the study are: (1) To locate sources of mine drainage that are degrading stream quality, (2) to determine seasonal variations in chemical composition and discharge of this drainage, and (3) to suggest alternatives for improving water quality in streams affected by mine drainage. Emphasis in this investigation has been concentrated on the Argo Tunnel in Clear Creek County, as this tunnel is one of the major mine-drainage sources in the study area. Results are presented for the period January 29, 1976, through March 18, 1977.

Background

Geographic Setting

The location of the study area is shown on figure 1. It includes all of Gilpin and Clear Creek Counties and most (86 percent) of Park County. All of the study area lies within the Missouri River basin.

Major streams draining the study area include the South Platte River, Tarryall Creek, and the North Fork South Platte River in Park County, Clear Creek in Clear Creek County, and North Clear Creek and South Boulder Creek in Gilpin County. Except for South Boulder Creek, water from all streams is received by the South Platte River at or upstream from Denver. South Boulder Creek is a tributary of St. Vrain

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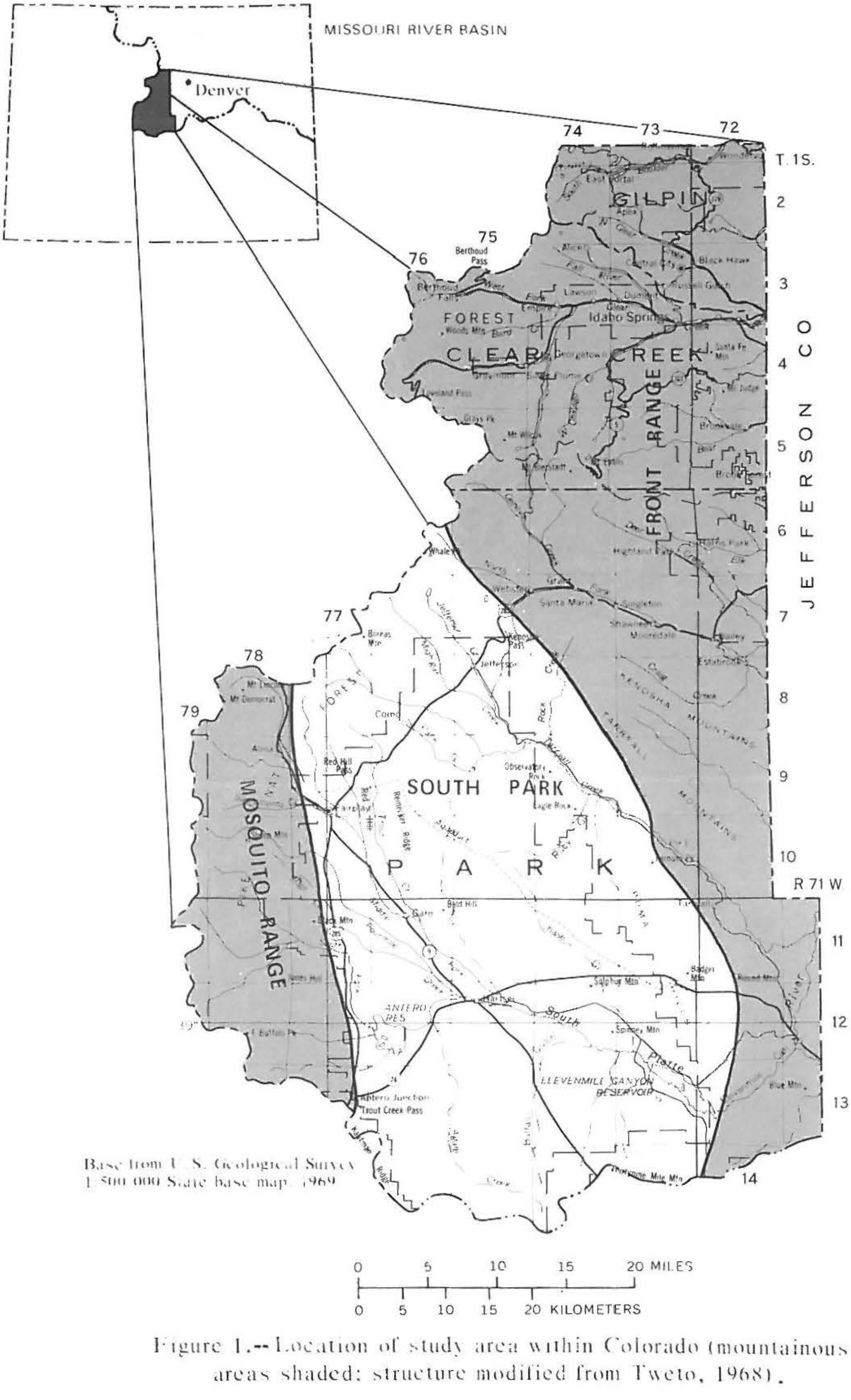
[1] The term trace elements refers to those elements which occur in relatively minor amounts (less than 1 mg/L) in most natural waters. In mine drainage, trace elements are often present in much higher concentrations. Trace elements include both metals and nonmetals.



Base from U. S. Geological Survey 1:500,000 State base map, 1969

Figure 1.--Location of study area within Colorado (mountainous areas shaded; structure modified from Tweto, 1968).

Creek (outside the study area), which enters the South Platte River approximately 36 mi (58 km) downstream from Denver.

Altitudes in the study area range from 14,286 ft (4,354 m) at Mount Lincoln in the Mosquito Range of western Park County to approximately 6,890 ft (2,100 m) where Clear Creek crosses the Clear Creek-Jefferson County line at the eastern edge of the study area. Topographic relief is greatest in the northern two counties where altitude differences of 7,000 ft (2,100 m) are encountered along the eastern slope of the Front Range within the 15- to 30-mi (25- to 50-km) width of the study area. Altitude differences in the southern part of the study area average 4,000 to 5,000 ft (1,200 to 1,500 m) over greater distances. Much of this area is dominated by South Park, an intermontane basin, at a relatively constant altitude of 9,000 to 10,000 ft (2,700 to 3,000 m).

Geology and Ore Deposits

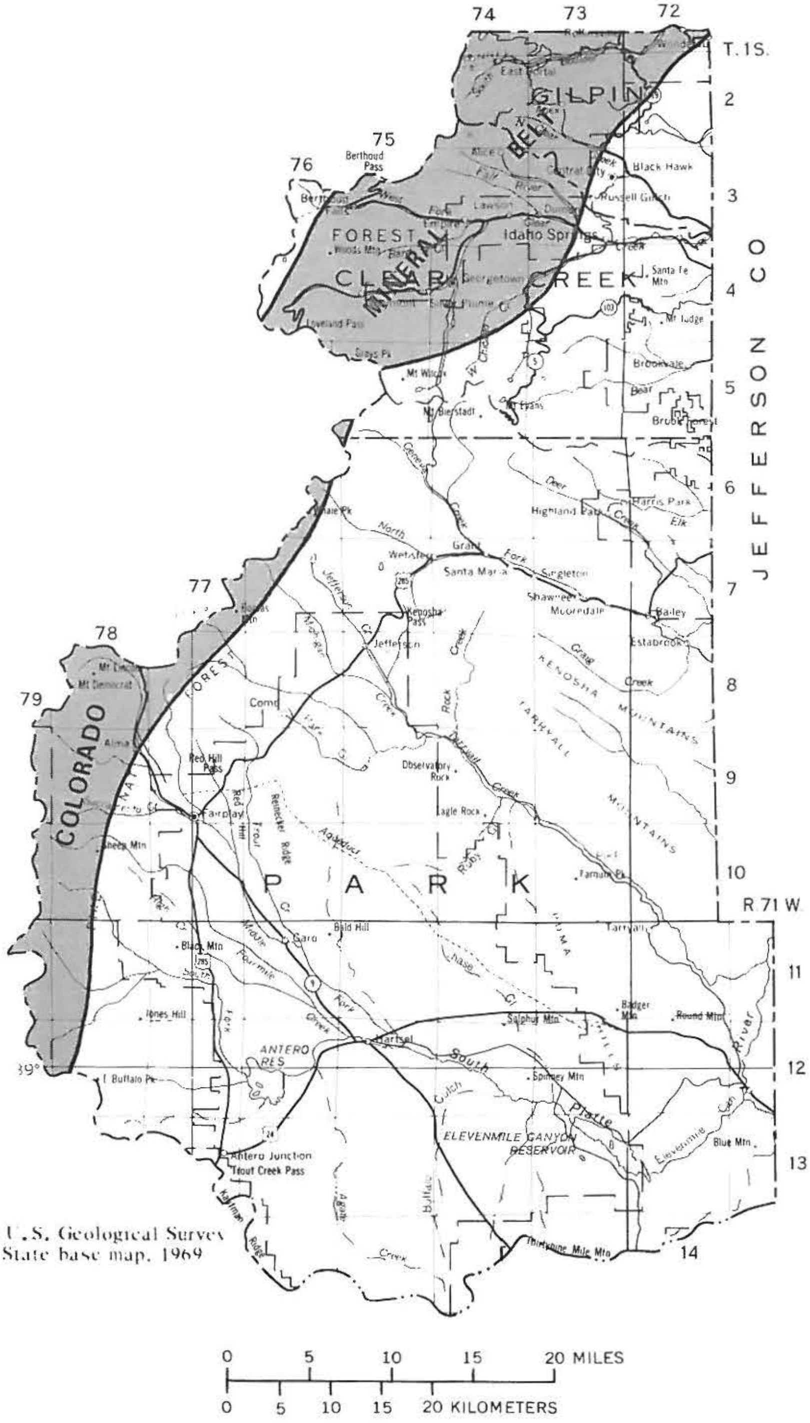
As intimated previously, the study area is composed of three prominent geologic features--the Front Range on the north and east being separated from the Mosquito Range in the southwest by South Park (see fig. 1).

The Front Range is composed primarily of Precambrian gneisses and schists that have been intruded by granite (Tweto, 1968). The Mosquito Range is a fault-block range of Precambrian granite capped with Paleozoic sedimentary rocks. It was formed from the eastern flank of the Sawatch anticline; the core of the latter forms the next mountain range to the west. South Park is a topographic and structural basin containing a sedimentary sequence extending downward to the Cambrian.

All three features were shaped predominantly during the Laramide Orogeny, a period of extensive uplift and erosion that formed the basis for most presently recognizable physiographic features of Colorado. According to Tweto (1968), the Laramide lasted from Late Cretaceous to middle Eocene time.

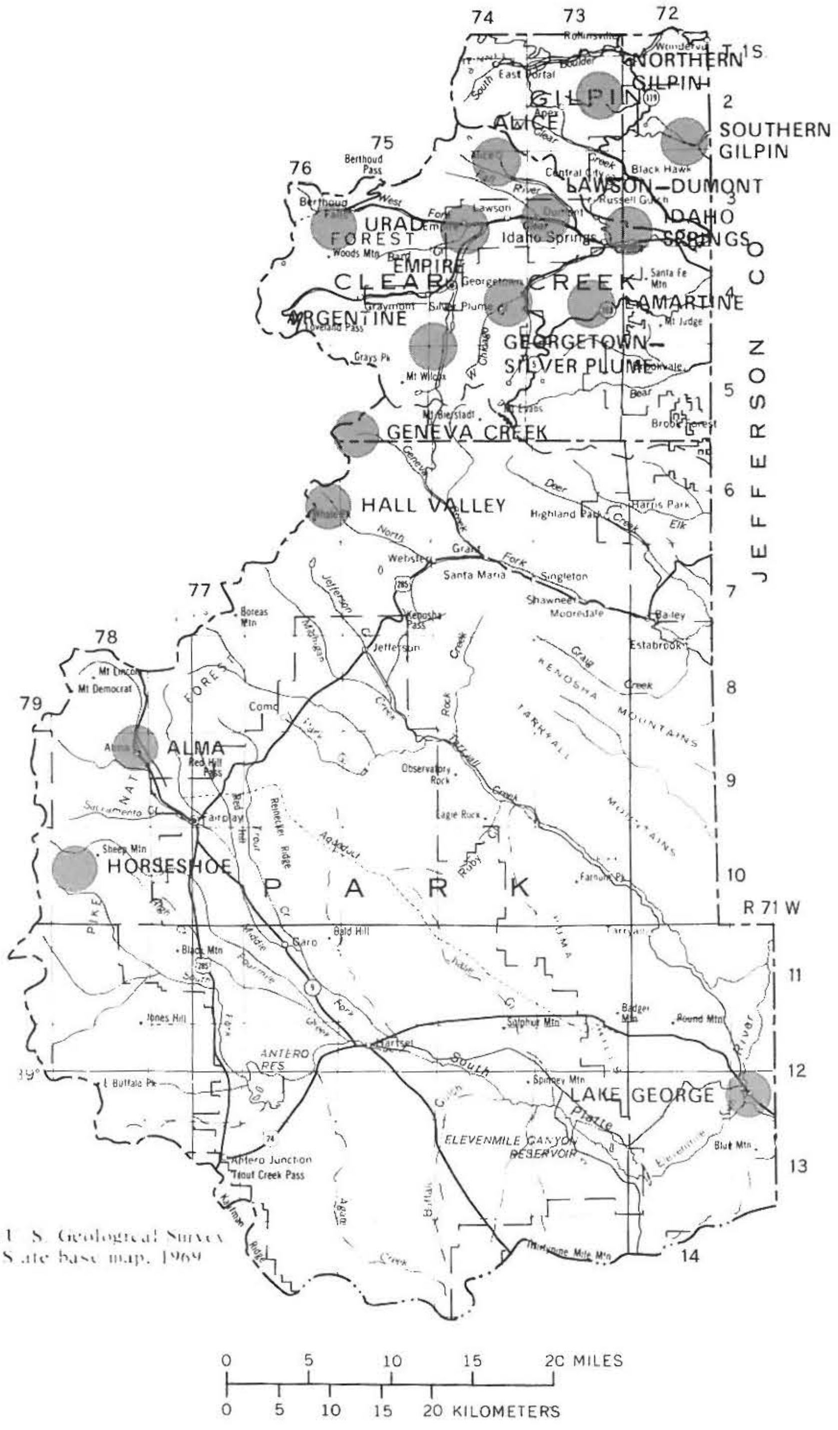
Most of the metal mining in the study area has occurred within the Colorado mineral belt, a narrow, irregularly shaped region that extends diagonally from the southwest corner of Colorado to the north-central portion of the State. This region coincides with a zone of weakness characterized by northeasterly trending Precambrian shear zones (Tweto and Sims, 1963). During and after the Laramide mountain-building episode, the shear zones were reactivated, resulting in extensive magmatic intrusion and volcanic emanations. This igneous activity produced the ore deposits. That part of the Colorado mineral belt lying within the study area is shown on figure 2.

The 15 principal metal-mining districts in the study area are located on figure 3. Metallic mineral production from these districts is summarized in table 1. Total dollar value of production through 1970 was $220,389,388.



Base from U.S. Geological Survey
1:500 000 State base map, 1969

Figure 2.--Colorado mineral belt (modified from Tweto and Sims, 1963).



Base from U. S. Geological Survey 1:500,000 State base map, 1969

Figure 3.--Principal metal-mining districts (modified from Marsh and Queen, 1974).

Table 1.--*Summary of metallic mineral production*

[from Marsh and Queen (1974);
Ag, silver; Au, gold; Be, beryllium; Cu, copper; Mo, molybdenum; Pb, lead;
Zn, zinc; U, uranium; W, tungsten]

County	Mining district	Ore type[1]	Metals[2]	Production (through 1970)[3]
Clear Creek-	Alice-------------	Complex-------	Au,Cu(Ag,Pb,Zn)	$ 951,400
	Argentine---------	Complex-------	Pb,Ag,Au,Cu,Zn	2,349,700
	Empire------------	Complex-------	Au(Ag,Cu,Pb,Zn)	4,486,400
	Geneva Creek------	Complex-------	Au,Ag,Cu,Pb[4]	[4]12,490
	Georgetown-Silver Plume-----------	Complex-------	Ag,Zn,Pb(Au,Cu)	9,907,900
	Idaho Springs-----	Complex-telluride---	Au,Ag,Pb(Cu,Zn)	15,988,800
	Lamartine---------	Complex-------	Au,Ag,Pb(Cu,Zn)	3,597,800
	Lawson-Dumont-----	Complex-------	Ag,Pb,Au(Cu,Zn)	1,134,700
	Urad--------------	Molybdenite-complex-----	Mo	44,998,452
Gilpin------	Northern Gilpin---	Complex-------	Au(Ag,Cu,Pb)	10,266,600
	Southern Gilpin---	Complex-telluride-pitchblende-	Au,Ag(Cu,Pb,Zn,U)	95,092,000
Park--------	Alma--------------	Placer-complex-----	Au(Ag,Cu,Pb,Zn)	29,557,100
	Hall Valley-------	Complex-------	Ag,Pb(Au,Cu)	124,800
	Horseshoe---------	Complex-------	Pb,Ag,Zn(Au,Cu)	1,425,100
	Lake George------	Beryl---------	Be(W)	496,146

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[1] From Vanderwilt (1947) and Del Rio (1960).

[2] Metals outside parentheses are listed in decreasing order of dollar value production; metals in parentheses are minor production and are listed in alphabetical order by chemical symbol.

[3] Dollar value at time of production.

[4] From Vanderwilt (1947); metals listed alphabetically; dollar value production through 1940, probably the last year of active mining.

The majority of ore mined in the study area is commonly termed "complex ore" (U.S. Congress, 1964, p. 29). This is predominantly a combination of base metals (copper, lead, and zinc) and precious metals (gold and silver), although small amounts of other metals (for example, cadmium and manganese) may be present. The base metals and silver are most commonly found as sulfides, with minor amounts of some nonmetals, including antimony, arsenic, and selenium, substituted for sulfur. Most of the gold and some silver occurs in the elemental form, generally disseminated in the gangue minerals; but occasionally they seem to be incorporated into the structure of metallic minerals (Sims and others, 1963). Some complex ores contain minor amounts of gold and silver tellurides. In the vicinity of the Alma district (fig. 3), some of the source complex ore has oxidized and eroded to form extensive gold placer deposits--metallic gold that has been concentrated in the alluvial gravels of the stream valleys downstream from the source.

A second ore type is one in which gold and silver tellurides are the predominant economic minerals. According to Tweto (1968), these deposits are post-Laramide. Molybdenite deposits, which also are reported to be post-Laramide (Tweto, 1968) and which often contain economic quantities of tungsten and tin (Wallace and others, 1968), represent a third category of metal ores. Of relatively minor importance are the pitchblende (uranium) occurrences in the Southern Gilpin district (fig. 3) and the beryl (beryllium) deposits in the Lake George district of southeastern Park County (fig. 3).

The geology and ore deposits of Gilpin, Clear Creek, and Park Counties are discussed in greater detail by Bastin and Hill (1917); Vanderwilt (1947); Del Rio (1960); Sims, Drake, and Tooker (1963); and Tweto (1968).

Metal-Mine Drainage-- Processes and Impacts on Water Resources

Draining mines and tailings piles are sources of concern because of the acid and trace elements they potentially can contribute to receiving streams. Pyrite (FeS_2) is closely associated with other economically important, metallic sulfides. Upon exposure to oxidizing conditions and water, the pyrite is broken down and acid (H^+) is produced. In addition, ferrous ions (Fe^{++}) are released and are oxidized by bacterial catalysis to the ferric state (Fe^{+++}). The ferric ions hydrolyze, thus forming relatively insoluble ferric hydroxide [$Fe(OH)_3$], which precipitates on the stream bottom. Other metal ions may be adsorbed on (Jenne, 1968) or coprecipitated with (J. D. Hem, written commun., 1973) the $Fe(OH)_3$, thereby forming a metal-rich orange coating (yellow boy) on rocks in affected streams. The overall process can be summarized as follows:

$$FeS_{2\,(s)} + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightleftarrows Fe(OH)_{3\,(s)} + 2SO_4^{=} + 4H^+. \qquad (1)$$

Metal sulfides other than pyrite will be dissolved by the acid released in reaction 1. This can be represented as:

$$MeS_{(s)} + 2H^{+} \rightleftarrows Me^{++} + H_2S, \qquad (2)$$

where Me represents any divalent metal that forms a sulfide ore mineral. Dissolution of these minerals releases trace elements to the water but does not result in the production of additional net acid (Wentz, 1974). More detailed discussions of the mechanism of pyrite oxidation and acid formation can be found in Coal Industry Advisory Committee (1965, 1968, 1970), Stumm and Morgan (1970), Ohio State University Research Foundation (1971), and Wentz (1974).

In a draining mine, the above sequence of events could occur as oxygen-laden snowmelt or rainwater infiltrated into a mineral seam and then drained to the surface. The system has been likened to a diffuse flow system (Wildeman, 1976) in which recharge occurs by seepage through small faults, voids, and intergranular spaces. Water movement is slow, and water residence time in the system is long--on the order of months, according to Wildeman (1976). The system thus shows little flow response to short-term, extreme variations in precipitation. Water quality of the discharge generally remains constant, presumably because some sort of dynamic equilibrium has been established. Such an equilibrium would require a reasonably constant average water residence time in the system. If there is a flow rise during spring snowmelt runoff, Wildeman (1976) notes that concentrations of chemical constituents may increase, "* * * as if the aquifer were flushing trapped water from its many small pores." The inference is that infiltrating water increases the hydrostatic head; this flushes larger quantities of water from the system. The flushed water would be expected to be poorer in quality than the infiltrating water because of the former's longer contact with pyritic materials and other metal sulfides. Normally, the flushed water would be expected to be comparable in quality to that previously draining from the system. However, if the average residence time of water in the system had increased prior to the flushing event, or if relatively more of the flushed water were from a portion of the system containing more easily degraded sulfide minerals or a larger surface to volume ratio in the pore spaces, then the flushed water would be expected to contain higher than normal concentrations of chemical constituents.

Pyritic materials and other metal sulfides also can be present in mine and mill tailings. Often these have been piled adjacent to stream channels. Acid and other chemicals accumulate in the pores within the tailings piles and are flushed rapidly during rainstorms or snowmelt events. These slugs of acid and trace elements can be detrimental to downstream water users, but they are very difficult to detect because of their sporadic and short-lived nature. Erosion of the tailings also can be detrimental to stream quality by causing excessive turbidity. In areas where mill tailings have been deposited directly in stream channels behind dams, water is constantly flowing through these materials. Relatively clean water enters, becomes contaminated, and exits directly over the spillway or, via seepage, through the bottom of the tailings pond. In areas where tailings ponds are located adjacent to stream channels, overflows or dam breakages during storm events can contaminate the stream. However, if the pond is located close enough to the stream channel, seepage from the pond may affect the water quality of the stream continuously.

Within the study area, Wentz (1974) determined approximately 67 mi (108 km) of stream reaches that are affected adversely by metal-mine drainage. These reaches are listed in table 2 and are indicated on figure 4. Streams were considered to be affected adversely if an analysis of the water revealed trace-element concentrations in excess of certain drinking-water standards or suggested criteria for aquatic life, or if measured pH values were less than 6.0. Details of the exact procedure are given by Wentz (1974, p. 102). The drinking-water standards used are those recommended by the U.S. Public Health Service (1962, 1970) and the Colorado Department of Health (1971); the suggested criteria for aquatic life were determined by Wentz (1974, table 3, p. 27) from the literature available at that time. Both sets of numbers are reproduced in table 3 (cols. 2 and 3).

The impact of a mine-drainage source on a stream depends upon many factors, including (1) the relative flows from the source and in the stream, (2) the relative acidity (pH) and concentrations of trace elements and other chemical constituents in the source and in the stream, and (3) the intended water use.

The effect of hydrology will vary and must be determined for each situation. Discharge of the receiving stream may be available directly from gages in the U.S. Geological Survey stream-gaging network. Alternatively, stream discharge can be estimated from basin characteristics and measurements at nearby stations (Livingston, 1970; Lowham, 1976), from stream-channel characteristics (Hedman and others, 1972; Lowham, 1976), or from rainfall-runoff (Dawdy and others, 1972) or snowmelt-runoff models (Leavesley, 1973). Water quality of the receiving stream is known less often than streamflow; but concentrations of major constituents can be estimated from specific-conductance measurements, if the appropriate relationships can be developed for the area of interest (Steele, 1976; D. A. Wentz and T. D. Steele, written commun., 1977). Concentrations of trace elements in unaffected streams can be estimated from analyses of streams draining similar geologic environments; however, stream trace-element concentrations should be measured if more reliable results are desired. The discharge and water quality of mine-drainage sources are seldom known from prior records; they usually must be measured to obtain current information.

Current national drinking-water standards (U.S. Environmental Protection Agency, 1975a, 1977) and proposed Colorado standards for water supply, aquatic life, and agriculture (Colorado Department of Health, 1977) are included in table 3 for trace elements, cyanide, and pH. Specific recommendations regarding trace elements and their effects on recreational and esthetic values of waters have not been made;

Table 2.--*Stream reaches affected adversely by metal-mine drainage*

[Modified from Wentz (1974); listed alphabetically]

Stream: Tributary(ies)	Number in figure 4	Point or approximate reach known to be affected	Estimated length of stream affected[1]	
			Miles	Kilometers[2]
Clear Creek	1	Above South Clear Creek to below Golden	17	27
Chicago Creek:				
Ute Creek	2	Mouth	1	2
North Clear Creek	3	Above Chase Gulch to mouth	8	13
Chase Gulch	4	Mouth	3	5
Gregory Gulch	5	Above Nevada Gulch to mouth	1	2
Russell Gulch	6	Mouth	4	6
Soda Creek	7	-----do-----	1	2
South Clear Creek:				
Leavenworth Creek	8	-----do-----	1	2
Virginia Canyon Creek	9	-----do-----	1	2
West Fork	10	Above Butler Gulch to below Woods Creek	4	6
Lion Creek	11	Minnesota mines to mouth	2	3
Woods Creek	12	Urad mine to mouth	1	2
North Fork South Platte River	13	Above Beaver Creek	6	10
Geneva Creek	14	Above Duck Creek	7	11
Handcart Gulch	15	------------	3	5
Sacramento Creek	16	Mouth	7	11

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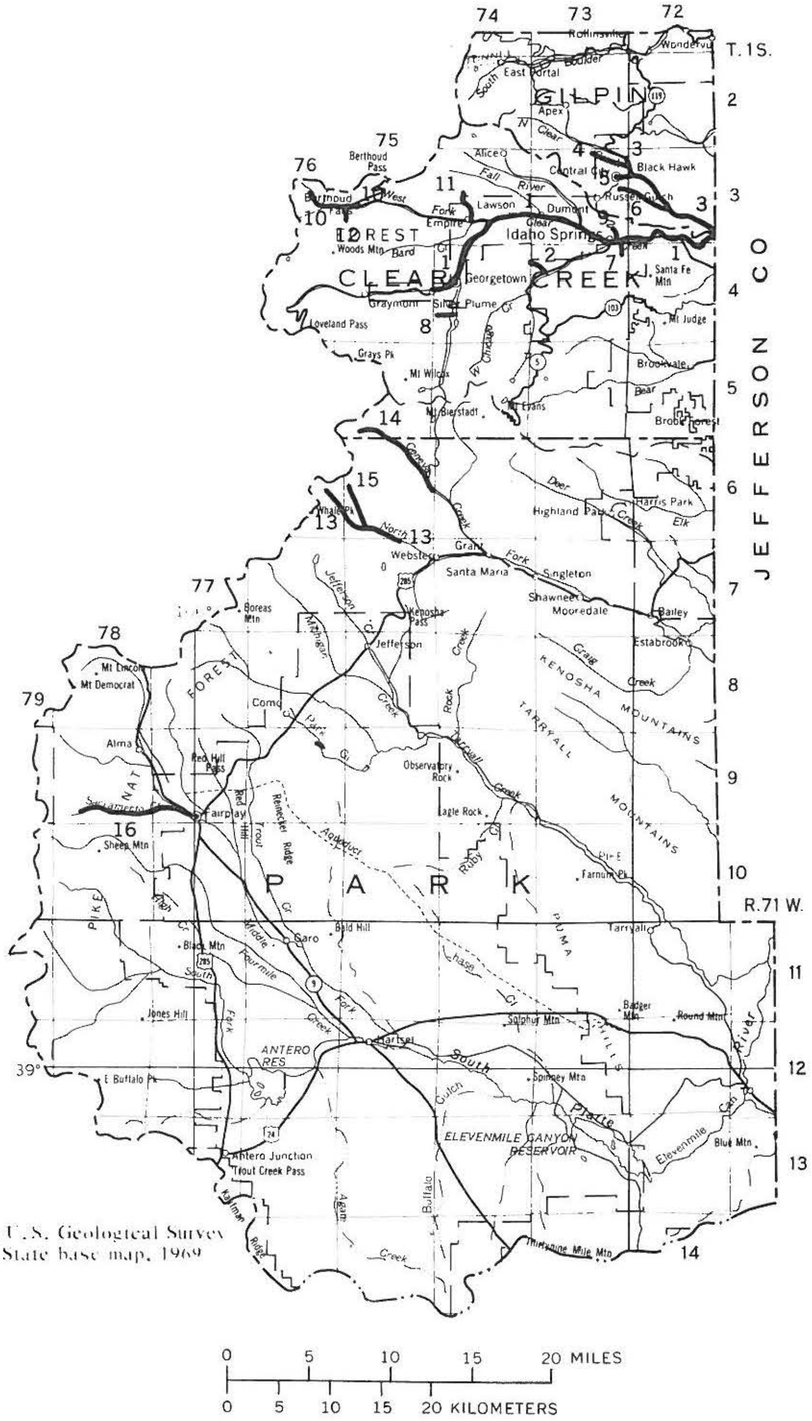
[1] Distances are shown to the nearest mile (kilometer).

[2] Because of rounding errors, the sum of this column is 109 km instead of 108 km, as indicated on page 10.



Base from U.S. Geological Survey 1:500,000 State base map, 1969

Figure 4.--Stream reaches affected adversely by metal-mine drainage (modified from Wentz, 1974: numbers refer to table 2).

Table 3.--*Maximum standards and criteria for trace-element and cyanide concentrations and pH in waters for various uses exclusive of recreation and industry*

[Range of values shown for pH; all values expressed as micrograms per liter, unless otherwise specified]

Water-quality parameter	Standards and criteria used to determine streams affected adversely by metal-mine drainage (table 3 and fig. 4)		Current standards			
	Drinking-water standards (U.S. Public Health Service, 1962; Colorado Department of Health, 1971)	Suggested criteria for fish and other aquatic life (Wentz, 1974)	National drinking-water regulations (U.S. Environmental Protection Agency, 1975a, 1977)	Proposed Colorado water-quality standards (Colorado Department of Health, 1977)		
				Water supply[1]	Aquatic life[2]	Agriculture
Aluminum------------	----------	-----------	-----------	------------	100	-----
Arsenic-------------	[3]50,[4](10)	1,000	[5]50	50	50	100
Barium--------------	[3]1,000	-----------	[5]1,000	------------	----------	-----
Beryllium-----------	----------	-----------	-----------	100	10	100
Boron---------------	----------	-----------	-----------	------------	----------	750
Cadmium-------------	[3]10	10	[5]10	10	.4	10
Chromium------------	[3,6]50	50	[5]50	50	100	100
Cobalt--------------	----------	500	-----------	------------	----------	-----
Copper--------------	[4]1,000	10-20	[7]1,000	1,000	10	200
Cyanide-------------	[3]200,[4](10)	-----------	-----------	[8]200	[8]5	[8]200
Iron----------------	[4]300	300	[7]300	[9]300	1,000	-----
Lead----------------	[3]50	5-10	[5]50	50	4	100
Manganese-----------	[4]50	1,000	[7]50	[9]50	2,000	200
Mercury-------------	[10]5	1	[5]2	2	.05	10
Molybdenum----------	----------	-----------	-----------	------------	----------	150
Nickel--------------	----------	50	-----------	------------	50	100
pH (standard units)-	----------	([11])6.0≤pH≤	[7]6.5≤pH≤8.5	[12]5.0≤pH≤9.0	6.5≤pH≤9.0	-----
Selenium------------	[3]10	1,000	[5]10	10	50	50
Silver--------------	[3,13]50	.1	[5]50	50	[14].1	-----
Thallium------------	----------	-----------	-----------	------------	15	-----
Zinc----------------	[4]5,000	30-70	[7]5,000	5,000	50	2,000

[1] Includes municipal and private ground-water supplies and municipal potable surface water (raw water).

[2] Includes cold-water biota (inhabitants, including trout, of waters where temperatures do not normally exceed 20°C) and warm-water biota (inhabitants of waters where temperatures normally exceed 20°C); standards apply to stream waters having total hardness from 0 to 100 mg/L as $CaCO_3$.

[3] Maximum permissible concentration.

[4] Recommended upper limit.

[5] Interim primary maximum contaminant level; applies to all systems providing piped water for human consumption, "* * * if such system has at least fifteen service connections or regularly serves at least twenty-five individuals." (U.S. Environmental Protection Agency, 1975a).

[6] Refers to chromium (VI).

[7] Secondary maximum contaminant level. These "* * * are not Federally enforceable and are intended as guidelines for the States * * *" (U.S. Environmental Protection Agency, 1977).

[8] Refers to free cyanide.

[9] Refers to soluble form.

[10] Proposed (U.S. Public Health Service, 1970).

[11] No maximum pH was listed.

[12] Applies only to municipal potable surface water (raw water).

[13] No drinking-water standard established by the Colorado Department of Health (1971).

[14] Applies only to cold-water biota; standard for warm-water biota is 0.2 μg/L.

however, it has been noted that water containing chemicals in such concentrations as to be "* * * toxic to man if small quantities are ingested * * *" or "* * * irritating to the skin or mucous membranes of the human body upon brief immersion * * *" are undesirable and should be avoided for general recreation, bathing, or swimming (National Academy of Sciences-National Academy of Engineering, 1973). Moreover, industrial water requirements have not been included because "* * * modern water treatment technology is capable of treating almost any raw water to render it suitable for any industrial use." (National Academy of Sciences-National Academy of Engineering, 1973).

Potential water use in the vicinity of the adversely affected stream reaches given in table 2 and figure 4 is generally restricted to fish and wildlife. Impacts on fish and wildlife use should be significant in the study area only within the 67 mi (108 km) of streams designated as adversely affected. Except for cadmium and mercury, these stream reaches were based on standards and criteria (cols. 2 and 3, table 3) that were approximately as restrictive as current standards (cols. 4, 5, and 6, table 3). The designated adversely affected stream reaches also were based on conditions obtained during low flows when the ratios of mine-drainage discharge to streamflow were expected to be highest. Thus, the estimated length of affected streams should approach a maximum for the water-use standards and criteria employed. These stream-reach lengths would have to be adjusted for different hydrologic conditions.

A few of the stream reaches (for example, reaches 13, 14, and 15, table 2 and fig. 4) pass through or near U.S. Forest Service campgrounds and picnic areas. In at least some of these areas, signs have been placed to warn visitors to avoid consumption of the water.

Domestic use of water directly from adversely affected stream reaches can be considered minimal. However, many permanent residences are located in or adjacent to the flood plains of these stream reaches, and wells probably supply the water needed by most of these residences. If the well is located in an area where the ground-water reservoir is recharged from an affected stream reach, the potential for deteriorated ground-water quality would exist.

Moran and Wentz (1974) have reported concentrations of arsenic, cadmium, copper, iron, lead, manganese, nickel, selenium, and zinc in water from three wells in alluvium located less than 20 ft (6 m) laterally from the adversely affected upper Kerber Creek in south-central Colorado. It is not known if the stream reach is gaining water from or losing water to the ground-water system; however, only iron in water from two wells and manganese in water from one well were found to exceed current national or proposed State drinking-water standards (table 3). Klusman and Edwards (1977) have indicated trace-element contamination of ground water might be expected in the alluvium of the lower reaches of North Clear Creek (fig. 4), even though it is located outside (in this case, downstream from) an area of intensive sulfide mineralization in the bedrock. These same authors have shown that wells in bedrock within the Colorado mineral belt in Gilpin and Clear Creek Counties and in the mountainous parts of Boulder and Jefferson Counties (immediately north and east, respectively, of the study area) are more likely to contain concentrations of cadmium, copper, iron, manganese, and zinc in excess of U.S. Public Health Service (1962) drinking-water standards than are bedrock wells located outside the mineral belt. It should be noted that the U.S. Public Health Service (1962) drinking-water standards for these trace elements are the same as the national secondary and interim primary drinking-water regulations (table 3).

Municipal water use is known to occur downstream from adversely affected stream reaches. The Denver Board of Water Commissioners, for example, routes water from Dillon Reservoir (west of the study area) through the Harold D. Roberts Tunnel to the North Fork South Platte River just upstream from Geneva Creek (fig. 4). Affected stream reaches 13, 14, and 15 (table 2 and fig. 4) contribute to this water as it travels to the main-stem South Platte River and on to Denver's water-treatment plants. Englewood--a suburb of Denver to the south--also obtains its municipal supply from the main-stem South Platte River. Water supplies for the communities of Broomfield, Federal Heights, Golden, and Westminster (suburbs to the north and west of Denver) originate from Clear Creek at least 10 mi (16 km) east of the study area and downstream from affected stream reaches 1 through 12 (table 2 and fig. 4). In all cases, the municipal intakes are located far enough downstream to allow dilution and chemical processes to decrease all trace-element concentrations, except possibly manganese, to innocuous levels (inferred from trace-element data given in Wentz, 1974).

Livestock grazing is important in parts of the study area, and some animals undoubtedly drink water from adversely affected stream reaches. Irrigation also is practiced actively within and downstream from the study area. No major irrigation diversions utilize water directly from affected stream reaches; however, smaller diversions used for irrigating single fields or ranches could exist in some areas. At least 12 diversions are known to exist on Clear Creek between a point approximately 11 mi (18 km) downstream from the eastern edge of the study area and the mouth of the stream, another 19 mi (31 km) farther downstream.

Industrial water use from adversely affected stream reaches probably is restricted to active mining operations.

It is seen readily from table 3 that any potential detrimental impact of a mine-drainage source is greatly dependent on the planned use for the water in the receiving stream. The impact also can become more evident as standards are revised based on more current information. For receiving waters subjected to multiple uses, the most stringent standards for a given use should be applied.

SOURCES OF METAL-MINE DRAINAGE

Sources of mine drainage were located by documenting, from the technical literature, mining-related discharges contributing to the adversely affected stream reaches designated by Wentz (1974) and given in table 2 and on figure 4. Documented metal-mine drainage sources are listed in table 4 and are located on figure 5. Other possible sources of mine drainage were determined by reviewing current records on active (1975) mining operations (table 5 and fig. 6).

Not all the adversely affected stream reaches listed in table 2 and shown on figure 4 have documented sources of metal-mine drainage (table 4 and fig. 5) or active metal-mining operations (table 5 and fig. 6) located within their drainage basins. These streams could be affected by natural mineral seeps or by other undocumented mine-drainage sources. The latter situation is more likely because most of these streams are located within or close to principal metal-mining districts (fig. 3).

Documented Mining-Related Discharges

The Colorado Game, Fish and Parks Division conducted studies on Woods Creek (table 4 and fig. 5) below the Urad Mine and on the West Fork of Clear Creek above and below Woods Creek from June 1965 to October 1968 (Bingham, 1966, 1967, 1968; Colorado Game, Fish and Parks Division, 1969). The study was discontinued because "Data accumulated indicate that the Urad Project has not had a deleterious effect upon the West Fork of Clear Creek * * *" and because the mine was "* * * scheduled for de-emphasis[2] * * *" (Colorado Game, Fish and Parks Division, 1969). Maximum observed concentrations of copper, iron, manganese, and zinc were 300, 2,200, 8,200, and 480 µg/L (micrograms per liter), respectively, in Woods Creek below the Urad tailings. Lead was reported as zero in all cases. It is not known if the water samples were filtered or preserved by acidification.

Four areas in the Clear Creek drainage were studied by Moran and Wentz (1974) during January and June 1973. With one exception (the Argo Tunnel drainage, which enters the main-stem Clear Creek at Idaho Springs), specific mine-drainage sources were not sampled; however, the locations of the sources were noted. For samples passed through 0.45-µm (micrometer)-membrane filters, concentrations of the following consituents were determined to exceed U.S. Public Health Service (1962) drinking-water standards and (or) aquatic biological criteria suggested by Wentz (1974, table 3, p. 27): pH, cadmium, iron, manganese, selenium, zinc in North Clear Creek; pH, copper, iron, manganese, nickel, zinc in Lion Creek; pH, cadmium, copper, iron, lead, manganese, nickel, zinc in the main-stem Clear Creek at Idaho Springs; and

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[2] The Urad Mine was shut down on November 29, 1974 (The Denver Post, December 1, 1974).

Table 4.--*Documented sources of metal-mine drainage*

Name	Number in figure 5	Type of drainage	Active or inactive (1975)[1]	Reference[2]
Argo Tunnel------------	1	Mine	Inactive	F, M, W
Blue Ribbon Tunnel-----	2	---do---	---do---	F
Bonanza Mine-----------	3	---do---	---do---	W
Central Tunnel No. 5---	4	---do---	---do---	F
Gregory Incline--------	5	---do---	---do---	F(?), W
Lucania Tunnel---------	6	---do---	---do---	W
McClellan Mine---------	7	---do---	---do---	F
Minnesota Mine---------	8	---do---	---do---	M
National Tunnel--------	9	---do---	---do---	W
Quartz Hill Tunnel-----	10	---do---	---do---	M, W
Rara Avis Tunnel-------	11	---do---	---do---	W
Silver King Mine-------	12	---do---	---do---	F
South London Tunnel----	13	---do---	Active[3]	F
Big Five Tunnel[4]-------	14	---do---	Inactive	M
Unnamed adit-----------	15	---do---	---do---	M
Virginia Canyon Creek[5]-	16	Mine(?)	Active(?)	M
Williams Tunnel--------	17	Mine	Inactive	W
Woods Creek------------	18	Tailings	---do---	B, F, W

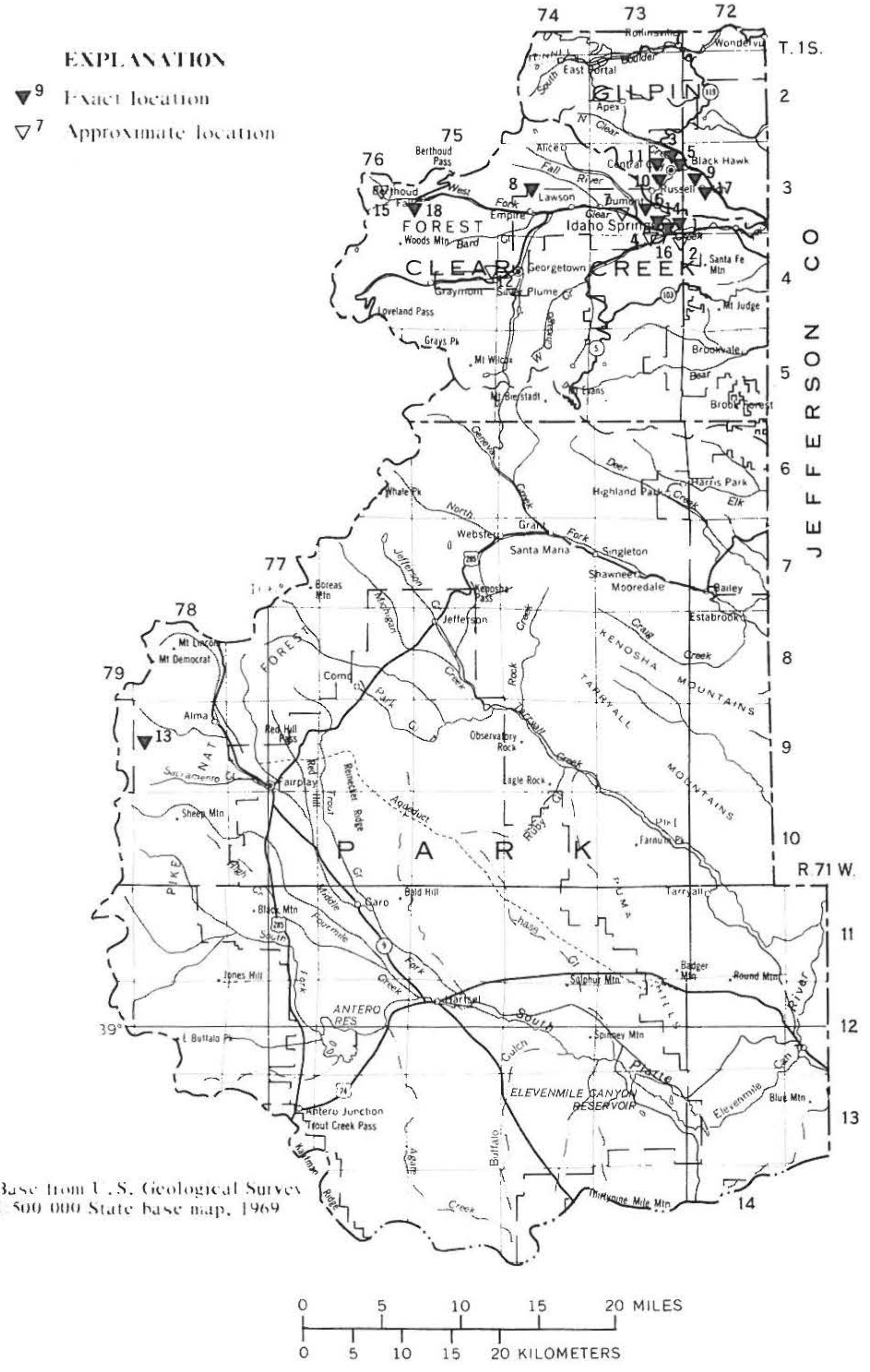
[1] According to Colorado Division of Mines (1976).

[2] B=Bingham (1966, 1967, 1968), Colorado Game, Fish and Parks Division (1969); F=Federal Water Pollution Control Administration (written commun., 1968); M=Moran and Wentz (1974); W=Wildeman, Cain, and Ramirez (1974).

[3] According to the Federal Water Pollution Control Administration (written commun., 1968), most of the internal drainage from London Mountain emerges at the South London Tunnel and enters into South Mosquito Creek at river-mile 1.0 (km 1.6). The London Extension Mine, which is in London Mountain upstream from this point, was listed as active by the Colorado Division of Mines (1976, p. 105).

[4] Name not published by Moran and Wentz (1974).

[5] Virginia Canyon Creek contributes mine drainage to Clear Creek during certain times of the year. Whether this is natural mineral seepage or drainage from active or abandoned mines is not known. The Colorado Division of Mines (1976, p. 76) listed at least two active mining operations (Santa Fe and Two Brothers Mines) in this area during 1975.



Base from U.S. Geological Survey 1:500 000 State base map, 1969

Figure 5.--Documented sources of metal-mine drainage (numbers refer to table 4).

Table 5.--*Currently active (1975) metal-mining operations*

Name[1]	Number in figure 6	Remarks[1]
CLEAR CREEK COUNTY		
Anglo Saxon Mine	1	Base metals.
Black Eagle Mill	2	Do.
Crazy Girl Mill	3	Do.
Dixie Mine	4	Gold, silver, lead, zinc.
Edgar Mine	5	Operated by Colorado School of Mines for educational purposes.
Empress Mill	6	Base metals.
Empress Mine	7	Do.
Eva Mines	8	Do.
Henderson Nos. 1 & 2 (Mine)	9	Molybdenum.
Lamartine Mine	10	Base metals.
Nabob Mine	11	Do.
New Europe Mine	12	Do.
Quito Mine Complex	13	Do.
Santa Fe Mine	14	Do.
Senator Mine	15	Do.
Two Brothers Mine	16	Do.
GILPIN COUNTY		
Apex Mine	17	Core drilling.
Bob Tail Mine	18	Tourist attraction.
Matchless No. 10 (Mine)	19	Base metals.
Chaffee Mine (Vic's Gold Placer)	20	Tourist attraction.
Clinkenbeard Mine	21	Base metals.
Cracker Jack Placer	22	Gold.
Diamond Lil Tunnel	23	Tourist attraction.
Glory Hole (Mine)	24	Do.
Golden Gilpin Mill	25	Base metals.
Linda No. 1 Mine	26	Do.
Mammoth 114A Mine	27	Gold, silver, copper.
Perseverance Mine	28	Gold, silver, lead, zinc.
Pittsburgh-Notaway	29	Exploratory drilling.
Rider Mine	30	Base metals.
Smith Mine	31	Do.

Table 5.--*Currently active (1975) metal-mining operations*--Continued

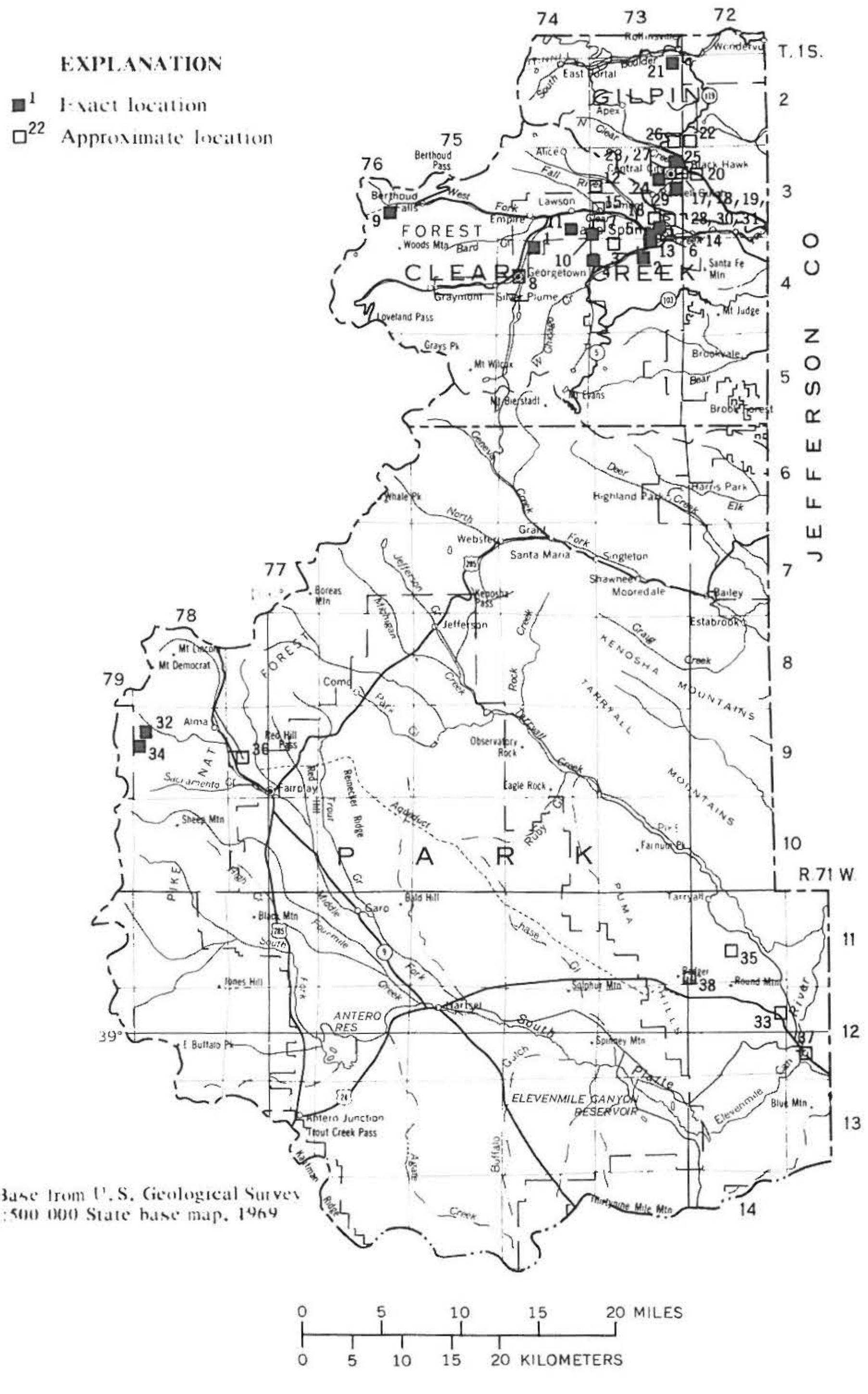
Name[1]	Number in figure 6	Remarks[1]
	PARK COUNTY	
American Mill---------------	32	Gold, silver, lead, zinc.
Caylor (Mine)---------------	33	Open-pit barrite mine.
London Extension Mine-------	34	Base metals.
Mary "B" (Mine)-------------	35	Open-pit barrite mine.
Penn Hill Placer------------	36	Gold.
Tarryall Mill---------------	37	Base metals.
Wheel of Fortune Mine-------	38	Uranium.

[1] From Colorado Division of Mines (1976, p. 74-76, 84-85, 105-106).

manganese, molybdenum, zinc in Woods Creek and West Fork Clear Creek. Mine-drainage sources (table 4 and fig. 5) noted to be discharging to streams in these areas include the Quartz Hill Tunnel on North Clear Creek; Minnesota Mines on Lion Creek; the Argo Tunnel, Virginia Canyon Creek, and at least one unnamed adit (now known to be the Big Five Tunnel, T. R. Wildeman, oral commun., June 8, 1977) in the Idaho Springs area; and Woods Creek and at least one unnamed adit in the upper reaches of West Fork Clear Creek.

Wildeman, Cain, and Ramiriz (1974) analyzed water from eight draining mine adits in the Central City district (combined Idaho Springs and Southern Gilpin districts, fig. 3) during the period July 1973 to February 1974. The eight adits are the Argo, Lucania, National, Quartz Hill, Rara Avis, and Williams Tunnels, the Gregory Incline, and the Bonanza Mine (table 4 and fig. 5). Except for the Williams Tunnel, all drains contained at least one toxic trace element (specifically, cadmium or lead) at total concentrations in excess of the U.S. Public Health Service (1962) drinking-water standards. All drains, including the Williams Tunnel, contained total iron and total manganese at concentrations greater than the recommended standards.

A correlation between the quality of the drainage and the position of the mine adit in the ore body has been noted. Mines located in the central ore zone, where pyrite veins are most common, exhibited greater concentrations of acid and total trace elements than mines on the outer edges of the ore body. According to Wildeman, Cain, and Ramiriz (1974, p. 225), "* * * highest concentrations of Zn [zinc], Cd [cadmium], and Pb [lead] occur in [water draining] the central zone even though sphalerite and galena, the ore minerals which concentrate these elements, occur in greatest abundances in the intermediate and peripheral zones * * *. Thus, there is not necessarily a correlation between the economic grade of an ore extracted from a mine and the



Base from U.S. Geological Survey
1:500 000 State base map, 1969

Figure 6.--Currently active (1975) metal-mining operations (numbers refer to table 5).

harmfulness of the water draining from a mine. On the other hand, there is a direct correlation between the abundance of pyrite in the veins and the harmfulness of the water draining from the mine * * *." This supports a conclusion reached earlier by Wentz (1974, p. 20-21), who noted that only pyrite oxidation contributes to the formation of acid waters, but that dissolution of other metal sulfides in these acid waters, in turn, can yield high trace-element concentrations. (See also p. 8-9 of this report.)

Active Metal-Mining Operations

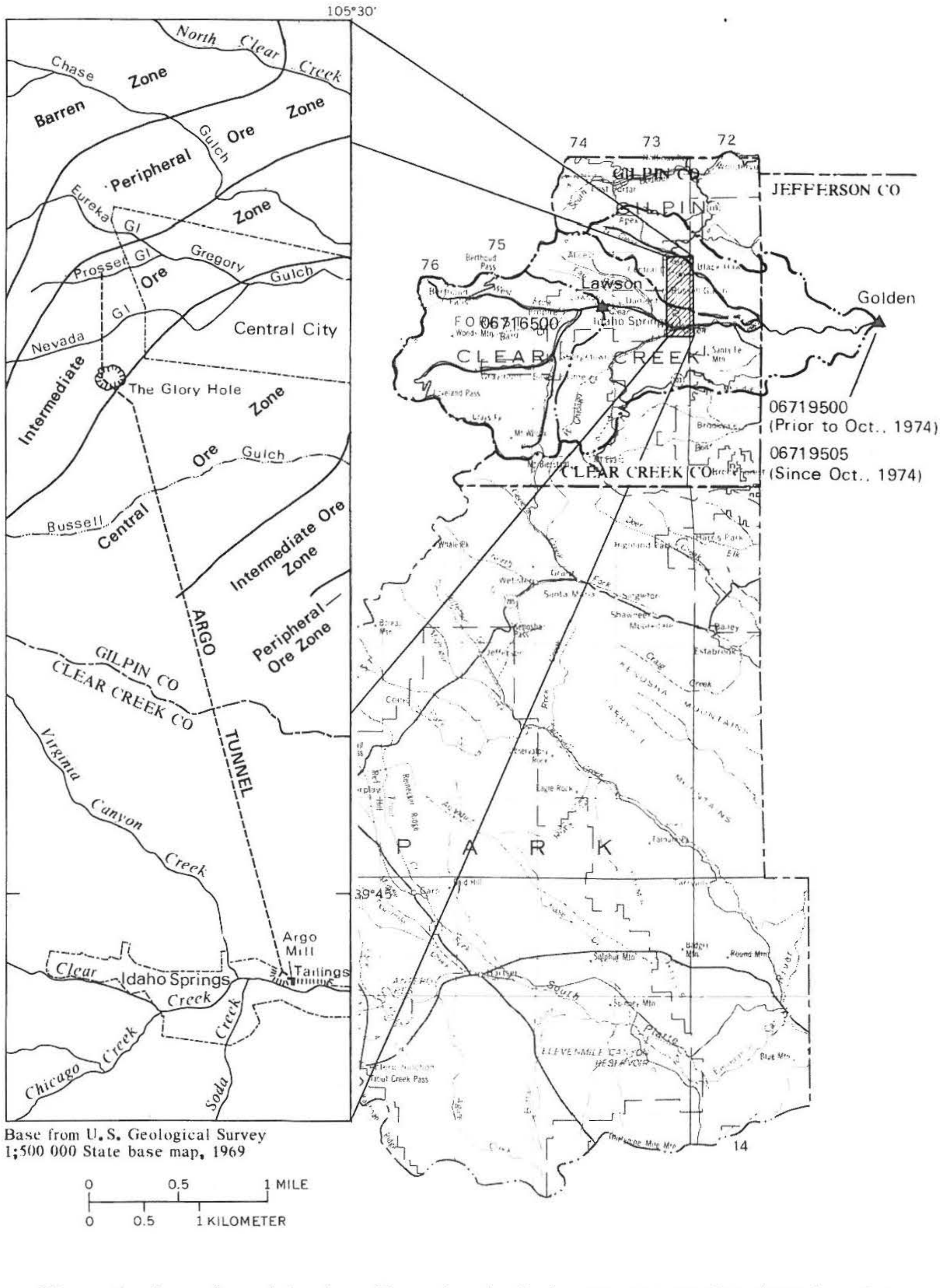
The Colorado Division of Mines (1976) listed 38 active metal-mining operations in the study area in 1974, including 16 in Clear Creek County, 15 in Gilpin County, and 7 in Park County (see table 5 and fig. 6). Together, Gilpin and Clear Creek Counties accounted for only 0.04 percent ($88,879 of $245,522,034) of Colorado's metallic mineral production for the year 1975; no metallic mineral production was reported in Park County during 1975.

CHARACTERISTICS OF DRAINAGE FROM THE ARGO TUNNEL

The Argo Tunnel (formerly, the Newhouse Tunnel) (fig. 7)--one of the major mine-drainage sources in the study area--is 21,968 ft (6,696 m) or 4.16 mi (6.69 km) long and intersects about 26 ore veins (Bastin and Hill, 1917). The country rock in the vicinity of the tunnel is Precambrian schist, gneiss, and granite; the porosity of these rocks results from fractures. Construction of the tunnel was begun on November 1, 1893 (Ripley and others, 1906), to intersect the largest veins in the Idaho Springs-Central City area at greater depth than the deepest shaft workings. The tunnel decreased mining costs, provided cheap transportation of the ore to the mill and railroad at Idaho Springs, and provided a means for draining the workings. That drainage was a major consideration is indicated by Lakes (1900), who noted that "The arrival of the tunnel at or rather beneath the mines will be an enormous help to them, especially in getting rid of the water with which they are at present overburdened." And, more specifically, that "One mine [in the Central City area] for years raised on an average 40 tons [36 t] of water for every ton of ore and rock." The drainage currently enters Clear Creek several hundred feet from the tunnel entrance.

Previous Scientific Studies

Moran and Wentz (1974) studied the Argo Tunnel drainage in 1973. Two samples were collected--one on January 24 and one on June 28. The field-measured pH was 2.8 on January 24 and 2.6 on June 28, a relatively insignificant difference. Calcium and magnesium concentrations also were very similar on the two dates; however, most dissolved (0.45-μm membrane-filtered) and total concentrations of cadmium, cobalt, copper, iron, lead, manganese, nickel, silver, and zinc showed a net increase of



Base from U.S. Geological Survey
1;500 000 State base map, 1969

Figure 7.--Location of the Argo Tunnel and relation to ore zonation (based on data provided by the U.S. Bureau of Mines, unpublished data, July 1977, and presented in Ripley and others, 1906, and in Sims and others, 1963, fig. 11, p. 39).

1.4 to 2.7 times between January and June. Dissolved cobalt and dissolved lead increased 4.4 and 6.7 times, respectively. Except for cobalt and lead in January, iron in June, and silver at both times, all trace elements were almost completely dissolved (88 percent or greater).

The Argo Tunnel was studied by Boyles, Cain, Alley, and Klusman (1974) from May 17 through September 28, 1973. They noted no change in flow (1.2 ft^3/s or 0.034 m^3/s) from the tunnel during the period July 3 to August 16, and stated that the flow averaged 1.2 ft^3/s (0.034 m^3/s) during the period June 25 to August 31.

Concentrations of dissolved cadmium, copper, iron, manganese, zinc, and sulfate in the drainage on May 17 were higher than during the rest of the study period. Variations in concentrations of these parameters from June 29 through September 28 were relatively insignificant. The pH varied only from 2.6 to 2.8 for the entire period of May 17 through September 28. The analytical methods and quality-control procedures used have been endorsed by the U.S. Geological Survey.

Data published by Moran and Wentz (1974) for June 28, 1973, and data presented by Boyles, Cain, Alley, and Klusman (1974) for June 29, 1963, are shown in table 6. With the possible exceptions of iron and lead, excellent agreement is shown between the Argo Tunnel drainage analyses.

Table 6.--*Comparison of recent chemical analyses of the Argo Tunnel drainage*

Date	pH (standard units)	Dissolved concentrations, in µg/L						Reference
		Cadmium	Copper	Iron	Lead	Manganese	Zinc	
1973								
June 28	2.6	300	12,000	220,000	200	140,000	81,000	Moran and Wentz (1974).
June 29	2.8	300	12,000	320,000	140	150,000	78,000	Boyles, Cain, Alley, and Klusman (1974).

Wildeman, Cain, and Ramiriz (1974) published analyses for three samples from the Argo Tunnel for the period October 30, 1973, through February 8, 1974, and found no dramatic changes in major or trace-element concentrations. They used the same analytical methods and quality-control procedures as Boyles, Cain, Alley, and Klusman (1974). Although Wildeman, Cain, and Ramiriz (1974) did not filter their water samples, it has been shown previously that most trace elements in the drainage are primarily in the dissolved state (p. 24).

Combination of the data from the three previous studies should reflect any seasonal variations in water quality of the Argo Tunnel. Variations of cadmium, copper, iron, lead, manganese, and zinc for the period January 24, 1973, through February 8, 1974, are shown in figure 8. An increase in trace-element concentrations was observed between January and May, but the exact time-series pattern cannot be determined from the sampling intervals. Lead apparently decreased during this same period, a situation that is not readily explained, but that may be related to the generally poorer analytical precision for this element as compared to cadmium, copper, iron, manganese, and zinc (Boyles and others, 1974, p. 43; Wentz, 1974, p. 34). Following the initial rise, concentrations of most trace elements gradually decreased, at least through February 8, 1974. Again, lead was an exception to the general trend; its concentrations were relatively constant, but variable.

The pH remained remarkably constant throughout the period of record, ranging from 2.5 to 2.8. Somewhat surprisingly, the pH did not decrease appreciably (only from 2.8 to 2.6) between January and May of 1973. This is probably because any excess acid flushed from the ore body during this period was utilized to dissolve metal sulfides by reaction 2 (p. 9). Calculations based on reaction 2 indicate that 0.0088 mol/L additional acid would have been required to raise the concentrations of cadmium, copper, manganese, and zinc from the levels reported for January 1973 to those reported for May 1973. This acid could have been contributed by the dissolution of additional FeS_2 as given in the reaction

$$FeS_{2(s)} + \frac{15}{4}O_2 + \frac{1}{2}H_2O \rightleftarrows 2SO_4^{=} + Fe^{+++} + H^{+}, \qquad (3)$$

which shows that equal amounts of H^+ and Fe^{+++} should be produced. The measured increase in iron from January to May 1973 was 0.0086 mol/L, providing good evidence for the postulated mechanism. The additional acid could have lowered the pH of the Argo drainage to 2.2, had metal-sulfide dissolution not utilized it.

Monitoring Program--1976 to 1977

Discharge, Water Temperature, and Specific Conductance

On January 29, 1976, the U.S. Geological Survey began collecting a continuous record of discharge of the Argo Tunnel drainage using a battery-powered 16-channel digital recorder (Fischer & Porter, Type 1542)[3]. This unit records the height of water above a known datum in a

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[3] The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

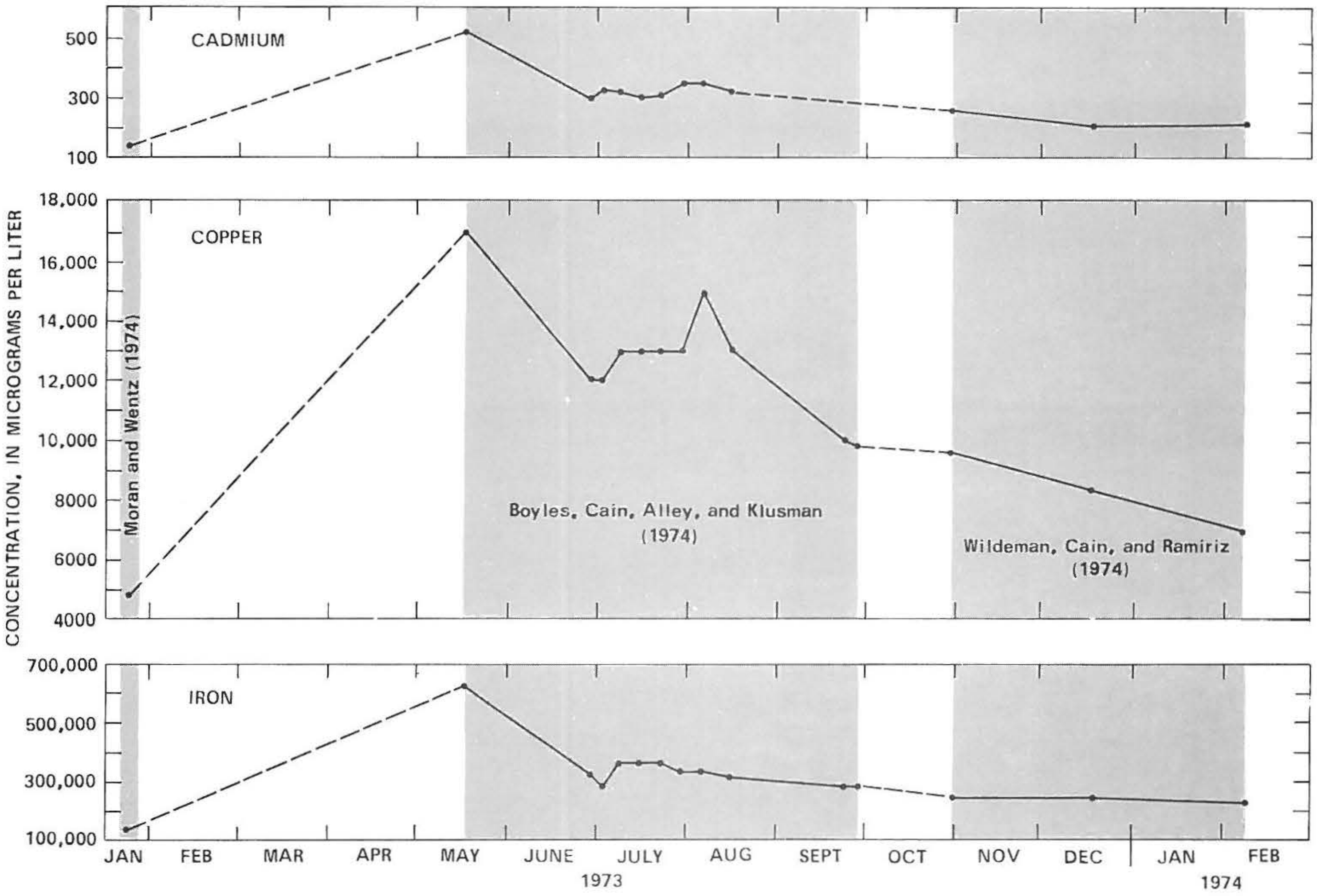

Figure 8A.--Variation of cadmium, copper, and iron in the Argo Tunnel drainage, January 24, 1973, through February 8, 1974.

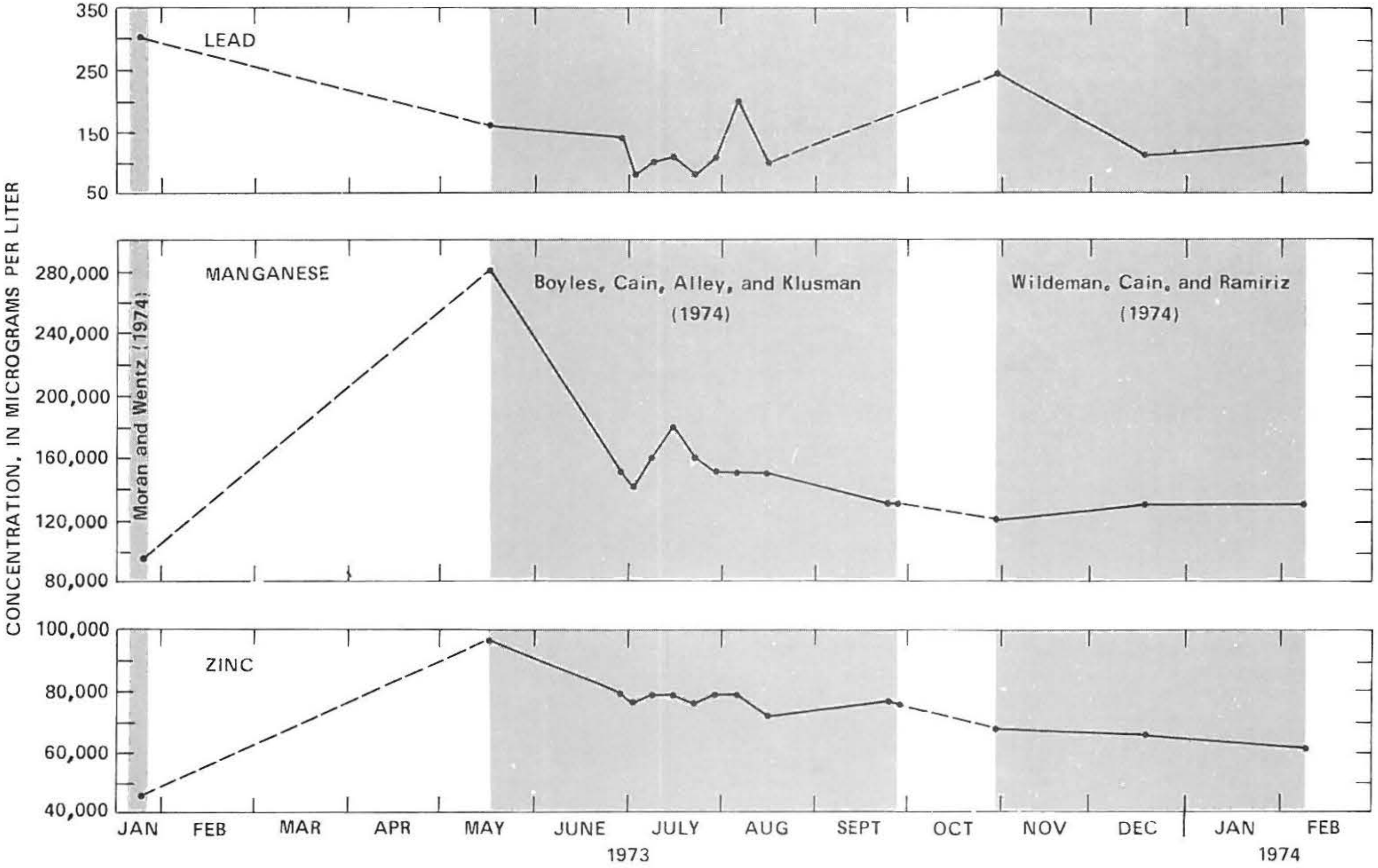

Figure 8B.--Variation of lead, manganese, and zinc in the Argo Tunnel drainage, January 24, 1973, through February 8, 1974.

pool upstream from a control structure--a Parshall flume in this case. Stage measurements are recorded hourly and are converted to discharge using a standard rating supplied with the flume.

Because of equipment failure, vandalism, and the fact that the stage indicated little discharge fluctuation (ranging from 0.37 to 0.55 ft^3/s or 0.010 to 0.016 m^3/s) from January 29 through June 24, 1976, it was decided to discontinue collection of hourly stage data. Beginning August 13, discharge measurements were made at approximate monthly intervals using standard stream-gaging procedures (Buchanan and Somers, 1969). The last monthly measurement was made on March 18, 1977.

A second continuous monitor installed at the Argo Tunnel consists of a servo-programer attached to a digital recorder. Sensors measure water temperature and specific conductance hourly. With two exceptions, the monitor operated continuously from its installation on January 29, 1976, until March 18, 1977. The temperature-sensing system malfunctioned from February 13 through April 5, 1976; however, because of the relative constancy of the water-temperature record for the rest of the period, this omission is not considered serious. Also, during the period November 8-16, 1976, the batteries were dead, and neither water-temperature nor specific-conductance data were recorded during this period.

Daily mean values of Argo Tunnel discharge are shown in figure 9 for the period January 29 through June 24, 1976; monthly measurements of instantaneous discharge are plotted thereafter through March 18, 1977. The accuracy of all monthly measurements is estimated to be ±5 percent. The minimum daily mean value of 0.37 ft^3/s (0.010 m^3/s) occurred on April 5. The maximum daily mean discharge of 0.55 ft^3/s (0.016 m^3/s) occurred just before and just after the missing record of May 18 through May 30. This is unfortunate, as it appears the maximum peak of the annual hydrograph may have occurred during this period.

Instantaneous monthly discharge measurements since June 24, 1976, range from 0.35 to 0.51 ft^3/s (0.010 to 0.014 m^3/s), with the low value of 0.35 ft^3/s (0.010 m^3/s) having been measured on February 22, 1977. A Kendall's Tau nonparametric test (Conover, 1971) on all instantaneous discharges (table 7, p. 32) indicates a 95-percent probability of a decreasing trend for the period March 11, 1976, through March 18, 1977. The discharge is estimated to be 14 percent less during the period October 14, 1976, through March 18, 1977, than during the period March 11 through September 13, 1976, and is based on an Aspin-Welch test (Duncan, 1965) at the 95-percent-probability level for the difference between the means of the respective periods. The decrease may simply reflect a portion of an annual cycle, but this cannot be confirmed with the available data.

Daily mean water temperature and specific conductance for the period January 29, 1976, through March 18, 1977, also are shown in figure 9. Temperature measurements beginning April 5 indicate a slight warming (about 1°C) of the water through the middle of May. Immediately

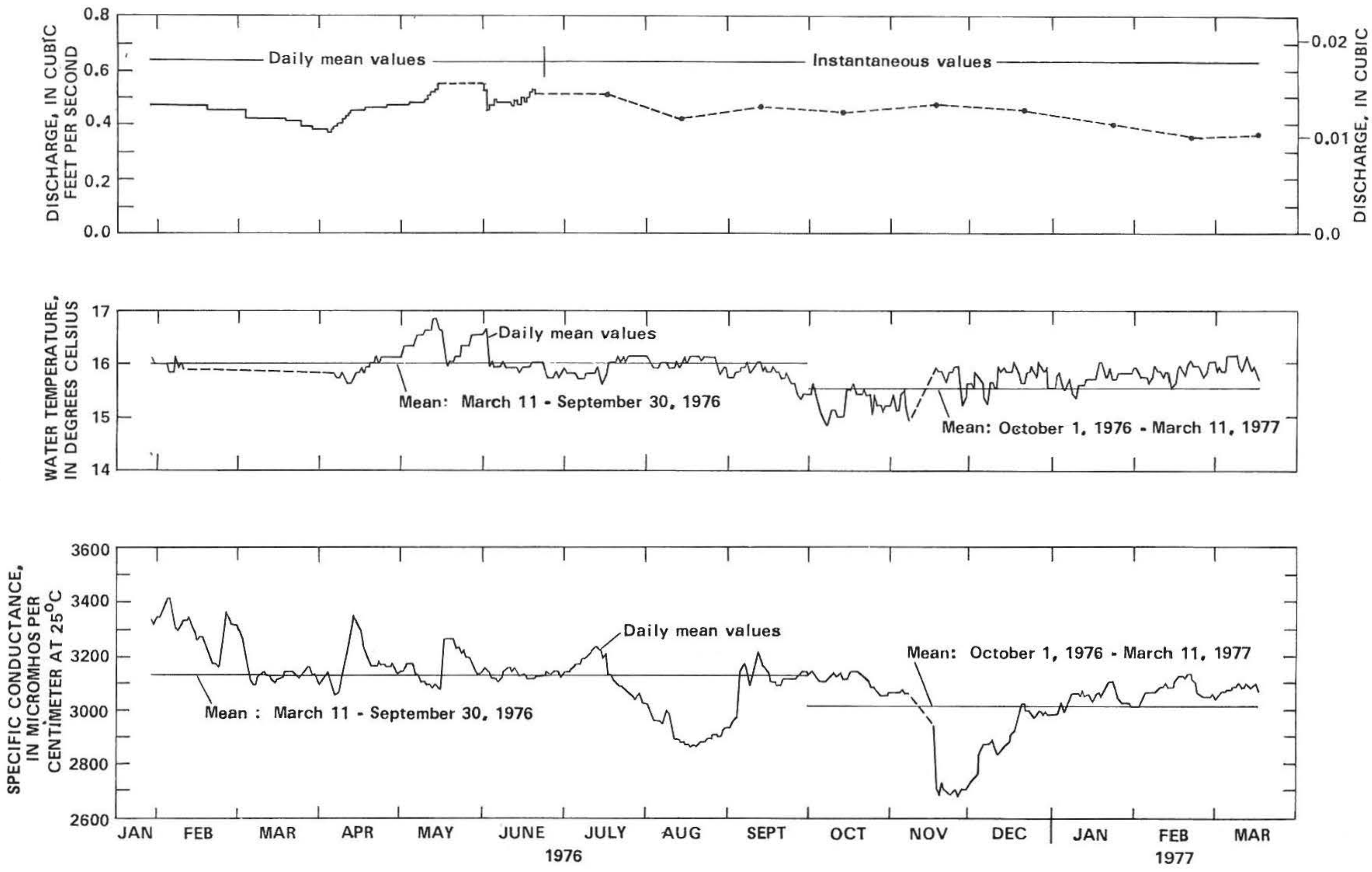

Figure 9.--Variation of discharge, water temperature, and specific conductance in the Argo Tunnel drainage, January 29, 1976, through March 18, 1977.

thereafter, a rather sharp temperature decrease occurred. This decrease corresponds nicely with a specific-conductance increase. Unfortunately, it was about this time that vandals blocked the throat of the flume and caused considerable ponding of the water in the vicinity of the water-temperature and specific-conductance sensors. As this ponded water would be reached by direct solar radiation during most of the day, this could account for the second temperature peak toward the end of May. Also, because of the mixing induced by ponding of the water, any specific-conductance peak that might have occurred probably would be considerably reduced. Therefore, interpretation of water quality in relation to the hydrology of the system during this period should be approached with caution. Following removal of the plank at the end of May, the temperature recovered to about 16°C and remained fairly constant through the middle of September.

An apparent drop in water temperature to between 15° and 15.5°C occurred during October 1976 (fig. 9). This is not readily explained, except perhaps as an artifact related to the monitor batteries going dead on November 7. After the batteries were replaced on November 17, the temperature record varied on either side of 16°C through March 18, 1977. Mean water temperatures (to the nearest 0.5°C) are seen to be 16.0°C for the period January 29 through September 30, 1976, and 15.5°C for the period October 1, 1976, through March 18, 1977 (fig. 9). The mean temperature for the latter period also would be 16.0°C if the record for October 1976 were disregarded. These means correspond nicely to the instantaneous water temperatures measured during monthly visits to the Argo Tunnel (table 7, p. 32).

Temperature of the Argo Tunnel drainage appears to be controlled by the temperature of the earth at the level of the tunnel. The mean annual air temperature above the tunnel for the period 1973 through 1976 is estimated to be 3.9°C from data given by the U.S. Environmental Data Service (1973-76). Average depth of the tunnel below land surface is about 1,200 ft (370 m). The geothermal gradient in a well 20 mi (32 km) east of the tunnel has been measured at 0.92°C per 100 ft (3.0°C/100 m) of depth. Thus, the calculated earth's temperature at the tunnel level is 15°C or very close to the observed mean water temperature of 16°C.

Interpretation of the specific-conductance data generally involves isolation of three apparent components (see fig. 9). These are (1) the overall trend, upon which are superimposed (2) many smaller peaks of 5- to 10-days' duration, and (3) several larger peaks of 15- to 20-days' duration.

The overall trend shows a decrease in specific conductance from about 3,400 micromhos per centimeter at 25°C at the end of January 1976 to about 3,100 micromhos in early March. Specific conductance remained fairly constant through the middle of July, decreased to approximately 2,900 micromhos by mid-August, returned to about 3,100 micromhos by mid-September, and remained at this level through October. An abrupt decrease in specific conductance to about 2,700 micromhos occurred during the latter half of November 1976; gradual recovery back to the

3,100-micromho level extended into early 1977. Neither the decrease at the beginning of the period of record nor the minimums in August or November are associated with obvious discharge or water-temperature changes.

An analysis of the differences between specific conductances measured by the monitor and those measured by a calibrated portable field meter indicates a standard deviation of less than 4 percent for the continuous record. Thus the second component--the smaller peaks of 5- to 10-days' duration--are considered part of the background noise and can be disregarded.

At least five larger peaks of 15- to 20-days' duration, the third component, must be considered real. These occurred during late February and early March, the middle of April, the last half of May, the first half of July, and the first half of September (fig. 9). One of these peaks, the one occurring during the latter half of May, has been discussed previously as possibly being associated with artificially ponded water behind the flume (see p. 30). No ready explanation exists for the other four peaks: for example, they do not correlate with precipitation measured at Georgetown, about 10 mi (16 km) west of Idaho Springs. It is somewhat unusual, however, that all the large peaks are of about the same magnitude (150 to 225 micromhos), and the first four peaks are separated by a regular interval of about 1½ months.

Toward the end of the period of record, the above three-component description of the specific-conductance data seems to break down. The peaks in February and March 1977 are somewhat longer in duration (20 to 25 days) and lower in amplitude (50 to 100 micromhos), the latter being within what is considered to be background noise.

Mean specific conductances for the periods January 29 through September 30, 1976, and October 1, 1976, through March 18, 1977, are 3,130 and 3,010 micromhos, respectively (fig. 9)--the value for the latter period being lower because of the relatively large effect of the November 1976 minimum. There is no strong evidence for a time trend within the instantaneous specific-conductance values shown in table 7. The mean of the values in table 7 is 3,100 micromhos.

Chemical Quality

Water was collected from the Argo Tunnel drainage for detailed chemical analyses at approximate monthly intervals from March 11, 1976, through March 18, 1977. The analyses are listed in table 7. In order to estimate the precision of the trace-element data given in table 7, six replicate water samples were collected from the Argo Tunnel drainage on January 24, 1977. The mean, standard deviation, and range for dissolved (0.45-μm membrane-filtered) and total fractions of selected trace elements are presented in table 8. The statistics reflect both analytical and sampling errors, and account for the fact that dissolved concentrations in table 7 sometimes slightly exceed total concentrations for a given trace element on a given date.

TABLE 7.--*Physical and chemical data for the Argo Tunnel drainage, March 11, 1976, through March 18, 1977*

DATE	TIME	INSTANTANEOUS DISCHARGE (CFS)	TEMPERATURE (DEG C)	SPECIFIC CONDUCTANCE (MICROMHOS)	DISSOLVED SOLIDS (SUM OF CONSTITUENTS) (MG/L)	DISSOLVED OXYGEN (MG/L)	PH (UNITS)	TOTAL ACIDITY AS H+ (MG/L)	DISSOLVED CALCIUM (CA) (MG/L)	DISSOLVED MAGNESIUM (MG) (MG/L)
MAR , 1976										
11...	1200	.42	16.0	3130	2890	1.6	2.9	14	350	120
APR										
13...	1500	.45	16.0	3280	2830	1.4	2.9	14	330	110
MAY										
17...	1415	.55	16.0	3080	--	1.4	2.9	16	350	120
JUN										
02...	1515	.53	16.0	3140	--	1.4	2.9	--	350	120
16...	1130	.50	16.0	3140	2920	1.4	2.9	15	320	120
JUL										
17...	1530	.51	16.0	3140	3040	1.4	2.9	--	320	110
AUG										
13...	1130	.42	16.0	2870	2760	1.7	3.0	14	340	120
SEP										
13...	1355	.46	16.0	3130	2740	1.9	2.9	14	320	120
OCT										
14...	1400	.44	16.0	3130	2750	1.5	3.0	16	330	120
NOV										
17...	1130	.47	16.0	3070	3110	1.4	2.9	--	320	110
DEC										
21...	1330	.45	16.0	3020	--	1.5	3.0	15	320	110
JAN , 1977										
24...	1200	.40	16.0	3050	2830	1.6	3.0	14	330	110
FEB										
22...	1300	.35	16.0	3120	2830	1.3	3.1	14	330	120
MAR										
18...	1400	.36	16.0	3060	2710	1.5	3.1	14	330	110

TABLE 7.--*Physical and chemical data for the Argo Tunnel drainage, March 11, 1976, through March 18, 1977*--CONTINUED

DATE	DIS-SOLVED SODIUM (NA) (MG/L)	DIS-SOLVED PO-TAS-SIUM (K) (MG/L)	BICAR-BONATE (HCO3) (MG/L)	CAR-BONATE (CO3) (MG/L)	DIS-SOLVED CHLO-RIDE (CL) (MG/L)	DIS-SOLVED FLUO-RIDE (F) (MG/L)	DIS-SOLVED SULFATE (SO4) (MG/L)	DIS-SOLVED SILICA (SIO2) (MG/L)	DIS-SOL-VED ORGANIC CARBON (C) (MG/L)	DIS-SOLVED NITRITE PLUS NITRATE (N) (MG/L)
MAR , 1976 11...	22	3.5	0	0	2.3	2.9	2000	38	.7	.01
APR 13...	22	3.7	0	0	2.7	2.6	2000	39	1.4	.00
MAY 17...	18	2.6	0	0	--	--	--	--	--	--
JUN 02...	18	2.3	--	--	2.7	4.0	1900	43	--	--
16...	19	2.5	0	0	2.9	3.5	2100	45	--	.00
JUL 17...	22	3.4	0	0	2.9	2.7	2200	38	1.0	.01
AUG 13...	21	3.4	0	0	2.8	2.6	1900	41	.0	.00
SEP 13...	22	3.5	0	0	2.5	2.8	1900	43	.6	.04
OCT 14...	21	3.4	0	0	2.7	2.7	1900	40	.6	.00
NOV 17...	22	3.4	0	0	2.6	2.8	2300	40	.8	.22
DEC 21...	22	3.2	0	0	--	2.5	2000	38	.8	.00
JAN , 1977 24...	21	2.8	0	0	2.8	2.3	2000	36	--	.01
FEB 22...	22	3.4	0	0	2.8	2.3	2000	37	3.2	.01
MAR 18...	23	3.5	0	0	3.1	2.2	1900	40	.9	.00

TABLE 7.--*Physical and chemical data for the Argo Tunnel drainage, March 11, 1976, through March 18, 1977*--CONTINUED

DATE	DIS-SOLVED ANTI-MONY (SB) (UG/L)	TOTAL ANTI-MONY (SB) (UG/L)	DIS-SOLVED ARSENIC (AS) (UG/L)	TOTAL ARSENIC (AS) (UG/L)	DIS-SOLVED BARIUM (BA) (UG/L)	TOTAL BARIUM (BA) (UG/L)	DIS-SOLVED CAD-MIUM (CD) (UG/L)	TOTAL CAD-MIUM (CD) (UG/L)	DIS-SOLVED CHRO-MIUM (CR) (UG/L)	TOTAL CHRO-MIUM (CR) (UG/L)
MAR , 1976										
11...	2	2	120	180	0	0	160	170	0	0
APR										
13...	1	1	140	140	0	200	170	170	20	30
MAY										
17...	0	1	130	150	0	0	140	140	0	20
JUN										
02...	0	1	130	130	0	0	150	160	5	20
16...	0	0	140	140	0	0	--	--	0	20
JUL										
17...	2	2	--	110	0	0	160	150	20	10
AUG										
13...	0	2	100	100	0	0	160	150	10	20
SEP										
13...	0	0	150	150	0	100	--	150	20	20
OCT										
14...	2	2	150	150	0	0	150	170	10	20
NOV										
17...	2	2	100	100	0	0	--	140	10	10
DEC										
21...	0	0	160	160	0	0	150	140	0	10
JAN , 1977										
24...	0	0	130	130	0	0	150	140	0	20
FEB										
22...	0	0	120	130	0	0	140	140	20	20
MAR										
18...	0	0	120	120	0	0	130	140	10	10

TABLE 7.--*Physical and chemical data for the Argo Tunnel drainage, March 11, 1976, through March 18, 1977*--CONTINUED

DATE	DIS-SOLVED COPPER (CU) (UG/L)	TOTAL COPPER (CU) (UG/L)	DIS-SOLVED IRON (FE) (UG/L)	TOTAL IRON (FE) (UG/L)	DIS-SOLVED LEAD (PB) (UG/L)	TOTAL LEAD (PB) (UG/L)	DIS-SOLVED LITHIUM (LI) (UG/L)	TOTAL LITHIUM (LI) (UG/L)	DIS-SOLVED MAN-GANESE (MN) (UG/L)	TOTAL MAN-GANESE (MN) (UG/L)
MAR , 1976										
11...	4300	5600	170000	170000	34	100	40	40	110000	110000
APR										
13...	5500	5400	130000	180000	32	<100	40	50	120000	110000
MAY										
17...	6000	6200	170000	190000	24	<100	40	40	85000	93000
JUN										
02...	6200	6200	160000	--	30	<100	40	40	89000	89000
16...	6400	6500	190000	200000	40	<100	40	30	90000	80000
JUL										
17...	6200	6200	170000	170000	36	160	40	50	97000	96000
AUG										
13...	5600	5800	180000	180000	29	120	40	40	89000	97000
SEP										
13...	5600	5500	160000	190000	29	200	40	40	97000	98000
OCT										
14...	5700	5800	170000	190000	37	100	40	40	90000	93000
NOV										
17...	6100	5800	170000	170000	15	100	40	40	89000	90000
DEC										
21...	5400	6600	170000	180000	28	<100	40	40	85000	90000
JAN , 1977										
24...	5300	5100	170000	170000	27	100	40	40	88000	91000
FEB										
22...	5000	5200	160000	160000	25	100	40	40	92000	95000
MAR										
18...	5300	5000	160000	180000	24	100	40	40	82000	90000

TABLE 7.--*Physical and chemical data for the Argo Tunnel drainage, March 11, 1976, through March 18, 1977*--CONTINUED

DATE	DIS-SOLVED MERCURY (HG) (UG/L)	TOTAL MERCURY (HG) (UG/L)	DIS-SOLVED MOLYB-DENUM (MO) (UG/L)	TOTAL MOLYB-DENUM (MO) (UG/L)	DIS-SOLVED SELE-NIUM (SE) (UG/L)	TOTAL SELE-NIUM (SE) (UG/L)	DIS-SOLVED SILVER (AG) (UG/L)	TOTAL SILVER (AG) (UG/L)	DIS-SOLVED ZINC (ZN) (UG/L)	TOTAL ZINC (ZN) (UG/L)
MAR , 1976										
11...	.0	.0	2	2	0	0	0	10	49000	49000
APR										
13...	.0	.0	0	0	0	0	0	10	50000	49000
MAY										
17...	.1	.1	0	0	0	0	0	<10	43000	43000
JUN										
02...	.0	.1	0	0	0	0	0	<10	41000	41000
16...	.2	.2	0	0	0	0	0	<10	--	40000
JUL										
17...	.0	.0	1	2	0	0	0	30	45000	45000
AUG										
13...	.0	.0	2	2	0	0	0	60	44000	47000
SEP										
13...	.0	.0	0	1	0	0	0	10	45000	45000
OCT										
14...	.0	.0	0	0	0	0	0	<10	46000	45000
NOV										
17...	.0	.0	0	0	0	0	0	<10	43000	44000
DEC										
21...	.0	.0	1	0	0	0	0	30	46000	46000
JAN , 1977										
24...	.0	.1	0	0	0	0	0	<10	44000	44000
FEB										
22...	.0	.0	0	0	0	0	0	<10	42000	43000
MAR										
18...	.0	.0	0	0	0	0	0	<10	40000	42000

Table 8.--*Precision of selected trace-element concentrations in the Argo Tunnel drainage, January 24, 1977*

Trace element and fraction	Statistics[1]			
	Mean ($\bar{X}$)	Standard deviation(s)		Range
	µg/L	µg/L	Percentage of $\bar{X}$	µg/L
Dissolved arsenic--	130	4.1	3.2	120-130
Total arsenic------	140	12	8.6	130-160
Dissolved cadmium--	150	0	0	150
Total cadmium------	140	4.1	2.9	140-150
Dissolved copper---	5,200	120	2.3	5,000-5,300
Total copper-------	5,200	140	2.7	5,000-5,400
Total iron[2]--------	170,000	0	0	170,000
Dissolved lead-----	29	3.4	12	25-35
Total lead---------	100	0	0	100
Total manganese[2]---	91,000	1,600	1.8	89,000-93,000
Dissolved zinc-----	44,000	550	1.3	43,000-44,000
Total zinc---------	44,000	410	.93	43,000-44,000

[1] All statistics were determined from 6 replicates and reflect both analytical errors and sampling errors.

[2] Dissolved iron and manganese were not determined on replicate samples. However, because the iron was 100-percent dissolved and the manganese was 97-percent dissolved on January 24, 1977 (calculated from data given in table 7), the statistics for the dissolved fractions are presumed to be very similar to the statistics for the total fractions.

Concentrations of dissolved and total antimony, barium, chromium, lithium, mercury, molybdenum, and selenium are relatively constant at very low values and will not be discussed further. Arsenic, cadmium, copper, iron, lead, manganese, and zinc, on the other hand, all occur at high concentrations. Except for lead in general, arsenic and copper in March 1976, and iron in April 1976, these trace elements are mostly dissolved (82 percent or greater). Lead occurs predominantly in the suspended phase (15 to greater than 40 percent dissolved), and silver, when present, appears to be entirely suspended.

Dissolved concentrations of arsenic, cadmium, copper, iron, lead, manganese, and zinc are plotted in figure 10. Analysis of these data indicates little variation in the concentrations of dissolved arsenic, cadmium, or iron for the period of record. Dissolved lead is somewhat more variable; but a definite pattern is not discernible, and the variations probably are related to the somewhat poorer precision reported for this constituent (table 8). The concentration of dissolved copper increased from a minimum of 4,300 µg/L in March 1976 to a maximum of

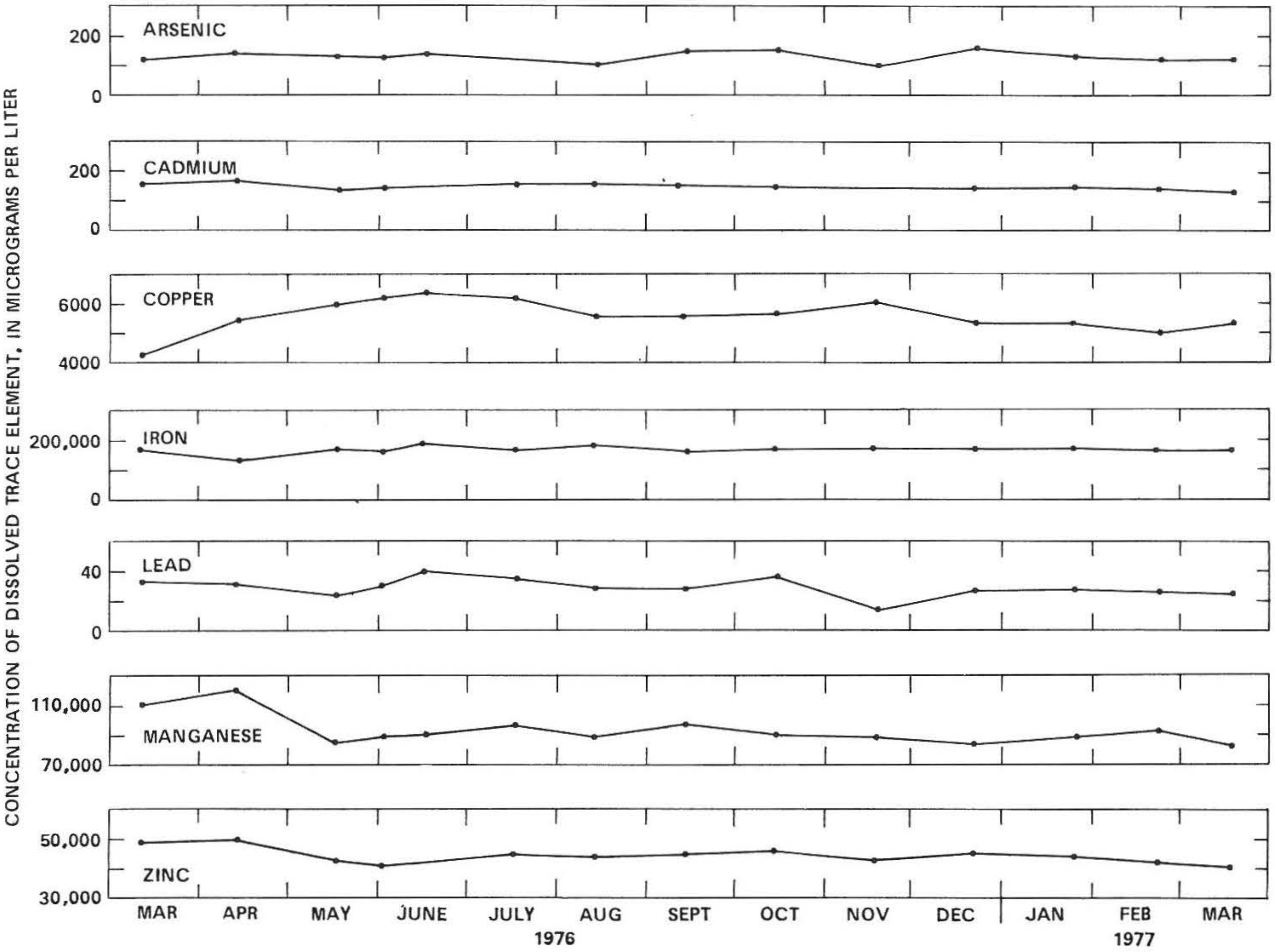

Figure 10.--Variation of dissolved arsenic, cadmium, copper, iron, lead, manganese, and zinc in the Argo Tunnel drainage, March 11, 1976, through March 18, 1977.

6,400 µg/L in June and generally has decreased gradually since that time. Dissolved manganese and zinc were high during March and April 1976, decreased by the middle of May, and have varied relatively little since then. Reasons for the observed changes in copper, manganese, and zinc are not obvious.

Controls on Chemical Quality

A comparison of the data presented in figure 10 with that shown in figure 8 indicates a general decrease by one-half or more in the concentrations of dissolved cadmium, copper, iron, lead, manganese, and zinc since May 1973. As a matter of fact, except for lead, current (1976-77) levels of these trace elements are very similar to those concentrations reported for January 1973 by Moran and Wentz (1974). The data in figure 8 show that a major chemical flushing event occurred between January and May 1973. Additional data presented by Wildeman (1976, p. 57, fig. 4) indicate that a similar event of considerably lesser magnitude occurred in the spring of 1974, but that little or no chemical flush occurred in the spring of 1975. A 1976 spring flush also is not indicated by the data presented in figure 10.

Because of the similarities between the data for January 1973 and current (1976-77) data, these trace-element concentrations are considered to be indicative of baseline conditions--conditions that might be expected to obtain over the long term--in the Argo Tunnel drainage. The baseline conditions, so defined, are presented in table 9. A baseline value for pH has not been determined because a Kendall's Tau test (Conover, 1971) indicates a 95-percent probability of an increasing trend for the period March 11, 1976, through March 18, 1977. Extrapolation of recovery times following the May 1973 chemical flush indicates that baseline conditions would have been reached by the summer of 1974, a period longer than 1 year, if another chemical flush had not occurred that spring. This also would imply that a significant spring flush (similar to that of 1973) did not occur in 1972, as baseline conditions would not have been reached by January 1973 (see table 9).

The following model is presented as a possible explanation of the factors controlling water quality of the Argo Tunnel drainage. Evidence indicates that prior to driving the tunnel, the altitude of the regional ground-water table in the immediate vicinity of the tunnel was considerably higher than at present (see quotes by Lakes, 1900, p. 22, this report.) That the tunnel acted as an effective drain suggests good hydraulic connection to the surface. This connnection is in the form of fractures,which usually occur more frequently near and in mineral veins. In support of this, Lakes (1900) noted that "The approach to a vein in the tunnel is generally heralded by a copious supply of water pouring in." Continuous flow from the tunnel, since its completion, points to at least a small flow component from the ground-water reservoir. All this leads to the conceptualization in figure 11, showing a hypothesized lowering of the ground-water table in the vicinity of the Argo Tunnel after its construction.

Table 9.--*Baseline concentrations of selected trace elements in the Argo Tunnel drainage*

Trace element and fraction	Number of analyses	Mean ($\bar{X}$)[1] (µg/L)	Standard deviation(s)[1] (µg/L)	Range (µg/L)	January 24, 1973[2]
Dissolved arsenic	13	130	18	100-160	-------
Total arsenic	14	140	23	100-180	-------
Dissolved cadmium	11	150	11	130-170	140
Total cadmium	13	150	13	140-170	160
Dissolved copper	14	5,600	560	4,300-6,400	4,800
Total copper	14	5,800	510	5,000-6,600	4,900
Dissolved iron	14	170,000	13,000	130,000-190,000	140,000
Total iron	13	180,000	11,000	160,000-200,000	140,000
Dissolved lead	14	29	6.4	15-40	30
Total lead	14	100	41	<100-200	100
Dissolved manganese	14	93,000	10,000	82,000-120,000	94,000
Total manganese	14	94,000	7,900	80,000-110,000	95,000
Dissolved zinc	13	44,000	2,900	40,000-50,000	45,000
Total zinc	14	44,000	2,700	40,000-49,000	45,000

[1] The mean and standard deviation are presented because of the lack of strong evidence for long-term time trends in this data.

[2] Moran and Wentz, 1974, p. 213.

Figure 12 shows the relation of the Argo Tunnel to the land surface and ore zonation (see discussion of ore zonation on p. 20, 22). The greater permeability (as measured by numbers of fractures and veins intersected by a given length of the tunnel) in the central and intermediate ore zones, in combination with the topographic depression above the central ore zone, provides evidence for potentially greater recharge in this area. This thesis is supported by the observations of Wildeman, Cain, and Ramiriz (1974), who noted that the quality of the Argo Tunnel drainage is more similar to that of the Quartz Hill Tunnel, which drains only the central ore zone, than to the quality of drainages from the intermediate or peripheral ore zones. Thus, most of the baseline drainage from the Argo Tunnel appears to have been recharged in the vicinity of the central ore zone. Most of this water probably is supplied by spring snowmelt, as Hurr and Richards (1974) have shown that less than 10 percent of the annual ground-water recharge in the vicinity of the Straight Creek Tunnel (22 mi or 35 km to the west) results from summer and fall precipitation. Most of the annual recharge to the Straight Creek Tunnel, where the altitude is greater than 11,200 ft (3,410 m), occurs from mid-May to early July (Hurr and Richards, 1974). Recharge to the Argo Tunnel would be expected somewhat earlier in the year.

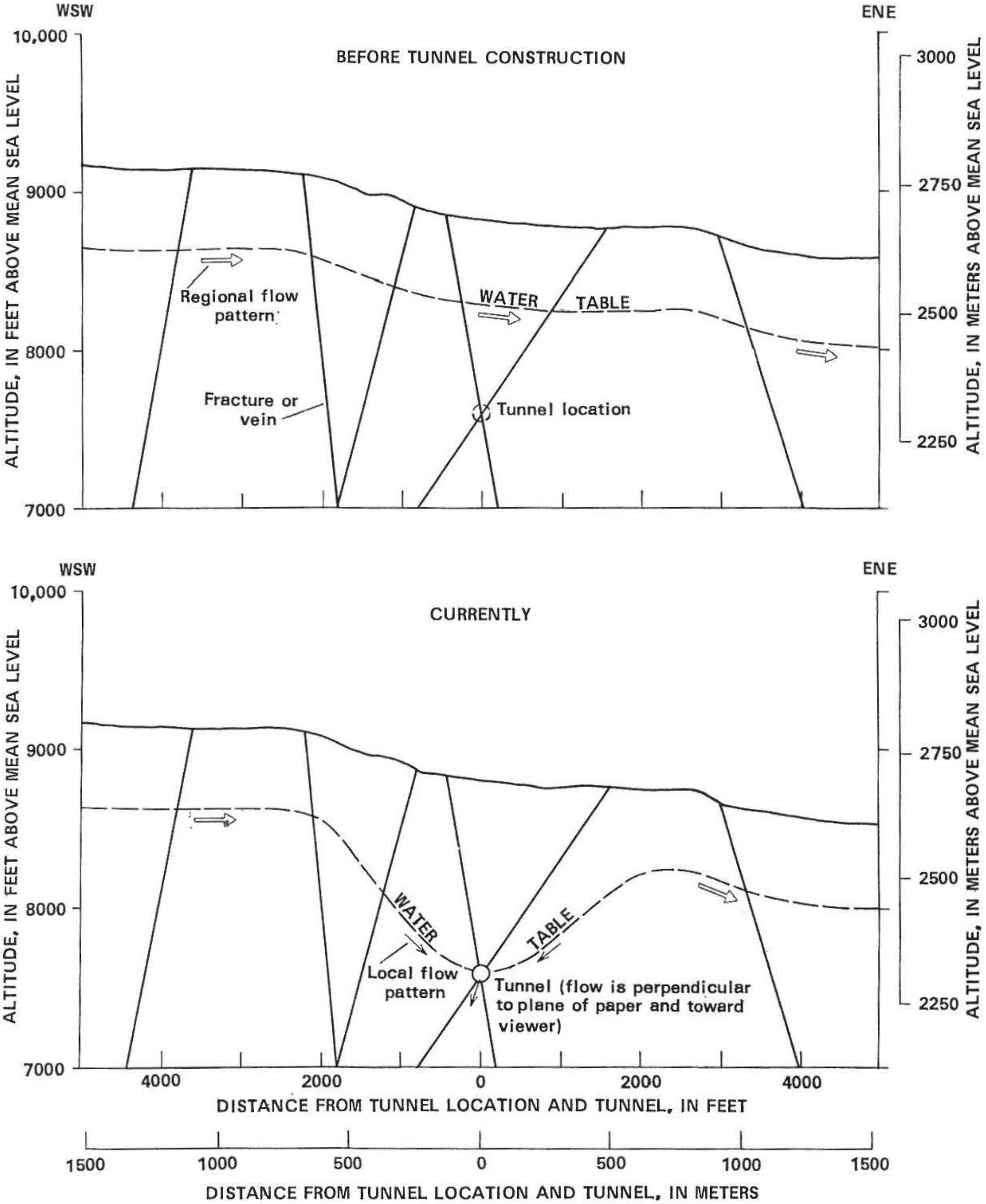

Figure 11.--Hypothesized effect of the Argo Tunnel on ground-water flow. (Location of water table, fractures, and veins is arbitrary. Cross section is perpendicular to the tunnel at the point it passes beneath Russell Gulch, See figure 7.)

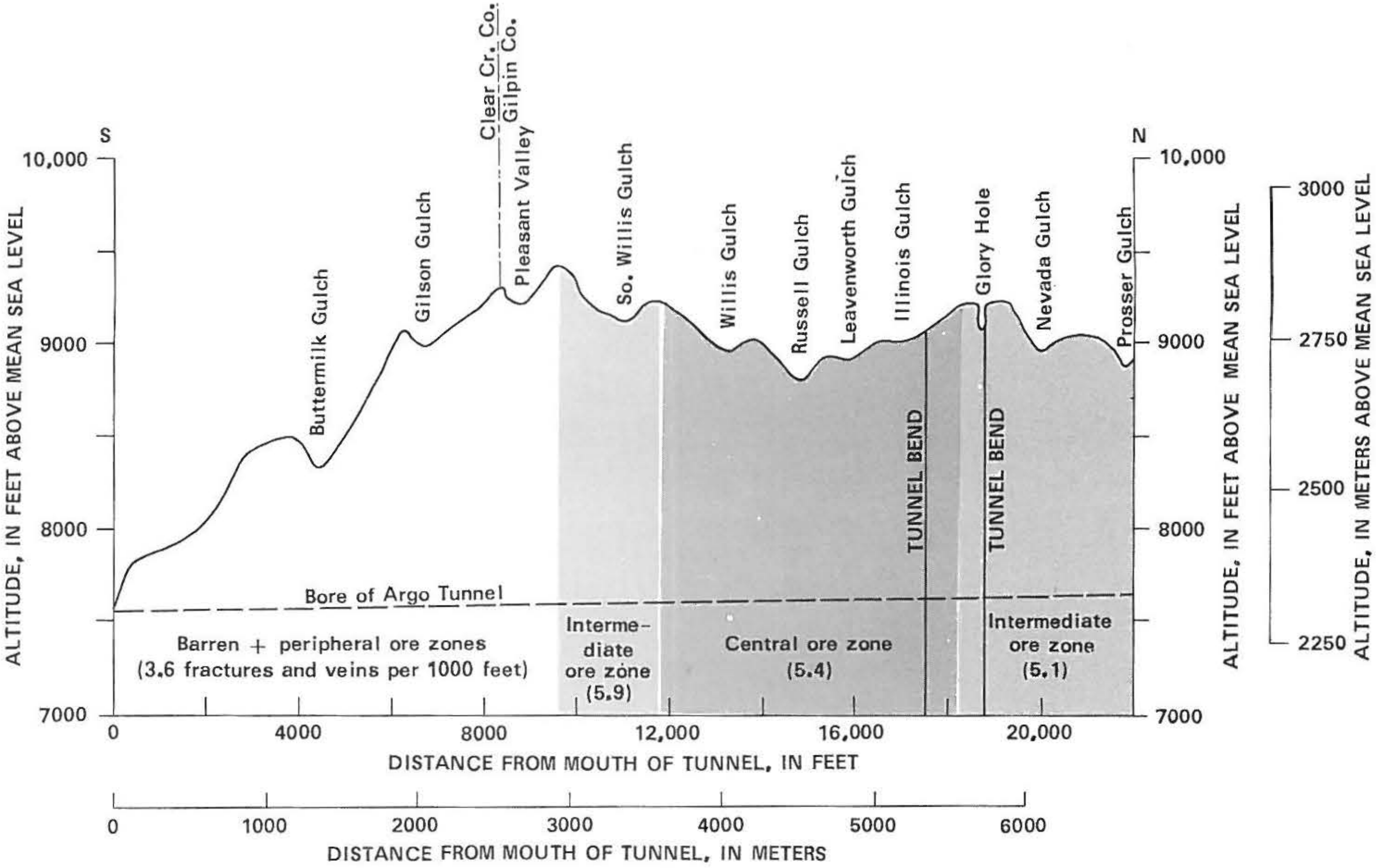

Figure 12.--Relation of Argo Tunnel bore to altitude of land surface and to ore zonation (compiled from data provided by U.S. Bureau of Mines, unpublished data, July 1977, and presented in Bastin and Hill, 1917, plate XXI, Lovering and Goddard, 1950, plate 16, and Sims and others, 1963, fig. 11, p. 39).

The U.S. Geological Survey operates two gaging stations in the Clear Creek watershed that are of some interest here. The gage near Lawson (06716500, fig. 7) reflects a greater proportion of high altitude runoff than the gage near Golden (06719500; this gage was in operation prior to October 1974) or the gage at Golden (06719505; this gage has been in operation since October 1974) (fig. 7). By subtracting the discharge recorded near Lawson from that recorded near or at Golden, an estimate of the runoff from the lower altitudes (including the area drained by the Argo Tunnel) can be obtained. Monthly mean discharges so computed for the period January 1973 through February 1974 are shown in figure 13. The large discharge in May 1973 corresponds nicely with the high trace-element concentrations in the Argo Tunnel drainage reported for the month (fig. 8). May discharges for the lower altitude basin for the period 1972 through 1976 are given below, along with the relative magnitude of the spring chemical flush from the Argo Tunnel. The intensity of the May discharge for the lower altitude basin thus appears to be a good indicator of spring chemical flushes from the Argo Tunnel.

Year	May discharge, Clear Creek near or at Golden, minus Clear Creek near Lawson, in cubic feet per second	Relative magnitude of spring chemical flush from the Argo Tunnel
1972-----	73	None.[1]
1973-----	498	Major.[2]
1974-----	206	Lesser.[2]
1975-----	45	Little or none.[2]
1976-----	28	None.[2]

[1] Postulated; see p. 39, this report.
[2] Documented; see p. 39, this report.

One way of explaining this would be to require the flow emanating from the tunnel during a chemical flush to have two components. The first would be the component from the ground-water reservoir mentioned on p. 39. The second component is postulated as coming rather directly to the tunnel from the unsaturated zone immediately above the tunnel, particularly in the central ore zone. This latter component would be a small portion of the infiltration resulting from snowmelt in the spring of the year. (The other portion would recharge the ground-water reservoir.) Water traveling down the ore veins would be in intimate contact with sulfide mineralization (including pyrite) and oxygen, the two ingredients necessary for producing acid and high trace-element concentrations (reactions 1 and 2, p. 8, 9). The unsaturated zone component would likely flush water that previously had been held in contact with sulfide mineralization in small faults, voids, and intergranular spaces by surface tension. This capillary water would have had considerable contact time with the mineralization and atmospheric oxygen, and the water likely would be extremely acid and

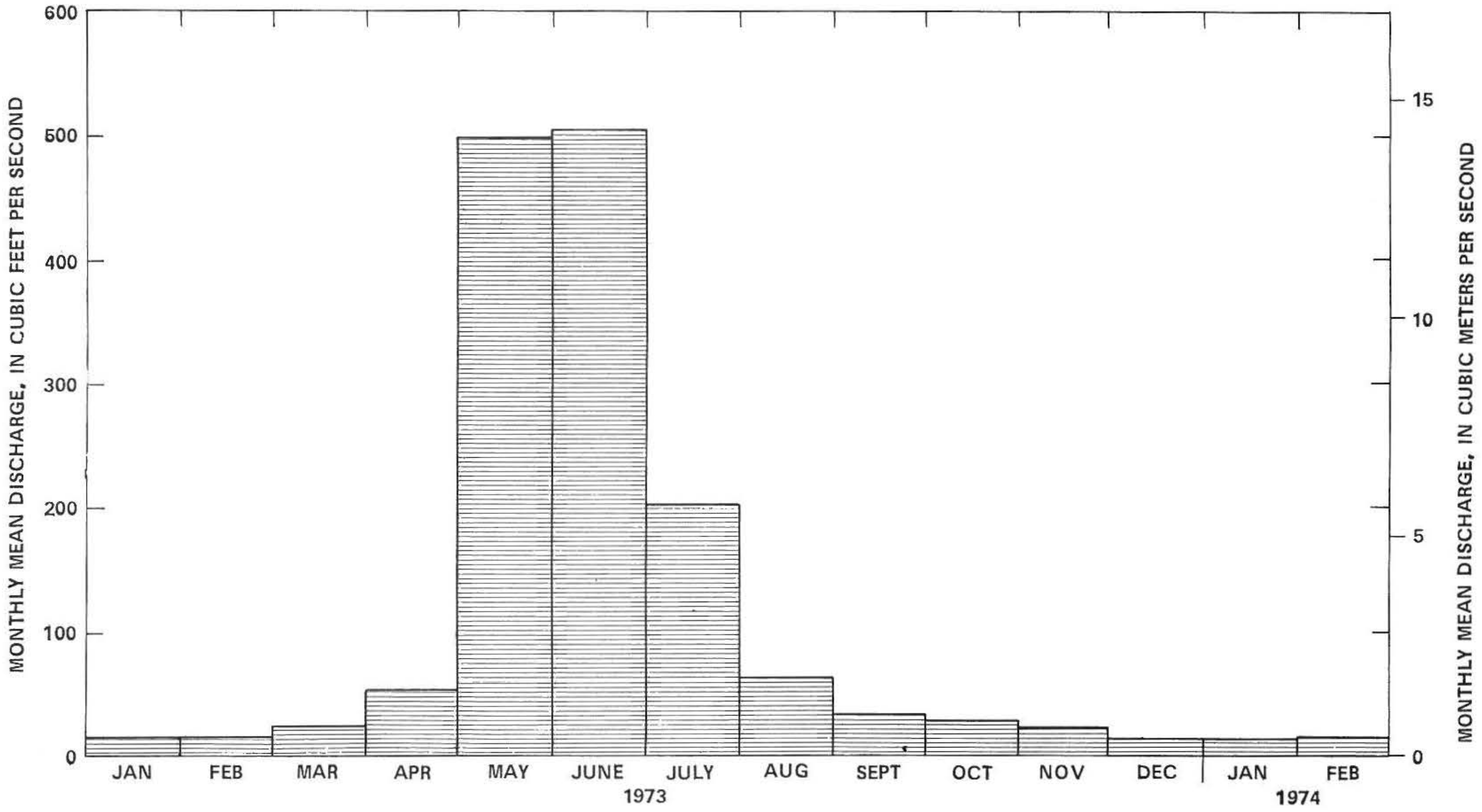

Figure 13.--Discharge for Clear Creek near or at Golden, minus Clear Creek near Lawson, January 1973 through February 1974.

high in trace elements. A small amount of this water thus could have a large effect on the quality of the tunnel drainage, and concentrations of acid and trace elements in the drainage initially could be increased significantly without appreciably increasing the tunnel discharge. The effect would fit Wildeman's (1976) diffuse-flow system model in which it appears "* * * as if the aquifer were flushing trapped water from its many small pores." (See also p. 9.) After this initial flushing, concentrations would be expected to return to baseline values.

By comparing the temporal distribution of spring runoff in Clear Creek above and below Lawson, and considering Hurr and Richards' (1974) information on the time of occurrence of recharge to the Straight Creek Tunnel, it is estimated that recharge to the Argo Tunnel starts in late April or early May. Residence time of water in the tunnel bore itself is estimated from discharge measurements to be a maximum of about 1 week during May. As the spring chemical flush is usually seen in May, this would indicate that the water residence time in the unsaturated zone above the tunnel is on the order of a few weeks to a month.

Long-term changes in the chemical quality of the Argo Tunnel drainage can be estimated by comparing current data with a chemical analysis published by Ripley, Gorden, Freeland, and Finigan (1906). Little information is given regarding the collection and preservation of the 1906 sample, but it is inferred that the sample was unfiltered and unpreserved. The water was collected from the tunnel portal when the tunnel had been driven to a length of about 15,000 ft (4,600 m), or to about the center of the central ore zone discussed by Sims, Drake, and Tooker (1963) (see also figs. 7 and 12). The 1906 analysis is presented in table 10, along with mean 1976-77 data for comparable constituents. The 1906 figures have been recalculated so that they can be compared directly to the current data.

The ratios of mean 1976-77 concentrations to 1906 concentrations show how various constituents have changed over the 70 years that the tunnel has been in existence. These ratios must be considered minimum values, because the 1906 sample is thought to have been unfiltered. This is especially true in the case of iron. The 1906 value for dissolved iron probably would be considerably lower than that listed in the table after correcting for the aluminum included in the analysis and after considering that most of the iron would be expected to be suspended at a neutral pH.

Perhaps the most interesting information contained in table 10 is the large observed decrease in silica since 1906. The larger 1906 concentration might be explained by increased silica solubility resulting from mechanical disturbances associated with driving the tunnel and with the increased silica solubility expected at somewhat greater than neutral pH's. Or, it might simply have resulted from inclusion of a large amount of suspended silica in the water sample. The large decrease in pH and increases in sulfate and iron since 1906 are not unexpected in view of reaction 3, p. 25. In fact, these changes support the theory of acid production after exposure of pyrite to oxidizing conditions upon lowering of the ground-water table in the vicinity of the tunnel. Increased solids, including calcium and magnesium, are to be expected in the more acid-weathering environment thus produced. The only apparent enigma in table 10 is the observed decrease in chloride. This might be a true decrease, resulting, for example, from precipitation of chloride by silver released in the process of sulfide ore dissolution. Or, it might be related to analytical errors inherent in the determination of chloride at low concentrations around the turn of the century.

Table 10.--*Comparison of current and historical chemical analyses of the Argo Tunnel drainage*

1906[1]		1976-77[2]		Ratio
Constituent	Concentration, in milligrams per liter	Constituent	Mean concentration, in milligrams per liter	$\left(\frac{\text{Mean } 1976\text{-}77}{1906}\right)$
Total solids-------	870	Dissolved solids--	2,950	3.4
Silica-------------	300	Silica------------	40	.13
Iron and aluminum--	54 (as iron)	Iron--------------	170	3.2
Calcium------------	130	Calcium-----------	330	2.5
Magnesium----------	20	Magnesium---------	120	6.0
Sulfate------------	250	Sulfate-----------	2,000	8.0
Chloride-----------	4.1	Chloride----------	2.7	.6
Acidity------------	neutral	pH (standard units)----------	2.9[3]	----

[1] One analysis published by Ripley, Gorden, Freeland, and Finigan (1906); sample is inferred to have been unfiltered.

[2] Means of data presented in table 7; all constituents are dissolved.

[3] Median value.

An attempt has been made to estimate trace-element concentrations from field measurements of pH and specific conductance in the Argo Tunnel drainage through the use of linear, bivariate regression equations. [See Duncan (1965) or any general statistics text for an explanation of the technique.] Results based on 16 water analyses--January 24 and June 28, 1973 (Moran and Wentz, 1974), and March 11, 1976, through March 18, 1977 (table 7)--have not been very encouraging.

Lack of success can be attributed partially to the limited ranges of both dependent and independent variables. The pH range, for example, is 2.6 to 3.1. Specific conductance varies from 2,870 to 3,400 micromhos; but, if these two extremes are removed, the range of the 14 remaining measurements decreases to 3,020 to 3,280 micromhos. The minor variations in the dependent variables through March 18, 1977, are exhibited in figure 10. Because the total range of the daily mean specific conductances recorded during the period January 29, 1976, through March 18, 1977 (2,680 to 3,410 micromhos), is not very different from the range for collected samples, little additional information would be gained even if trace-element concentrations could be estimated as accurately as they can be measured. In order for the usefulness of estimation of trace-element concentrations from specific conductance to be adequately evaluated, data must be collected throughout a significant flushing event. This would provide a wider range of observed dependent and, hopefully, independent variables.

Effects on Downstream Water Use

Concentrations of trace elements in the Argo Tunnel drainage are not discussed in the context of compliance with drinking-water standards or other water-use criteria (table 3) because the water is not used before entering Clear Creek.[4] However, downstream water users should be aware of the potential adverse effects of the drainage on the water quality of Clear Creek. These effects are discussed by Boyles, Alley, Cain, Gladfelter, and Rising (1973), Boyles, Cain, Alley, and Klusman (1974), and Moran and Wentz (1974). The magnitudes of the effects vary with distance downstream from the tunnel, with season (and relative flows of the tunnel drainage and of Clear Creek), and, as indicated in this report, with the magnitude of any preceding spring chemical flush. In addition, heavy rains, which erode mine and mill tailings from the vicinity of the tunnel into the stream (Boyles and others, 1973), may cause additional adverse impacts.

On August 16, 1973, Boyles, Cain, Alley, and Klusman (1974) found that, in Clear Creek at a point 1.1 mi (1.8 km) downstream from the Argo Tunnel drainage, concentrations of dissolved and total copper, iron, manganese, and zinc were 2.3 to 4.3 times greater than concentrations of these trace elements in Clear Creek upstream from the drainage. The daily mean flow at the U.S. Geological Survey gage on Clear Creek near Lawson, Colo. (fig. 1)--approximately 7 mi (11 km) upstream--was 158 ft^3/s ($4.47 \, m^3/s$). Reported concentrations of copper, iron, lead, and zinc at the site below the tunnel were in excess of recently proposed Colorado standards for aquatic life, but only iron and manganese

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[4] In a recent discussion (March 18, 1977), Mr. James Maxwell, owner of much of the property surrounding the Argo Tunnel portal, indicated that he has acquired water rights to the Argo Tunnel discharge and that he plans to use the water to generate power for lighting the large mill on the property.

concentrations were greater than current national and proposed State drinking-water standards (table 3).

Moran and Wentz (1974) also have published analyses of water from sites on Clear Creek upstream and downstream from the Argo Tunnel drainage. The downstream site is the same as that sampled by Boyles, Cain, Alley, and Klusman (1974), but the upstream site is just above Virginia Canyon Creek (fig. 7). This creek also is a documented mine-drainage source (table 4 and fig. 5), but flow from this drainage generally is quite small. Samples were collected from Clear Creek on January 24 and June 28, 1973. Daily mean flows near Lawson were 30 ft^3/s (0.85 m^3/s) and 855 ft^3/s (24.2 m^3/s), respectively. In January, total copper and iron, and both dissolved and total manganese and zinc increased downstream from the Argo Tunnel (1.6 to 3.4 times, except for total iron, which increased 16 times). In June, only total copper, manganese, and zinc increased below the tunnel (1.3 to 2.0 times). The generally smaller increase in fewer trace-element concentrations during June is probably a reflection of the higher flow in Clear Creek at this time of year. Reported concentrations of cadmium, copper, iron, manganese, silver, and zinc at the site below the tunnel were in excess of recently proposed Colorado standards for aquatic life, but again only iron and manganese concentrations were greater than current national and proposed State drinking-water standards (table 3).

Approximately 2 years earlier, on December 22-23, 1971, Wentz (1974) collected samples from Clear Creek at the same downstream site sampled by Moran and Wentz (1974) and by Boyles, Cain, Alley, and Klusman (1974). The closest upstream site sampled was on Clear Creek just above Chicago Creek (fig. 7), an unaffected tributary of relatively significant flow. For comparison with previous sampling times, the daily mean discharge in Clear Creek near Lawson was 38 ft^3/s (1.1 m^3/s). Concentrations of dissolved manganese and zinc both increased significantly below the Argo Tunnel drainage (3.2 and 2.2 times, respectively). Reported concentrations of dissolved cadmium, copper, manganese, mercury, silver, and zinc at the site below the tunnel were in excess of recently proposed Colorado standards for aquatic life, but only the concentration of dissolved manganese was greater than current national and proposed State drinking-water standards (table 3). Total trace-element concentrations were not determined. The effect due to the Argo Tunnel, and related mine-drainage sources, extended downstream some 8 mi (13 km) to the confluence with North Clear Creek (fig. 4), which also is known to be adversely affected by mine drainage (table 2 and fig. 4).

Based on trace-element data published by Wentz (1974) and on stream-discharge data published by the U.S. Geological Survey (1964), North Clear Creek could be the dominant contributor of dissolved trace elements, particularly copper and iron, present in the main-stem Clear Creek below the confluence of the two streams. This probably would be especially true in regard to total trace-element contributions during high spring flows when trace-element laden chemical precipitates are scoured from the channel bottom in North Clear Creek.

"Mine-related sources of pollution including new, current and abandoned surface and underground mine runoff * * *" are considered to be nonpoint sources (U.S. Environmental Protection Agency, 1975b). Under Section 208 of Public Law 92-500, these sources shall be identified and procedures set forth to control them, to the extent possible. Such control is based on four premises (U.S. Environmental Protection Agency, 1976): (1) That any earth disturbance resulting from mining procedures alters the hydrologic environment and produces some water pollution; (2) that each mining site is unique in regard to the hydrologic conditions encountered; (3) that effective and efficient environmental protection requires a comprehensive mining and reclamation plan that is implemented throughout the mining operation; and (4) that a combination of several management and engineering techniques is required to minimize water pollution from mining operations.

The optimum control measure for minimizing water-pollution effects under a particular set of circumstances may be regarded as the best management practice for that particular situation. Herein only management alternatives will be considered. Management alternatives include all those practices that are considered to be effective, practical means of potentially reducing water-pollution effects to levels compatible with prevailing water-quality goals. The actual alternative to be employed will depend upon constraints dictated by the hydrologic system, by the physical environment (primarily accessibility), and by political and fiscal considerations. Only the hydrologic system will be considered here.

Before choosing the best management practice for a given situation, an analysis of the problem must be performed. The presumption, of course, is that a problem already exists. This may not be the case. Many mining-related water-pollution problems can be avoided by anticipating the problems to be encountered and adjusting the mining procedures accordingly.

For situations where mine drainage has been determined to be an existing problem, it is necessary to determine the specific activity causing the drainage. The type of drainage also must be established, as must the general physicochemical characteristics of the drainage. The following table shows one way of categorizing these various drainage properties.

Next, the hydrologic system must be defined. This includes characterization of such things as the source of the drainage (deep ground water versus local infiltration), water-table or potentiometric surface, infiltration characteristics, the type of aquifer system, response of the system to external precipitation events, and temporal variations in discharge and water quality of the drainage.

Finally, the best management practice must be chosen from a list of management alternatives. The management alternatives currently avail-

General categorization of mine drainage

[More than one category in each column may apply]

Activity causing drainage	Type of drainage	General physicochemical characteristics of drainage
Exploration	Adit or tunnel	Saline.
Construction	Mill tails in dammed stream channels	Turbid.
Mine operation	Mine or mill tails flushed during storm events	Acid.
Improper reclamation	Overflow of mill tailings ponds during storm events	Toxic.

able are summarized in table 11 (from Skelly and Loy, Engineers-Consultants; Penn Environmental Consultants, Inc., 1973, and Scott and Hays, 1975). Most of these are designed to attack the problem of water draining from an adit or tunnel, but many of the techniques, particularly those in the categories "water infiltration controls" and "treatment controls" are equally applicable to drainage from mine tailings. Schematic diagrams of the various techniques are published in Skelly and Loy, Engineers-Consultants; Penn Environmental Consultants, Inc. (1973) and in Scott and Hays (1975).

The management alternatives can be divided into two major groups, those that seek to prevent or control mine-drainage discharge ("at source" controls) and those that treat the drainage to an acceptable level of quality. The "at source" controls generally have been developed based on experience with coal mines in the eastern United States. Compared with treatment techniques, the "at source" controls are more feasible for abandoned underground mines, they are more permanent, and they are less expensive to maintain and operate. Several of the "at source" controls can be employed during the actual mining operation.

Treatment techniques are often quite expensive, and most of them have not been tested except in the laboratory or under pilot-plant conditions. In addition, most of these so-called solutions simply alter the form of the residual[5] to be dealt with. For example, most techniques for treating mine drainage result in the formation of a brine (see table 11). Brine disposal presents a new problem that must be

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[5] The term residual refers to any noneconomic byproduct and is preferred here to the often-used term pollutant.

Table 11.--*Management alternatives applicable to the abatement of mine drainage*

[Summarized from Skelly and Loy, Engineers-Consultants; Penn Environmental Consultants, Inc. (1973) and from Scott and Hays (1975)]

Management alternative	Problem	Solution	Remarks
	"AT SOURCE" CONTROLS		
	Controlled Mining Procedures		
Downdip mining	Mine drainage is anticipated.	Mine openings are located high in the mineral seam, and the mine is developed downdip. When the mine is abandoned, flooding is automatic; this minimizes oxidation of sulfide minerals. Hydrostatic head at sealed openings also is minimized.	Water must be pumped to the surface during active mining, thus increasing mining costs. Controlled flooding can be employed during mining. This method has been applied successfully.
Roof fracture control	-------------do-------------	Various techniques, including pillars, roof supports, limiting width of openings, and backfilling voids, are used to reduce fracturing above the active mine.	Back filling may increase mining costs significantly.
Controlled mineral extraction	-------------do-------------	Areas where pollution is less likely to occur are mined in preference to areas of high pollution potential.	Use of this technique is based on the assumption that improved technology will allow removal, in the future, of minerals from areas of high pollution potential.
Controlled atmosphere mining	-------------do-------------	Oxygen in the mine is replaced with an oxygen-free, non-combustible atmosphere to minimize sulfide mineral oxidation.	Workers must wear complex life-support systems. A more conventional abatement technique must be applied after abandonment.
Daylighting	An abandoned underground mine is a known source of mine drainage, but contains recoverable mineral resources.	The technique is the same as stripping. Overburden is removed, minerals are recovered, the area is backfilled, graded and revegetated. Mine drainage is eliminated by removing sulfide minerals.	The amount of overburden and recoverable minerals determine whether or not this is an economical approach. This method has been applied successfully.
	Water Infiltration Controls		
Subsidence sealing and grading	Fracturing or subsidence of strata overlying the mine has increased the vertical permeability to the mine.	Fill surface depressions with impermeable material and grade the surface to reduce infiltration by increasing runoff.	Concrete and clay seals seem to be effective. This method has been applied successfully.
Borehole sealing	Boreholes drilled during exploration intercept the the mine and short-circuit ground and surface waters to the mine.	Pack and seal the boreholes. Packers should be placed below aquifers overlying the mine, but above the mine roof.	Concrete and clay seals seem to be effective. This method has been applied successfully.

Table 11.--*Management alternatives applicable to the abatement of mine drainage*--Continued

Management alternative	Problem	Solution	Remarks
	"AT SOURCE" CONTROLS--Continued		
	Water Infiltration Controls--Continued		
Surface-mine regrading	A contour-stripped outcrop intercepts underground workings on the updip side, and water is short-circuited to the mine. Or, contour-stripping allows surface water to infiltrate more easily to the mineral seam and to the underground workings.	Seal all connections between the surface and underground mines. Regrade to divert surface water away from the highwall of the surface mine and revegetate.	This method has been applied successfully.
Surface sealing	The vertical permeability to an underground mine is naturally high.	Apply an impervious meterial to the surface, inject the material below the surface, or simply compact the surficial material.	The application of an impervious material to the surface imposes a serious limitation on land use. In severely fractured areas, subsurface grouting can be ineffective. Large-scale applications of subsurface sealants to control mine drainage have not been demonstrated.
Surface-water diversion	Surface cracks, subsidence areas, non-regraded surface mines, and shaft, drift, and slope openings increase infiltration to underground mines.	Ditches, trench drains, flumes, pipes, and dikes are used to divert water around or carry water over these areas.	This method has been applied successfully.
Channel reconstruction	Streams flowing across areas of vertical fractures or subsidence lose flow to underground mines through infiltration.	Reconstruct the stream channel to divert flow around the area connecting the surface to the underground workings. Line the channel with impervious material to prevent infiltration.	Concrete and clay seals seem to be effective. This method has been applied successfully.
		Mine Sealing	
Dry seals	Mine openings allow air and water inside.	The openings are sealed with impermeable materials, generally rock and earth, to retard sulfide oxidation and flushing.	Only use where there is little or no danger of hydrostatic head buildup. This technique is generally used in conjunction with air sealing. This method has been applied successfully.

Table 11.--*Management alternatives applicable to the abatement of mine drainage*--Continued

Management alternative	Problem	Solution	Remarks
"AT SOURCE" CONTROLS--Continued			
Mine Sealing--Continued			
Air Seals	-------------do-------------	An air seal at the mine discharge point allows water to come out but prevents air from getting in; thus oxidation is retarded. Earth and rock fill are placed over a discharge pipe with a trap similar to that used in sink drains.	All air passages to the mine must be located and sealed with dry seals. If this is not done, or if the overburden is porous or fractured, the mine will "breathe" with changes in barometric pressure; and the seal will be ineffective. Long-term effectiveness of this technique has not been documented.
Hydraulic seals	Mine drainage is discharging from an underground mine.	Impermeable material is placed at the discharge point, and the mine is inundated. This retards sulfide oxidation and stops the drainage.	Many types of hydraulic seals are possible. All except one completely stop discharge from the mine. (The one exception, the permeable limestone seal, initially allows the drainage to seep through; however, the porous material eventually plugs from precipitated metals and the flow ceases.) A properly designed and constructed seal will withstand a hydrostatic head in excess of 1,000 feet (300 meters). This method has been applied successfully.
Water Handling			
Interception of aquifers	Water is infiltrating into underground workings from an overlying aquifer or is flowing into the workings from an underlying aquifer.	Water is pumped from the aquifer and discharged at the surface or into another aquifer.	The techniques employed are only theoretical at this time.
Slurry trenching	Mine drainage is discharging from an underground mine.	The area around the mine opening generally is backfilled. A long, narow trench is dug around the mine opening with the top level of the trench above the discharge point. This trench is filled with a clay slurry that hardens and forms a ground-water dam. Ground water is backed up; and the mine is inundated, thus retarding oxidation of sulfides.	Bentonite clay is usually used. This method has been applied successfully.

Table 11.--*Management alternatives applicable to the abatement of mine drainage*--Continued

Management alternative	Problem	Solution	Remarks
	"AT SOURCE" CONTROLS--Continued		
	Water Handling--Continued		
Alkaline regrading	Mine drainage is discharging from an underground mine that has been intercepted by a highwall.	Unconsolidated alkaline materials are backfilled around the highwall to neutralize the mine drainage.	This technique is limited to areas where alkaline materials, such as aggregate limestone, are readily available; it can be combined with the slurry trenching technique. This method has been applied successfully.
Controlled release ponds	Discharge of mine drainage from an underground mine is highly variable.	Large holding ponds are constructed so that mine drainage can be impounded during periods when the receiving stream cannot assimilate it and released when the stream is more able to assimilate it.	This method has been applied successfully.
	TREATMENT CONTROLS		
Neutralization	The existence of an underground mine that is a known source of mine drainage is implied.	Acidity is neutralized and many metals are removed as precipitated hydroxides. The the processes of coprecipitation with or adsorption by ferric hydroxide probably contribute to metal removal.	Various neutralizing agents, including pulverized and crushed limestone, lime, and a combination of lime and limestone have been used. The process creates a sludge that must be disposed. An in-stream process for neutralizing mildly acidic waters containing low concentrations of metals has been developed.
Evaporation	-------------do-------------	Mine drainage is held in ponds until the water evaporates.	This technique is restricted to areas having high evaporation rates. The ponds must be sealed to prevent seepage to ground water or adjacent streams. Documented cases of evaporation as the sole treatment of mine drainage have not been found.

Table 11.--*Management alternatives applicable to the abatement of mine drainage*--Continued

Management alternative	Problem	Solution	Remarks
TREATMENT CONTROLS--Continued			
Distillation	-------------do-------------	Mine drainage is heated under reduced pressure to produce a vapor of relatively pure water that condenses and is withdrawn. The dissolved solids remain in the feed water and produce a brine.	Good quality water (50 mg/L dissolved solids) is produced. Expensive alloys must be used to handle the incoming mine drainage and the brines. Brine disposal presents a problem, as does scaling in the pipes handling the brines. This technique has not been used in full-scale plants.
Reverse osmosis	-------------do-------------	Mine drainage is forced through a permeable membrane under pressure. The solvent (water) passes through the membrane, but the solute (dissolved solids) remains behind forming a brine.	Good quality water (less than 70 mg/L dissolved solids) is produced, but pH is still low (4.2 to 4.4) and iron and manganese are high (400 to 1,200 µg/L and 100 to 500 µg/L, respectively). The brines present a disposal and handling problem. This technique has not been tested in full-scale plants.
Electrodialysis	-------------do-------------	Cationic and anionic components of the mine drainage migrate through selective membranes under an electric potential forming both purified water and brine.	The cation selective membranes quickly foul with ferric iron. Brine presents a handling and disposal problem. This technique has not been documented in full-scale plants.
Ion Exchange	-------------do-------------	Mine drainage is passed through successive ion exchange columns where cations are replaced by hydrogen ions and anions (primarily sulfate) are replaced by hydroxide or bicarbonate. Carbon dioxide is removed by decarbonation procedures.	Dissolved-solids concentrations of about 300 mg/L are attainable. High iron concentrations cause fouling of the exchange resin beds. Some beds are difficult to regenerate and require large volumes to do so. Disposal of the spent regenerant can be a problem. Some procedures are not applicable to acid waters. The technique has been field tested.
Freezing (crystallization)	-------------do-------------	Mine drainage is frozen. The ice is relatively pure, and most of the dissolved solids remain in the unfrozen liquid.	The technique is essentially theoretical at the present time.
Iron oxidation	-------------do-------------	Mine drainage containing high concentrations of ferrous iron are oxidized by air, ozone, or electrochemical techniques to produce ferric iron. The ferric iron is then removed by precipitation as the hydroxide.	This technique can be used in conjunction with other techniques where high iron concentrations present problems.

solved. Thus, treatment techniques often result in a residuals-management problem, whereas "at source" controls effectively reduce the total amount of residuals that are created.

In Gilpin, Clear Creek, and Park Counties, and in Colorado in general, most discharges seem to be from abandoned underground metal mines and tunnels (Wentz, 1974; table 4, this report) that probably are draining a combination of the regional ground-water reservoir and the unsaturated zone. Most of the areas are highly fractured. On the other hand, the severity of the acid and trace-element problems varies considerably depending on the source of the drainage in relation to the local mineralization pattern (Wildeman and others, 1974; Wildeman, 1976). Indeed, the quality of some Colorado mine drainages outside the study area readily conforms to current water-use standards (Wentz, 1974; D. A. Wentz, unpub. data, 1977), and presumably similar quality water could be draining from mines within the study area. Discharges from draining mines throughout Colorado range from practically zero (D. A. Wentz, unpub. data, 1977) to greater than 0.5 ft^3/s (0.01 m^3/s) (p. 28, this report). Because of the wide ranges in mine-drainage quality and quantity to be expected, each situation must be examined individually; and the alternative chosen must be tailored to solve that particular problem.

As noted on page 48, data indicate that the Argo Tunnel appears to be adversely affecting Clear Creek downstream to its confluence with North Clear Creek. Because no irrigation water or water supply is known to originate from this reach, and because the reaches both upstream and downstream have been rendered unsuitable habitats for aquatic life by other mine-drainage sources, it would be uneconomical and inefficient to abate or treat only the Argo Tunnel drainage. An integrated, comprehensive attack on the entire Clear Creek drainage basin would be necessary to attain a significant decrease in the total length of adversely affected stream reaches.

SUMMARY AND CONCLUSIONS

Those parts of Gilpin, Clear Creek, and Park Counties, Colo., lying within the confines of the Missouri River basin contain approximately 67 mi (108 km) of streams that are affected adversely by metal-mine drainage (Wentz, 1974). At least 18 drainage sources have been located in the area. Of these, 13 sources are known to contain high acidity and (or) trace-element concentrations or to contribute water to adversely affected streams (Bingham, 1966, 1967, 1968; Colorado Game, Fish and Parks Division, 1969; Moran and Wentz, 1974; Wildeman, Cain, and Ramiriz, 1974).

Discharge, water temperature, and specific conductance of the Argo Tunnel--one of the major mine-drainage sources in the study area--have been monitored from January 29, 1976, through March 18, 1977. The observed daily mean discharge varied from 0.37 to 0.55 ft^3/s (0.010 to 0.016 m^3/s) during the period January 29 to June 24, 1976. Indirect evidence indicates that a maximum daily mean discharge greater than 0.55 ft^3/s (0.016 m^3/s) may have occurred toward the end of May. Instantaneous discharge measurements after June 24, 1976, through March 18, 1977, varied from 0.35 to 0.51 ft^3/s (0.010 to 0.014 m^3/s). Discharge from the Argo Tunnel decreased 14 percent during the period of record, whereas water temperatures remained fairly constant at about 16.0°C. Specific conductances were somewhat variable--from 2,680 to 3,410 micromhos--but these variations are not readily explained. A value of about 3,100 micromhos persisted throughout most of the period of record.

Fourteen chemical analyses of the Argo Tunnel drainage from March 11, 1976, through March 18, 1977, indicate relatively high but fairly constant concentrations of arsenic, cadmium, copper, iron, lead, manganese, and zinc. Except for lead, these trace elements are mostly dissolved (82 percent or greater), and their concentrations are probably indicative of baseline conditions in the Argo Tunnel drainage. Long-term degradation of water flowing from the Argo Tunnel is shown by increases of at least 2.5 to 8.0 times for dissolved solids, dissolved iron, calcium, magnesium, and sulfate since 1906. The acidity has changed from neutral to a median pH of 2.9 in 1976-77.

Comparison of current data with data collected previously (Moran and Wentz, 1974; Boyles and others, 1974; Wildeman and others, 1974; Wildeman, 1976) indicates that chemical flushing events took place in the spring of 1973 and 1974. These flushes contained higher than baseline trace-element concentrations. Chemical flushing events did not occur in the spring of 1975 or 1976, and probably did not occur in the spring of 1972. The spring chemical flushes appear to be associated with increased infiltration from spring snowmelt in the catchment of the Argo Tunnel.

The literature (Skelly and Loy, Engineers-Consultants; Penn Environmental Consultants, Inc., 1973; and Scott and Hays, 1975) has been reviewed, and 26 management alternatives for mine-drainage abatement have been summarized. However, each situation must be examined individually, and the alternative chosen must be tailored to solve that particular problem.

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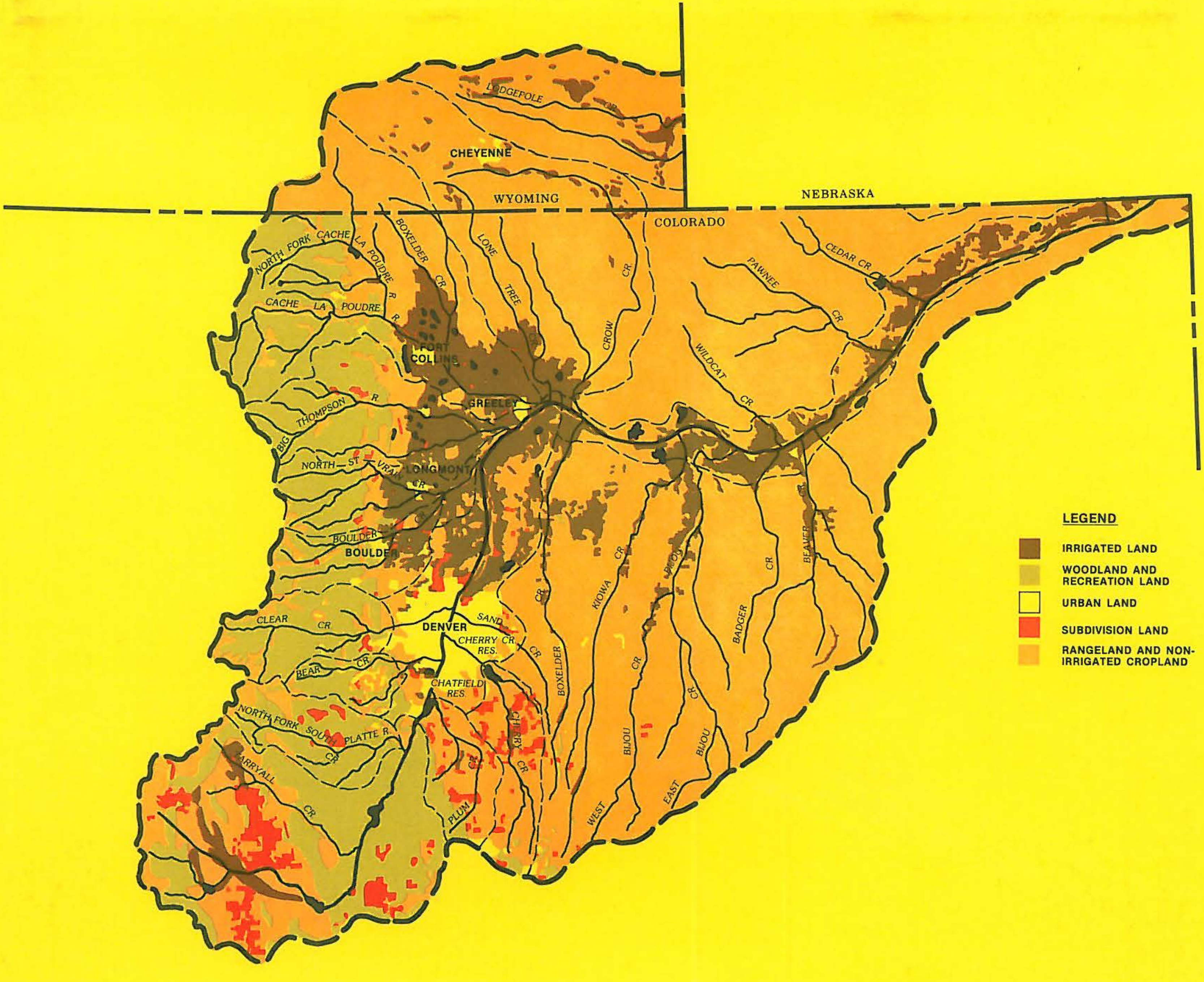
LEGEND
IRRIGATED LAND
WOODLAND AND RECREATION LAND
URBAN LAND
SUBDIVISION LAND
RANGELAND AND NON-IRRIGATED CROPLAND
WYOMING
NEBRASKA
COLORADO
CHEYENNE
LODGEPOLE CR
FORT COLLINS
GREELEY
LONGMONT
BOULDER
DENVER
NORTH FORK CACHE LA POUDRE R
CACHE LA POUDRE R
BOXELDER CR
LONE TREE CR
CROW CR
PAWNEE CR
CEDAR CR
WILDCAT CR
BIG THOMPSON R
NORTH ST VRAIN CR
BOULDER CR
CLEAR CR
BEAR CR
SAND CR
CHERRY CR RES.
CHATFIELD RES.
NORTH FORK SOUTH PLATTE R
TARRYALL CR
PLUM CR
CHERRY CR
BOXELDER CR
KIOWA CR
BIJOU CR
WEST BIJOU CR
EAST BIJOU CR
BADGER CR
BEAVER CR