RI 8767

Bureau of Mines Report of Investigations/1983

Long-Term Effectiveness of Deep Mine Sealing at Moraine State Park, Butler County, Pa.

By Slavoljub D. Maksimovic and Bernard R. Maynard

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8767

Long-Term Effectiveness of Deep Mine Sealing at Moraine State Park, Butler County, Pa.

By Slavoljub D. Maksimovic and Bernard R. Maynard

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
James G. Watt, Secretary

BUREAU OF MINES
Robert C. Horton, Director

This publication has been cataloged as follows:

Maksimovic, S. D

Long-term effectiveness of deep mine sealing at Moraine State Park, Butler County, Pa.

(Bureau of Mines report of investigations ; 8767)

Bibliography: p. 27-28.

Supt. of Docs. no.: I 28.23:8767.

1. Mine filling—Environmental aspects—Pennsylvania—Moraine State Park. I. Maynard, Bernard R. II. Title. III. Series: Report of investigations (United States. Bureau of Mines) ; 8767.

TN23.U43 [TD195.M5] 622s [622'.334] 82-600380

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

LONG-TERM EFFECTIVENESS OF DEEP MINE SEALING AT MORAINE STATE PARK, BUTLER COUNTY, PA.

By Slavoljub D. Maksimovic[1] and Bernard R. Maynard[2]

ABSTRACT

The Bureau of Mines conducted water sampling with flow measurements at Moraine State Park to determine the long-term effectiveness of the deep mine sealing completed between 1969 and 1971. Data collection in 1979 and 1980 consisted of taking two samples per weir location from a group of mine entries. These data were compared with baseline data from before and 1 year after seal completion, utilizing standard statistical procedure. The total mean water discharge and total mean iron load increased, whereas the mean acid load decreased. The minimum water discharge, minimum acid, and total minimum iron load increased, and the maximum water discharge, maximum acid, and total maximum iron load decreased as a result of sealing. The acid load variance was reduced approximately 55 pct. The water discharge and water quality were more consistent than before sealing. In general, the water quality was better within a mine pool than at the discharge points; the development of a pool did not insure improvement at the discharge points. Overall, mine sealing improved the water quality in the park's Lake Arthur.

---

[1] Mining engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[2] Supervisory geologist, Pittsburgh Research Center (Wilkes-Barre Field Office), Bureau of Mines, Wilkes-Barre, Pa. (now with Office of Surface Mining, Wilkes-Barre, Pa.).

INTRODUCTION

Acid drainage from underground mines has been a significant pollution problem for over 100 years. Prior to the 1930's, all mine sealing work was performed as a safety measure and not to reduce acid mine drainage, although the concept of sealing coal mines as a means of reducing such drainage was studied by the Bureau of Mines in the 1920's and 1930's (17).[3] As a result of this study, a large mine sealing program was started in the Appalachian region in 1933 as a joint effort of the Federal Government, State governments, and several relief Administrations--the Civil Work Administration, Federal Emergency Relief Administration, and Works Progress Administration. The degree of success and the effectiveness of the various programs, types of seals, and techniques used were determined and reported by several Agencies (1, 4-5, 16, 19).

To meet present U.S. Department of the Interior's Office of Surface Mining (OSM) regulations (30 CFR 816-817) and U.S. Department of Labor's Mine Safety and Health Administration (MSHA) requirements (30 CFR 75.1711) for mine closure and sealing (20), industry has continued to apply the technology first used by the Bureau of Mines in the 1920's and 1930's. Since that time, other programs of mine sealing have been conducted by various State and Federal Agencies with varying degrees of success. The effectiveness of these programs for reducing acid discharge is questionable, as short-term findings have indicated (3, 11-12, 14).

In the early 1960's, the Commonwealth of Pennsylvania initiated plans for the development of Moraine State Park, in Butler County. Because of past mining activities in the Muddy Creek watershed, pollution from abandoned deep mines was considered a potential hazard to the then proposed Lake Arthur. In 1967, before any mine sealing and reclamation work was started, the Pennsylvania Department of Mines and Mineral Industries contracted background studies. These studies involved geologic and engineering investigation of the area and an assessment of the remedial measures needed to alleviate the acid mine drainage problem. This work included the installation of 85 weirs to measure waterflow at all known mine drainage sources in the Muddy Creek watershed, and collection of water samples (9).

Periodic sampling and field flow measurements were started in May 1967 and continued through June 1971 to evaluate the effectiveness of the mine drainage abatement projects. These projects included deep mine sealing, surface sealing, grouting, regrading and backfilling surface-mined areas, revegetation, refuse pile removal, and plugging of oil and gas wells. In addition, water depths were measured and samples were obtained from observation holes on a periodic basis before and after the seals were completed.

The water sampling conducted throughout the planning and creation of Moraine State Park provided a short-term indication of the reduction in pollution. However, the long-term effectiveness of these measures was uncertain.

In the summer of 1979, the Bureau of Mines began to investigate unresolved environmental problems arising from the implementation of the OSM permanent regulatory program related to mine sealing, and to identify research needs. As part of this study, the Bureau evaluated the long-term effectiveness of deep mine hydraulic sealing completed during the period of 1969-71 in Moraine State Park. This study included the identification of the original weir locations with corresponding entries, evaluation of existing entry conditions, measurement of mine water discharges from the sealed areas and water level fluctuations in the mine pools behind the seals, water sampling, and evaluation of the quality of discharge in the study area 10 years after seal completion.

---

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

Also studied was the effect of mine sealing on mine pool water quality, water quality in Lake Arthur, total acid and total iron, and variation in mean, minimum, and maximum acid and total iron load.

ACKNOWLEDGMENTS

The authors thank J. W. Foreman and staff of Gwin, Dobson, and Foreman, Inc., Consulting Engineers, Altoona, Pa., for providing existing baseline data, and for technical review of the manuscript.

DESCRIPTION OF STUDY AREA

The study area is located in the Moraine State Park about 5 miles south of Slippery Rock, 9 miles northwest of Butler, and approximately 35 miles north of Pittsburgh, Pa. (fig. 1). This State recreational area covers approximately 15,000 acres and is situated within a 60-mile radius of over 4 million people (13). It is located in Franklin, Brady, Muddy Creek, and Worth Townships in the Prospect, Pa., 7.5-min quadrangle.[4]

The park name is derived from the glacial term "moraine," which is applied to the unstratified material deposited directly from the melting glacial ice. Harrisville and Slippery Rock mark the eastern edge of the glacial ice, which dammed the westward-flowing Muddy Creek and created a lake. The present constructed Lake Arthur occupies the site of this glacial lake, which existed during the Wisconsin period of Pleistocene glaciation more than 10,000 years ago.

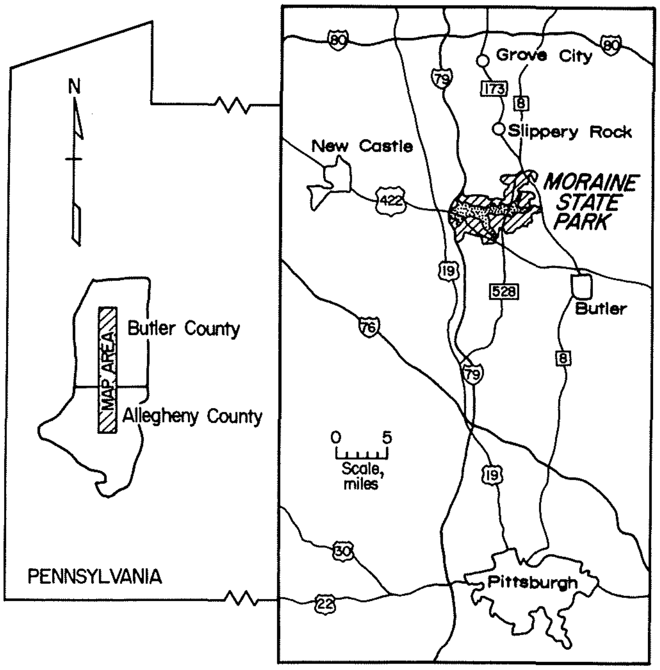

FIGURE 1. - Location map of Moraine State Park study area.

TOPOGRAPHY AND DRAINAGE

The relief of the study area ranges from approximately 1,525 ft along the northern park boundary to 1,160 ft along the thalweg of Muddy Creek (figs. 2-3). The major drainage channel is Muddy Creek, which, with its tributaries, feeds the 3,200-acre Lake Arthur. Muddy Creek is a tributary of the Slippery Rock Creek watershed. The confluence of Muddy Creek and Slippery Rock Creek is about 3 miles west of the park area. The study area includes about 25 of the 59 sq mi of Muddy Creek watershed. Muddy Creek and its tributaries, Swamp Run, Shannon Run, Big Run, and Bear Run, drain westward through a glacial valley that ranges from about 500 to 3,500 ft in width with a gradient of 1 ft per 1,000 ft (9).

GEOLOGY

The geology of the study area consists of sedimentary strata, which belong to the Conemaugh and Allegheny Formations of the Pennsylvanian System of Paleozoic Age, and unconsolidated Pleistocene deposits of the Quaternary System. These formations have a thickness of about 800 ft and consist mainly of a sequence of thin-bedded shales, siltstones, and sandstones. The sequence also includes the

---

[4] U.S. Geological Survey map 0052.5-W8000/7.5, 1961; photorevised 1970.

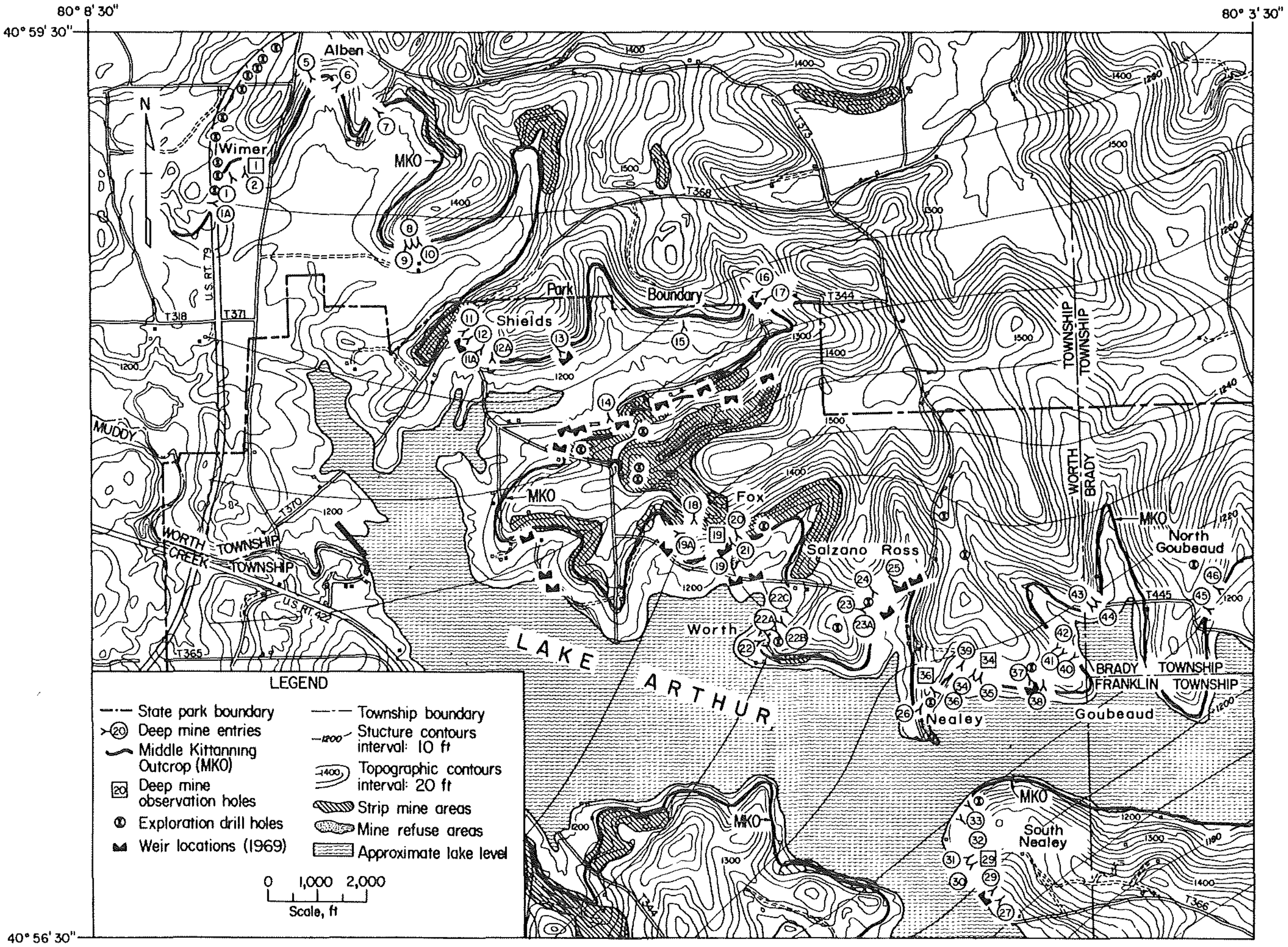

FIGURE 2. - Western half of Moraine State Park area showing locations of mine openings and related topographic data.

Vanport Limestone, a fairly persistent unit with a maximum thickness of about 20 ft, and several coal seams (6). A generalized stratigraphic column in the Moraine State Park is given in figure 4 (9).

The flat, rather broad valley sections in the park area contain unconsolidated deposits of the Pleistocene Wisconsin glacial advance. These deposits consist of sandy deltaic sediments overlying lacustrine laminated silts and plastic clays ranging in thickness from a few feet near the edge of the valley to 80 ft in the middle. Generally, the unconsolidated glacial material intercepts the bedrock at or near the Middle Kittanning coal seam along the valley sides (10).

The park area lies on the southeast flank of the Homewood anticline, which trends in a northeast-southwest direction. The sedimentary strata generally dip about 160 ft/mi to the southeast, with local variations (e.g., Kildoo area) along the northern side of Lake Arthur. The area is further located on the northwest flank of the Bradys Bend syncline with an axial trend southeast of Butler and trends in a northeast-southwest direction (10).

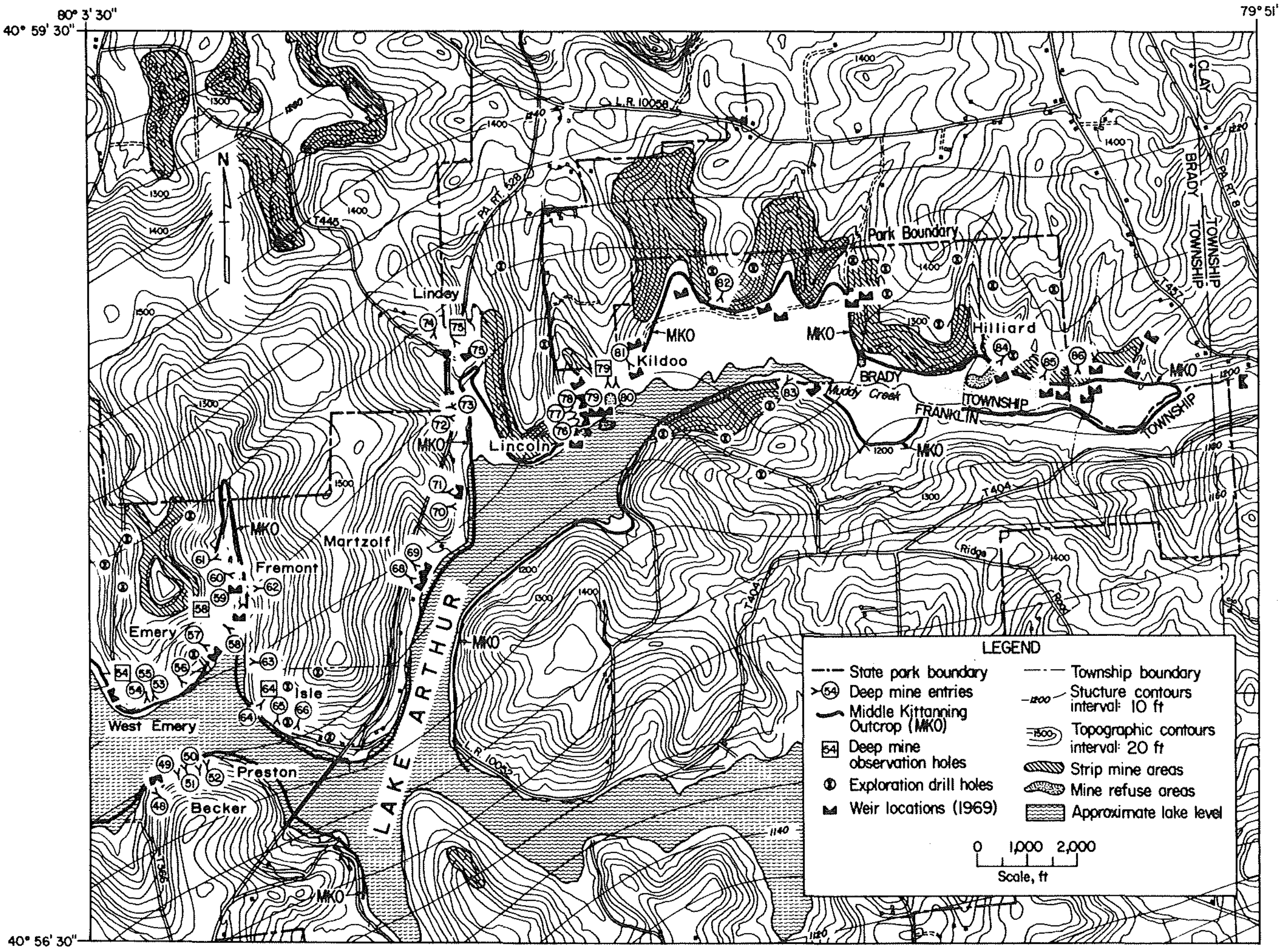

FIGURE 3. - Eastern half of Moraine State Park area showing locations of mine openings and related topographic data.

The minable coal seams in the park area are in the Conemaugh and Allegheny Formations of the Pennsylvanian System (fig. 4). Four important coalbeds, the Middle and Upper Kittanning and the Lower and Upper Freeport, crop out within the park boundaries. The Middle Kittanning or "C" Coal Seam is the most persistent and accounts for all of the deep mining and most of the strip mining in the park area. The Middle Kittanning Coal has been mined, along with the Upper Freeport Seam, in the north-central section of the park and was mined underground prior to surface mining. This is a high-sulfur seam (up to 3.8 pct), which outcrops along the valleys of the Muddy, Slippery Rock, and Connoquenessing Creeks and their tributaries, resulting in a considerable amount of acid drainage. In the valley of Muddy Creek, several small mines have been opened along the Western Allegheny Railroad, where the seam thickness ranges from 2 ft, 5 in to 3 ft, 3 in. The Upper Kittanning Coal is not sufficiently thick to be mined in the study area. The Freeport Coal is exposed over a large area in Muddy Creek Valley and its tributary valleys. Although variable in thickness, the coal seams are thicker in the eastern part of the area than in the western part. Except locally, the Lower Freeport Coal Seam is not minable, while the Upper Freeport has widespread distribution and has been strip mined on a limited scale. The Lower Freeport Coal Seam thickness in Muddy Creek Township ranges from under 6 in to 3 ft, 4 in. The Upper Freeport Coal Seam ranges in thickness from 2 ft to over

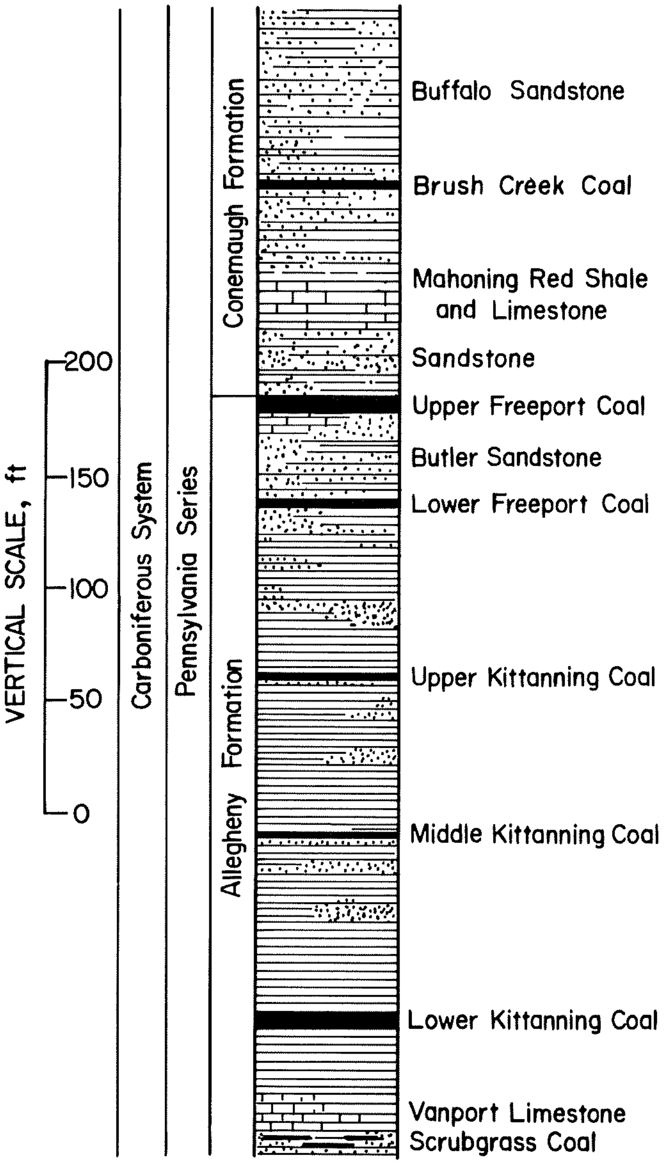

FIGURE 4. - Generalized stratigraphic column in Moraine State Park area.

5 ft. The Brush Creek Coal Seam is very errant and has been strip mined only in small areas. It occurs approximately 80 ft above the Upper Freeport Coal and ranges in thickness from 3 ft to 5 ft, 4 in (15, 18).

HYDROLOGY

Muddy Creek, with its watershed, drains about 59 sq mi. It is the southernmost tributary of Slippery Rock Creek, and the main stream supplying water to Lake Arthur (13). The evapotranspiration losses during the growing season in this area may be large, and as a result, little recharge reaches the zone of saturation, and water levels therefore decline. The water level generally rises during the remainder of the year.

The acid mine water pollution in Muddy Creek is directly attributed to past surface and underground coal extraction, because over 60 coal mines have been located in 5 productive coal seams within the watershed. The water pollution originates predominantly from abandoned underground workings; surface mining is believed to contribute less than 20 pct of the total pollution. However, surface mining frequently intersects and exposes abandoned underground mine workings (13). The water quality of Muddy Creek is related to the amount of waterflow in the watershed. Increases in acid content have been attributed to greater discharges of acid mine water from underground mines, predominantly during periods of high surface water runoff.

The average yearly precipitation for the 10-year period 1971-80 was 44.43 in at Butler and 42.94 in at Slippery Rock monitoring stations, which are about 10 miles and 8 miles, respectively, from the park area (21). More rainfall occurs during late spring and summer than in winter and early spring. Summer rains occur as intense storms of short duration that may be limited to certain areas. During periods of relatively heavy precipitation, the mine pool levels in the sealed areas rise and the discharge from the sealed entries presumably increases both in volume and in acid load.

The average yearly precipitation for 1967-70, before and during sealing, was 39.82 in at Butler and 39.25 in at Slippery Rock stations; this is more than 4 in below the 10-year average precipitation for the study period. This indicates that the period before and during sealing was relatively dry and the dryness may have had an effect on the amount of pollution formed.

During the late summer of 1979, the mean acid load from 27 weir locations

(35 mine entries) was 5 lb/day, with a mean water discharge of 8.3 gal/min; whereas in the spring of 1980, the mean acid load from the same weir locations had increased to 10 lb/day, with a mean water discharge of 18 gal/min. The correlation between mean water discharge and acid load was 0.64 and 0.68 and shows an approximate 41- and 46-pct relationship, respectively. The amount of the increased water discharge from the summer of 1979 to the spring of 1980 suggests that the mean acid load increased by less than 10 pct.

MINING HISTORY

The Middle Kittanning Coal Seam was extensively mined during the early 1900's, during World War I, and through the 1920's. Thirteen mines in the Moraine State Park area produced about 620,000 tons of coal from the Middle Kittanning Coal Seam by the room-and-pillar method during the period from 1916 to 1931. Mine production ranged from 11,000 to 304,000 tons from a coal seam of 32 to 36 in (8). Most of the deep mines were developed updip and were located along the outcrop on the north side of Muddy Creek along with a railroad, which facilitated mining. The mines were developed to take advantage of gravity drainage and underground transportation. Most of the deep mines were abandoned by 1930, and at the time of condemnation for the park, there was only one hand-loaded deep mine operation (9).

From the early 1940's to about 1966, strip and auger mining operations were extensive in the Middle Kittanning Coal Seam, and several strip mines were operated in the Lower Freeport and Brush Creek Coal Seams. Before being considered for a State park, this area was a marginal agricultural area, an oil and gas field, and a mining area of both deep and strip mines.

POLLUTION ABATEMENT MEASURES, 1967-71

The pollution abatement projects carried out between 1967 and 1971 to develop this area as a State park were conducted by the Pennsylvania Department of Environmental Resources, Operation Scarlift, project SL 105-3, and under the Appalachian Surface Mine Reclamation program. Work for surface mine reclamation is authorized under Section 205 of the Appalachian Regional Development Act of 1965 (Public Law 89-16) and is generally a cooperative effort by the State and Federal Governments. The work conducted in the Muddy Creek watershed included strip mine reclamation, refuse pile removal, surface sealing, deep mine hydraulic sealing, well plugging, and deep mine air-trap sealing (9).

Before any pollution abatement work could be started, the Commonwealth of Pennsylvania conducted a study to assess the conditions in the area. An important part of this work was determining the location and extent of the mines to be sealed. Since mine maps were not available, a diamond core drilling program was conducted, which consisted of drilling 1,859 ft of holes to determine the elevation and nature of the coal, the extent of the mined-out areas, stratigraphy, and other geologic data. A total of 23 exploratory holes were drilled and used to locate the openings of the major deep mines or to confirm major acid contribution points. It was also necessary to locate the strip mine areas and refuse piles in the area (9).

STRIP MINE RECLAMATION

Strip mine reclamation work included clearing, excavating, backfilling and regrading. This work was performed in 19 strip pits located in three general areas through the park, as indicated in figures 2 and 3. Most of the reclamation work involved the construction of diversion ditches and slope drain flumes, soil treatment, and planting (9).

REFUSE PILE REMOVAL

This part of the project included the excavation, loading, and transport of material from 19 refuse piles. The refuse was deposited in strip mine areas that were to be restored (9).

SURFACE SEALING

Twenty-three deep mine areas in the Muddy Creek watershed associated with the park were surface sealed. Although these mines were not points of actual acid mine discharges, they were areas where water could enter the mines after the lake had been filled and the deep mines inundated. Surface or dry sealing included the removal and burial of acid-producing material from the mine area and associated refuse piles, and also filling and regrading the abandoned deep mine drifts, slopes, shafts, and subsidence holes. After backfilling was completed, the areas were limed, fertilized, and planted with grasses (13).

DEEP MINE HYDRAULIC SEALING

The major sources of pollution in the park area were the abandoned deep mines. After several plans had been considered, the construction of double-bulkhead seals and pressure grouting in adjacent strata were selected as a means of eliminating or reducing acid mine drainage, while at the same time flooding, or at least partially flooding, the mine workings.

Remote installation of double-bulkhead seals from the surface directly above the entries was used. The exact location and extent of the mined area behind the caved mine entries was not known, and exploratory drilling was required for each seal (9). The double-bulkhead seals were constructed through drill holes, with pressure grouting in the area of the seal and adjacent strata to the mine entries. Curtain grouting was used in specific areas along the outcrop. A total of 69 mine seals were installed; 65 mine seals were located in the Muddy Creek watershed, and 4 seals in the Big Run watershed area.

Grout curtain holes were 3 in. in diameter on 10-ft centers with alignment parallel to, and approximately halfway between, the front and rear bulkhead drill holes. Pressure curtain grouting was extended to a minimum of 50 ft on both sides of the mine entries. The distance between the front and rear bulkheads ranged from 17 to 40 ft and averaged about 20 ft. The number of holes ranged from two to nine per rear and front bulkhead, and from two to six for the center plug, with hole depths from 23 to 66 ft. The number of grout curtain holes ranged from 4 to 58, with depths from 11 to 91 ft (8).

The seal material compositions included fly ash and cement; fly ash, cement, limestone, and sand; limestone and gravel; and fly ash, cement, and sand. The grout curtain material consisted of limestone, fly ash, and cement (8).

Deep mine seals installed in the Kildoo Mine area were found to be ineffective, and in the mid-1970's the Pennsylvania Department of Environmental Resources designed a new mine pollution abatement project. In 1979, exploratory borings indicated waterflow through a pervious shale zone located under the coal seam. During subsequent reclamation of the strip mine area, a subsurface drainage system was installed and the area regraded and resealed. Postconstruction monitoring data are not available for this project.

MINE OBSERVATION HOLES

A total of 25 observation holes were drilled from the surface into the deep mine entries at different locations behind the mine seals (9). These holes were used to obtain mine water samples and to monitor mine pool levels behind the seals. The diameter of the holes was 6 in, with a casing diameter of 4.5 in. Of the 25 holes drilled during the sealing operations, only 12 were sampled during the field studies in 1979 and 1980. The remaining observation holes were either dry, caved, blocked, or could not be located.

LONG-TERM CHANGES RESULTING FROM MINE SEAL CONSTRUCTION

In order to determine the long-term effectiveness of the deep mine sealing project at Moraine State Park, the Bureau of Mines collected field data from a selected group of mines that were sealed at Moraine State Park between 1969 and 1971. These field data were compared with the baseline data from the monitoring of mine water discharge levels and quality before and after mine sealing. The fieldwork was completed in 1979 and 1980 at 35 mine entries associated with 27 weir locations. It consisted of locating the original entries, evaluating the existing conditions, measuring the mine water discharge with a 90° V-notch weir, determining the field pH and water temperature, and collecting water samples for laboratory analysis. The type of mine seals involved in this study included 24 double-bulkhead or hydraulic seals and 3 dry or surface seals. One permeable limestone seal is located at the Wimer Mine in the northwest area of the watershed outside the park boundary with discharge into Lake Arthur (9).

The distribution of the 27 weir locations (figs. 2-3) extends from the Wimer Mine (weir 18, entry 1A) on the west to the Hilliard Mine (weir 79, entry 86) at the eastern inlet of Lake Arthur and Muddy Creek, a distance of approximately 7.5 miles. Mine names, entry numbers, and associated weir location numbers can be found in appendix A. Of the original 85 weirs that were installed and monitored, 66 were located along the north side of Lake Arthur. This evaluation is based on 27 of those weirs, which were located on the dip side of the southeastern flank of the Homewood anticline (13). The selection of these 27 weir locations was based on the existence of sufficient data for analysis. The remaining weirs on the north side of Lake Arthur either were not located, were at or below lake level, or did not have sufficient sampling data either before or after sealing was completed. The existing data for nine of these weir locations are given in appendix B.

During the presealing interval of monitoring, 709 water samples were collected from the 27 weir locations; the number of samples per weir ranged from 3 to 51. Sampling during this presealing interval was on a weekly basis the first year and on a monthly basis thereafter. In the year that followed the completion of each mine seal, water samples were collected on a monthly basis, with 2 to 17 samples from each location, for a total of 272. Ten years later, a total of 59 water samples were collected from 35 mine entries associated with the same 27 weir locations. A minimum of two water samples were collected from each of the weirs, one sample from what was judged to be the wet period and one from the dry period of the hydrologic year. Three of the original twenty-seven weirs were positioned to monitor the discharge from several mine entries. Four locations (weirs 20, 40, 44, and 46) each have two associated entries, and two (weirs 31 and 33) have three entries. The remaining 21 weirs are associated with single entries. For analysis purposes, two or more entries associated with a single weir are collectively considered as one location.

The existing baseline data from the monitoring periods before sealing and during the first year after sealing were obtained from Gwin, Dobson, and Foreman, Inc., Consulting Engineers, Altoona, Pa. (8). The water samples collected 10 years later were analyzed by the Bureau of Mines. Univariate statistics for each variable were obtained using a University of California computer program (2).

Mine conditions related to water discharge levels and quality are divided into and discussed here in three time periods: (1) the time before seal completion, 1969-71, (2) the first year after each seal was completed, 1970-72, and (3) 10 years after seal completion, 1979-80. Figure 5 shows the changes in parameter levels from before sealing to the first year and 10 years after seal completion. Each of the changes in mine water

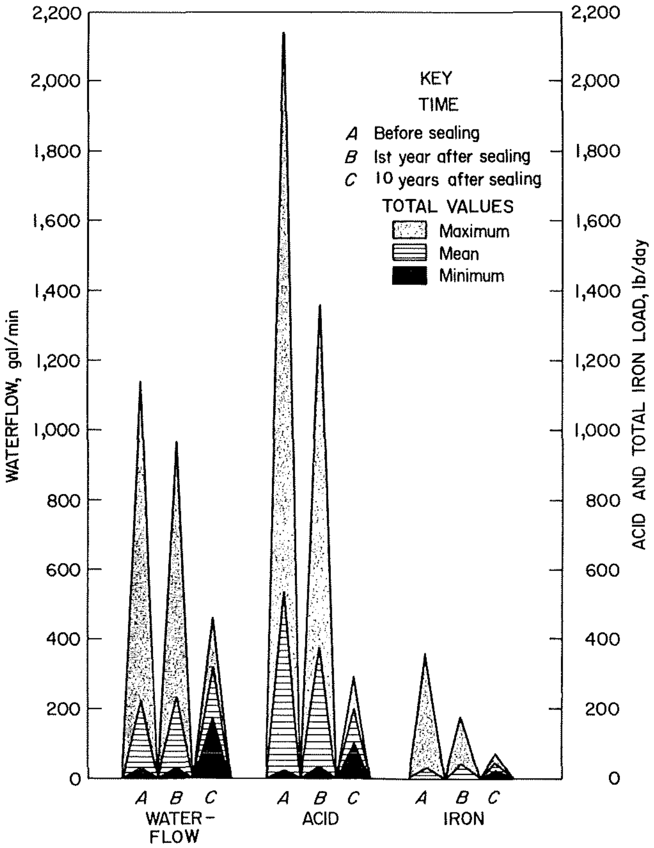

FIGURE 5. - Changes in parameter levels from conditions before sealing to those of the first year and 10 years after seal completion.

discharge (in gallons per minute) and in acid and total iron load (in pounds per day) that are the result of mine sealing are discussed in the following sections. Histograms are used to show the distribution of each parameter as to mean values, coefficient of variation, and rate of change, within the context of the three time periods.

The number of samples collected and analyzed for each of the mine entries and weir locations ranged from 3 to 51 before, 2 to 17 after, and 2 to 6 10 years after sealing. The frequency of sampling at all of the 27 selected locations met the minimum criteria for univariate analysis (2). The F ratio[5] was applied to the water quality parameters for each weir. The F ratio was determined, and an F test was used to determine the equality between two variances for two time intervals. The level of significance or level of error is 2.5 pct or 2.5 times in 100. The degree of freedom associated with each variance was n-1. The critical value of F, using n-1 degrees of freedom and a significance level of 2.5 pct, is located in an appropriate statistical table. If the calculated F exceeds the critical value of F, it can be concluded that the variance in the parameter is not the same in the two time intervals. If the calculated value is less than the critical value there is no evidence to conclude that the variances are different. The hypothesis tested was that the variability of a given parameter before sealing was equal to that of the parameter after sealing, against the alternative that they were different at the 2.5-pct level of significance. The same hypothesis was used to test the variability of the parameters before sealing to that of 10 years after sealing at the same significance level.

MINE WATER DISCHARGE

The effect of mine sealing on water discharge or flow is shown by the data in table 1. The table shows the changes in mine water discharge with reference to the three time periods and includes (1) the quantity for each time interval, (2) the quantity change from before sealing, and (3) the percent change from before sealing. Summary tables showing mine names, entry and associated weir location numbers, parameter values, and number of samples per weir location for mine water discharge can be found in tables A-1 through A-3 in appendix A.

---

[5] The F ratio (after R. A. Fisher) is a test statistic that is used for testing whether the variance of one population is equal to that of another.

TABLE 1. - Changes in water discharge

	Total mean	Total minimum	Total maximum
Quantity, gal/min:			
Before sealing..........	221	35	1,143
1st year after sealing...	236	38	972
10 years after sealing...	325	181	468
Quantity change from before sealing, gal/min:			
1st year after sealing...	+15	+3	-171
10 years after sealing...	+104	+146	-675
Percent change from before sealing:			
1st year after sealing...	+6	+8	-15
10 years after sealing...	+47	+417	-59

Mean Discharge

Mine sealing resulted in an increase in the total mean discharge of 15 gal/min during the first year following seal completion. Ten years later, the total mean flow had increased by 104 gal/min. This change represents a 47-pct increase in total mean water discharge since seal completion.

Histograms of mean water discharge for each of the three time intervals are shown in figure 6. The number above each bar is the number of weir locations at the indicated mean discharge level, within the time interval shown. The maximum water discharge before sealing was in the 22- to 24-gal/min range; 17 of the 27 weir locations (63 pct) discharged less than 10 gal/min. During the first year

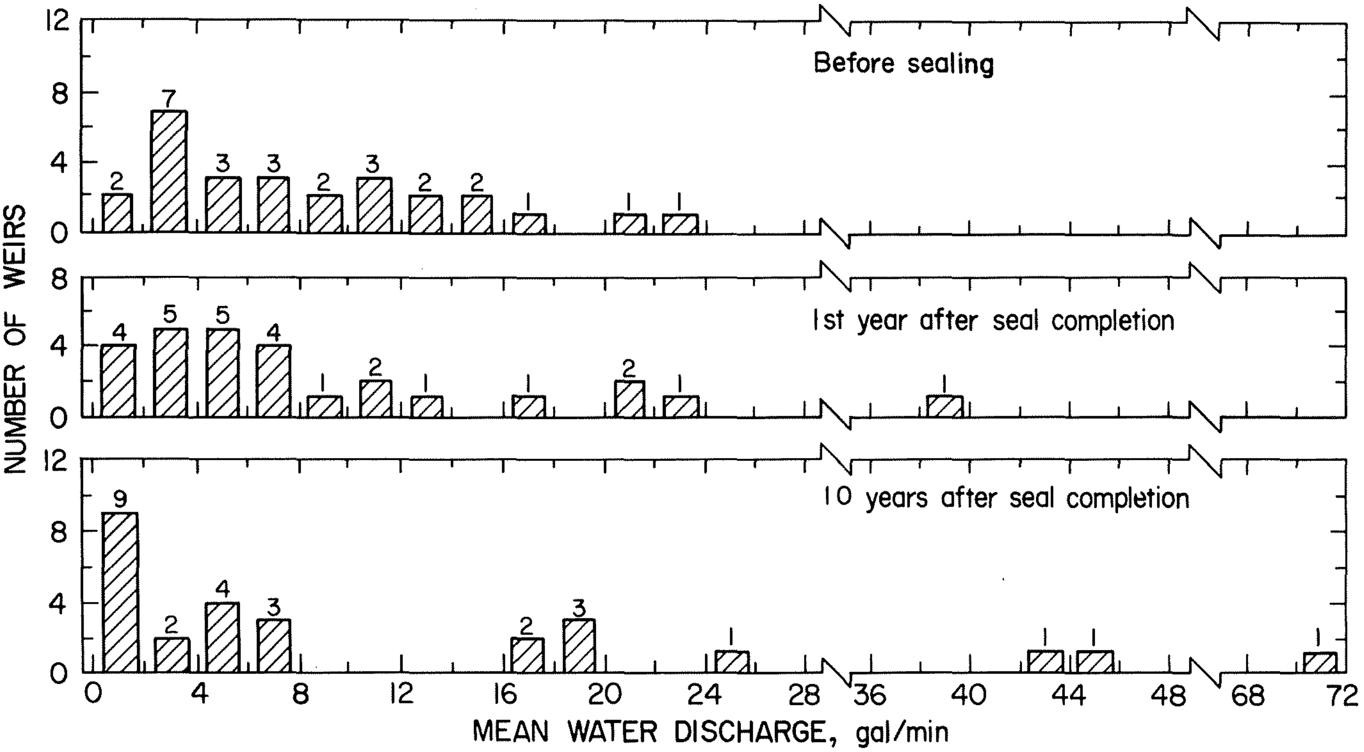

FIGURE 6. - Mean water discharge distribution before sealing, during the first year after seal completion, and 10 years after seal completion for 27 weir locations.

following seal completion, only one weir location had a mean discharge greater than 24 gal/min. Ten years later, 4 weir locations yielded mean discharges greater than 24 gal/min; the number of weir locations discharging less than 10 gal/min was 18 (67 pct). This implies that the increase in total mean water discharge (table 1), 10 years after sealing, may be attributed to the four weir locations with discharges greater than those before sealing (fig. 6). However, changes in mean water discharge from before sealing to 10 years later (fig. 7) show that the discharge increased at 10 weir locations, decreased at 12 weir locations, and remained unchanged at 5 weir locations. The largest changes are associated with those weirs showing increased water discharge, which is believed to be related to the establishment of the mine pool. Furthermore, these same locations appear associated with prominent lineaments of high potential waterflow, which is discussed later.

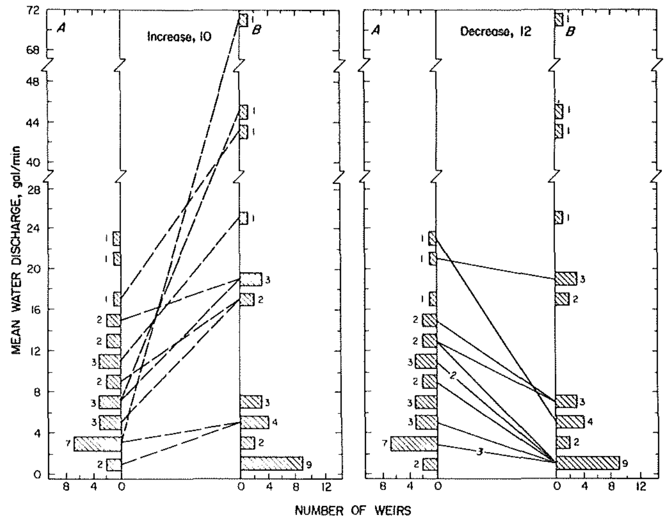

FIGURE 7. - Distributive rate of change for mean water discharge from before sealing *(A)* to 10 years after seal completion *(B)*. Dashed lines show increase; solid lines show decrease. Of the 27 weir locations, 5 remained unchanged.

Figure 8 shows the distribution of the standard deviation of the mean water discharge per weir location expressed as a percentage of the mean and called the coefficient of variation. Before mine sealing, the largest variation in mean water discharge for a given weir location was 208 pct of its mean value. During the first year following sealing, the largest variation in mean water discharge was reduced by 25 pct to the 175- to 200-pct interval. Ten years after seal completion, the largest variations in mean water discharge fell within the 125- to 150-pct interval. This reduction in the coefficient of variation indicates that the degree of scatter or variability in mean water discharge was reduced by mine sealing.

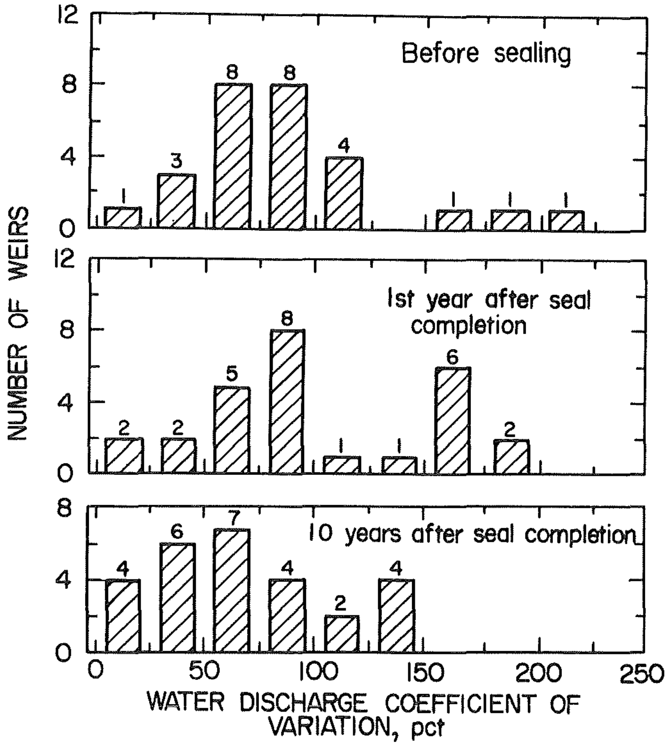

FIGURE 8. - Mean water discharge coefficient of variation distribution for conditions before sealing, during the first year after seal completion, and 10 years after seal completion for 27 weir locations.

Mine sealing affected the total mean water discharge coefficient of variation at 78 pct of the weir locations (fig. 9). The greatest degree of change took place at 13 weir locations (48 pct) that showed a reduction in the variation of mean water discharge. At eight weir locations (30 pct), the coefficient of variation increased as much as 100 pct from that before sealing.

Minimum and Maximum Discharge

The yearly minimum and maximum mine water discharge rates, which are believed to be related to seasonal variations in ground water availability, were also affected by mine sealing (table 1). Before sealing, the total minimum mine water discharge was 35 gal/min, and in the first year following seal completion it increased only 3 gal/min. However, it is significant that the total minimum mine water discharge increased fivefold from before sealing (35 gal/min) to 10 years later (181 gal/min). In contrast, the total maximum mine water discharge showed a slight reduction, from 1,143 gal/min before sealing to 972 gal/min in the first year after sealing. After 10 years, the total maximum mine water discharge dropped to 468 gal/min, an overall reduction of 675 gal/min. Comparing the total water discharge rates shows that mine sealing increased the total minimum discharge rate (417 pct) and reduced the total maximum discharge rate (59 pct) from before sealing to 10 years after seal completion.

Water Impoundment

The resultant change in water discharge after sealing is believed to be related to water impoundment behind the mine seals, with seasonal fluctuations in mine water discharge related to local precipitation. The total mean water discharge for the 27 weir locations was 222 gal/min during the summer and fall of 1979 and increased to 421 gal/min in spring 1980. The construction of a mine seal in an entry created what may be referred to as a partial barrier to the release of water, since it did not eliminate water discharge, and the total mean flow rates (table 1) showed a continued increase from before sealing to 10 years later. This poses a question as to whether the increase in mine water discharge is related to such factors as mine seal construction (material, location, and/or size), seal deterioration (chemical and/or physical), and geologic or other

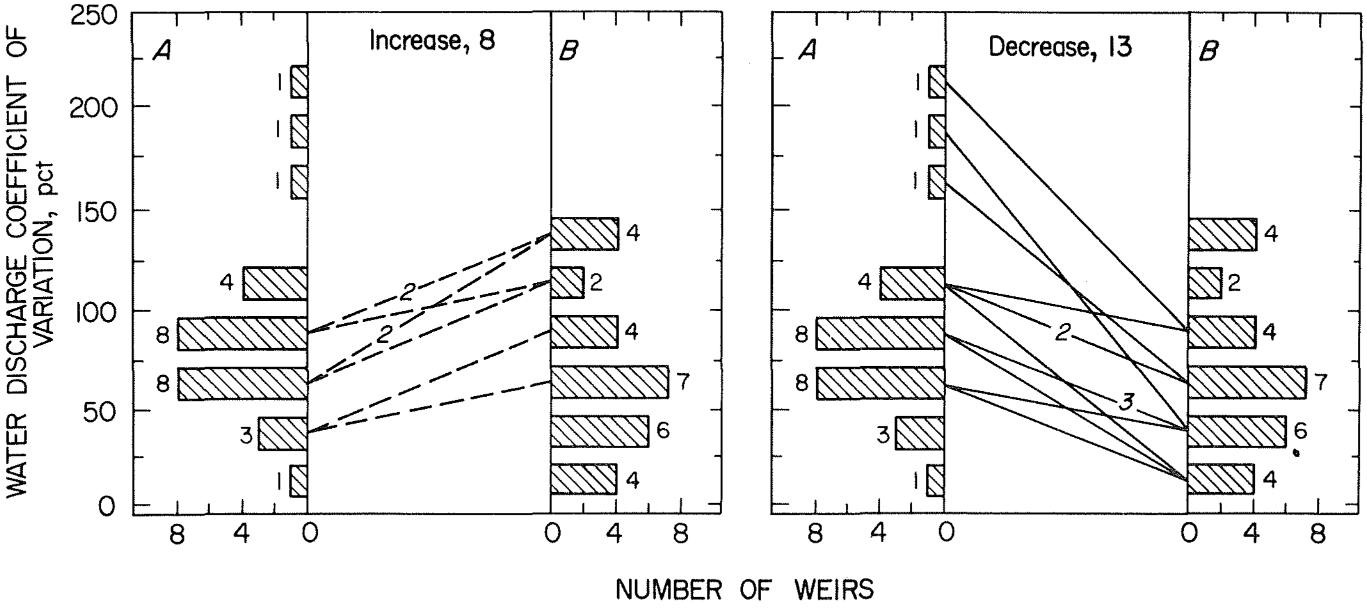

FIGURE 9. - Distributive rate of change for mean water discharge coefficient of variation from before sealing *(A)* to 10 years after seal completion *(B)*. Dashed lines show increase; solid lines show decrease. Of the 27 weir locations, 6 remained unchanged.

conditions. In time, a mine water pool may develop behind a seal and an equilibrium may be established for the existing hydrologic, geologic, and seal physical conditions. This mine pool represents a water source that did not exist before sealing and a ready source for increased water seepage or discharge during low water periods after sealing. Conversely, low seal permeability restrains overall water discharge and reduces total maximum flow rates.

Variance in Discharge

The variance in mine water discharge for each weir location for designated time intervals was subjected to a statistical F ratio test. The hypothesis tested was that the variability in mine water discharge before sealing was equal to that of the mine water discharge during the first year after sealing, against the alternative that they were different at the 2.5-pct level of significance. The same hypothesis was used to test the variability in mine water discharge before sealing to that of 10 years after sealing.

Table 2 compares the variance in water discharge before sealing with the variance after sealing, at 27 weir locations. During the first year after sealing, the water discharges at 14 locations were not significantly more variable. Of the 13 remaining locations, 8 increased and 5 decreased in flow rates. Ten years after sealing, the water discharges at 20 locations were not significantly more variable than those before sealing. The number of locations with a significant difference dropped to seven, with four increasing and three decreasing in discharge rates. This assessment, using sample variances, implies that the conditions of the seals and/or those areas surrounding the seals are changing with time.

It is apparent from the water discharge rates before sealing, and during the first year and 10-year intervals (tables A-1-A-3), that certain mines such as the Salzano Ross, Lincoln, and Hilliard have been or still are problem areas with regard to water discharge and pollution load. Video enhancement imagery[6] of Moraine State Park area and Lake Arthur revealed that there are prominent lineaments trending through the mine areas listed (22). Since water is known to follow these features, the relationship between lineament and fracture traces with regard to discharge and acid mine drainage should be explored. Prior knowledge of whether a proposed seal is to be constructed in a zone of high potential flow could be useful in establishing the seal type, size, and technology to be used.

TABLE 2. - Comparison of variance in mine water discharge after sealing with variance before sealing

	Not significantly different	Significantly different[1]
1 year after sealing:		
Number of weirs......	14	13
Percent.............	52	48
10 years after sealing:		
Number of weirs......	20	7
Percent.............	74	26

[1] 2.5-pct level of significance.

---

[6] Using LANDSAT, EDIES, Multispectral Scanner Subsystem, and Band 7 (near-infrared) imagery.

Observation Holes

As a result of sealing, a mine pool generally was formed behind the seal, as indicated by a survey of the depth of the water in observation holes behind the seals. Of the 25 observation holes drilled to monitor water levels behind the seals in the park area, 10 are associated with the 27 weir locations of this study. Comparisons of the water depths in these observation holes during 1970-71 and 1979-80 are shown in table 3. The water depths in the established mine pools indicate that after sealing, in 1970-71, five of the mines were completely inundated; 10 years later, two remained inundated, one was partially to completely inundated, and two were not located. Four observation holes indicated partial inundation after sealing, and 10 years later, one of these mines was inundated, two remained partially inundated, and one was not located. One observation hole contained less than 1 foot of water in 1970-71 and was dry in 1979-80.

Water depths in the observation holes listed in table 3 and data from seven other observation holes in the park area suggest that reservoirs of variable volume exist throughout the year behind some of the mine seals. This contributes to the concept that water impoundment may, in part, be responsible for an increase in total minimum water discharge and a decrease in total maximum water discharge from the mine entries sealed and the weir locations monitored.

Water Quality

Water quality was tested in a total of 12 observation holes during the field studies in 1979 and 1980. Eight of these holes were acid and three were alkaline. During the first year after sealing, only three were acid and seven were alkaline (9). This represents a 58-pct drop in the mine pool alkalinity behind the seals over the 10-year period. This may be attributed to the deterioration of the mine seal materials, lack of seal maintenance, and increased air content in the strata around the seals through time. The maximum overburden above any one seal was 66 ft.

Analyses of water discharge from the sealed entries and of water in the mine pool observation holes indicated that the water in the mine pool behind the seal was of better quality. One of the suggested reasons is the reduction of oxygen in the pool because of impoundment. Since the seals were not completely effective and leakage occurred around them, water from the pool, flowing through permeable strata at low velocity, reacted with oxygen and sulfuric material outside the pool and became acid at the discharge points with time.

TABLE 3. - Observation hole water depths

Mine name	Observation hole[1]	Weir	Water depth, ft: 1 year after sealing[2]	Water depth, ft: 10 years after sealing
Wimer............	1	18	2.0	1.3- 2.9
Fox..............	20	31	7.9-12.5	10.0-10.8
Salzano Ross.....	23	33	8.4-15.0	(3)
North Goubeaud...	44	40	0 - 0.4	Dry.
West Emery.......	54	41	3.4- 6.8	2.3
Fremont..........	60	46	0 - 2.7	(3)
Lindey...........	75	54	12.6-23.0	10.2-11.8
Lincoln..........	76	57	14.2-18.5	3.0-14.7
Kildoo...........	79	61	0 - 8.0	7.3-10.0
Hilliard.........	84	75	7.9-15.4	(3)

[1] Mine observation hole numbers correspond with mine entry numbers.
[2] From reference 9.
[3] Not located.

The water quality of Lake Arthur has been periodically monitored over the 10 years. After establishment, Lake Arthur in 1970-71 had an alkalinity level of 10 to 70 ppm, acidity of 0 to 6 ppm, and total iron of 0.2 to 3 ppm. Three years later, in 1973-74, the alkalinity was 4 to 57 ppm, the acidity was reduced to zero, and total iron was 0.1 to 1 ppm (7). In 1979-80, water samples were taken from Muddy Creek inlet and the gaging station located below the outlet dam of Lake Arthur. The alkalinity level was 53 and 61 ppm at the inlet and dropped to 23 and 11 ppm below the dam. The acidity level at both the inlet and outlet was zero. The total iron was 0.3 and 0.5 ppm at the inlet and ranged from not detectable to 0.25 ppm at the outlet.

Summary

The effects of mine sealing at Moraine State Park included a reduction in mine water discharge, with the subsequent development of a mine water pool behind the seal and mine entry that ranged in depth from less than 1 ft to complete inundation (table 3). The establishment of a mine water pool produced a source of water not previously available and resulted in an increase in total mean water discharge. Associated with the increase in total mean water discharge was a reduction in the total maximum flow rates and an increase in total minimum flow rates (table 1, fig. 6). Comparisons of mean water discharge changes and rates of change show the number of locations at which flow increased and at which flow decreased as nearly equal. However, the rate of change was much greater for those locations that showed increases in mean water discharge (fig. 7). Changes in the coefficient of variation show that the variability in mine water discharge 10 years later was smaller than it was before sealing. The rates of change and number of locations that changed indicate that sealing reduced the percent coefficient of variation (fig. 9). Comparisons of sample variance before and after sealing indicate that initial variability was decreased because of the formation of mine reservoirs. Although the overall parameter level suggests a balanced condition with time, some mines showed wider variations in discharge rates and appeared to be returning to presealing conditions (fig. 7, tables A-1-A-3).

Combined, these changes in mine water discharge over the 10-year period seem to suggest that the permeability of the sealed area is increasing. If one of the prime objectives in mine sealing is to reduce mine water discharge, then further investigation is needed to determine if the observed changes in discharge (mean, minimum, and maximum) are related to the permeability within the seal, the surrounding geological conditions, or a combination of the above. Water analyses from both the sealed entries and the mine pools indicated that, in general, the mine pool water was of better quality. Water samples from the inlet and outlet of Lake Arthur indicated that the water quality improved over the 10 years.

ACID LOAD

The effect of mine sealing on acid load production including total mean, minimum, and maximum loads, and relative percentage changes are shown in table 4. A summary of acid load data for the three sampling periods is given in tables A-4-A-6.

Mean Acid Load

The total mean acid load before sealing was 540 lb/day and dropped to 380 lb/day in the first year after seal completion. Figure 10 shows that the mean acid load before sealing ranged from a low of 0 to 4 lb/day to a high of 132 to 136 lb/day; 22 weir locations (81 pct) discharged less than 28 lb/day. During the first year after sealing, 26 weir locations (96 pct) discharged less than 28 lb/day. Seal construction resulted in a 30-pct reduction in total mean acid load at the end of the first year. By 1980, the total mean acid load was reduced to 206 lb/day. This represents a net reduction of 334 lb/day or a 62-pct decrease in the 10 years following seal completion.

TABLE 4. - Changes in acid load

	Total mean	Total minimum	Total maximum
Quantity, lb/day:			
Before sealing..........	540	23	2,140
1st year after sealing...	380	40	1,360
10 years after sealing...	206	107	300
Quantity change from before sealing, lb/day:			
1st year after sealing...	-160	+17	-780
10 years after sealing...	-334	+84	-1,840
Percent change from before sealing:			
1st year after sealing...	-30	+74	-36
10 years after sealing...	-62	+365	-86

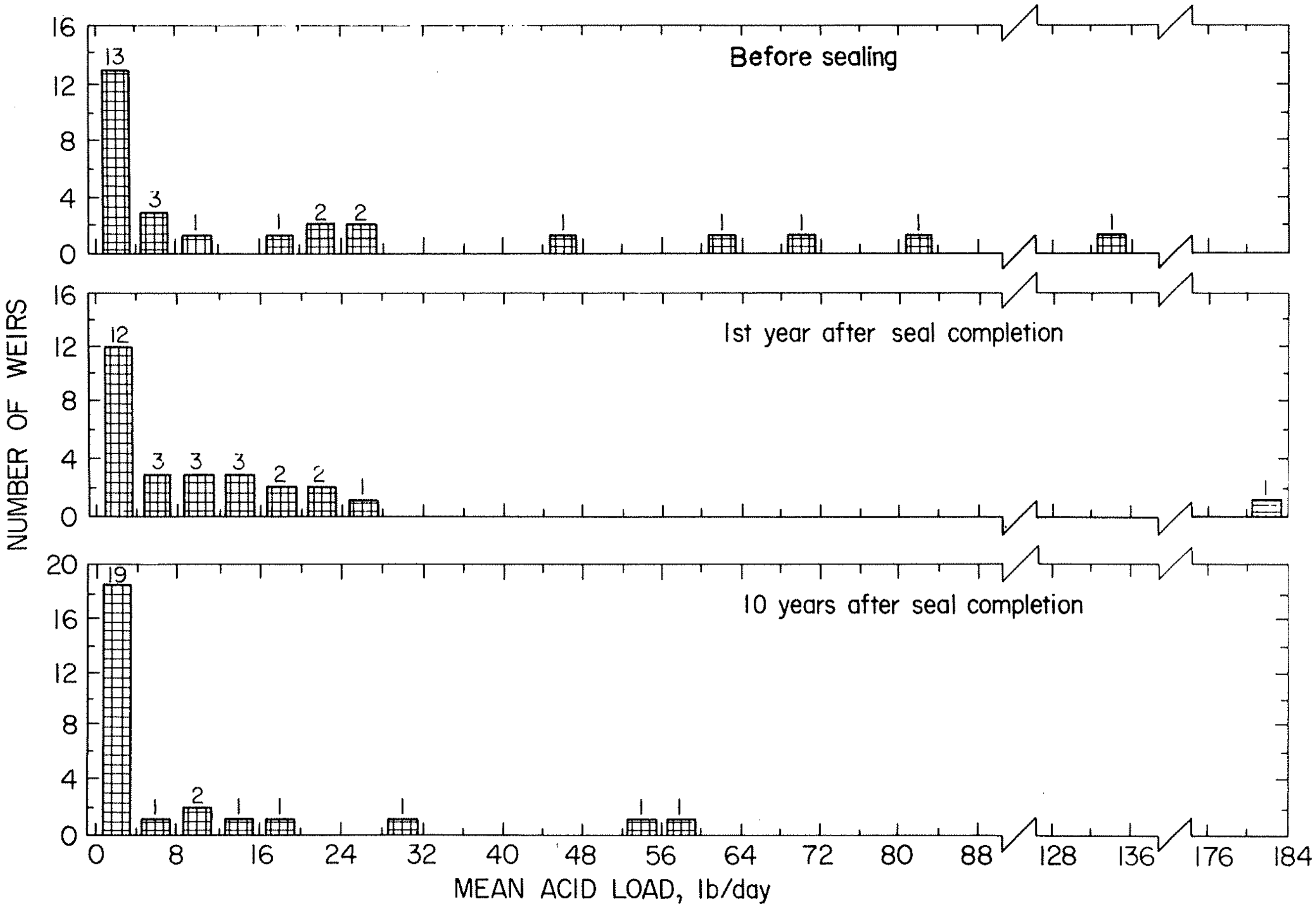

FIGURE 10. - Mean acid load distribution before sealing, during the first year after seal completion, and 10 years after seal completion for 27 weir locations.

Figure 11 shows the distribution and rates of change for mean acid load conditions before and 10 years after sealing. Over the 10-year period, 3 weir locations (11 pct) increased, while 10 (37 pct) decreased in mean acid load production. It is evident that there is a greater degree of change for those weir locations showing a decrease in mean acid load. However, of greater possible importance are the 14 remaining weir locations (52 pct) for which the acid load output remained relatively unchanged regardless of seal construction. It should be remembered that even though sealing resulted in a total mean acid load reduction, the acid levels at 17 weir locations (63 pct) either increased or remained unchanged.

Minimum and Maximum Acid Load

Mine sealing produced the same type of effect on total minimum and maximum acid load rates (table 4) as it did on total minimum and maximum water discharge rates (table 1). Namely, the total minimum acid load and water discharge rates increased with time, while the maximums decreased. Comparison of total minimum and maximum acid loads before sealing to those during the first year and 10 years later shows that the total minimum acid load increased to 40 lb/day (74 pct) and then to 107 lb/day (365 pct), while the total maximum acid load decreased to 1,360 lb/day (36 pct) and then to 300 lb/day (86 pct). In addition, the total mean acid load production is inversely proportional to total mean water discharge with time (tables 1 and 4).

Variance in Acid Load

The variations in mean acid load values before sealing (fig. 12) ranged from 50 to 425 pct with one-third between 50 and 75 pct. Within the first 12 months, sealing resulted in a reduction in percent mean variation in acid load production. Ten years after sealing, the acid load coefficient of variation ranged from 0 to 150 pct: half that of the first year after seal completion. Figure 12 suggests that mine sealing has contributed to a reduction in the variability of acid formation over the 10-year

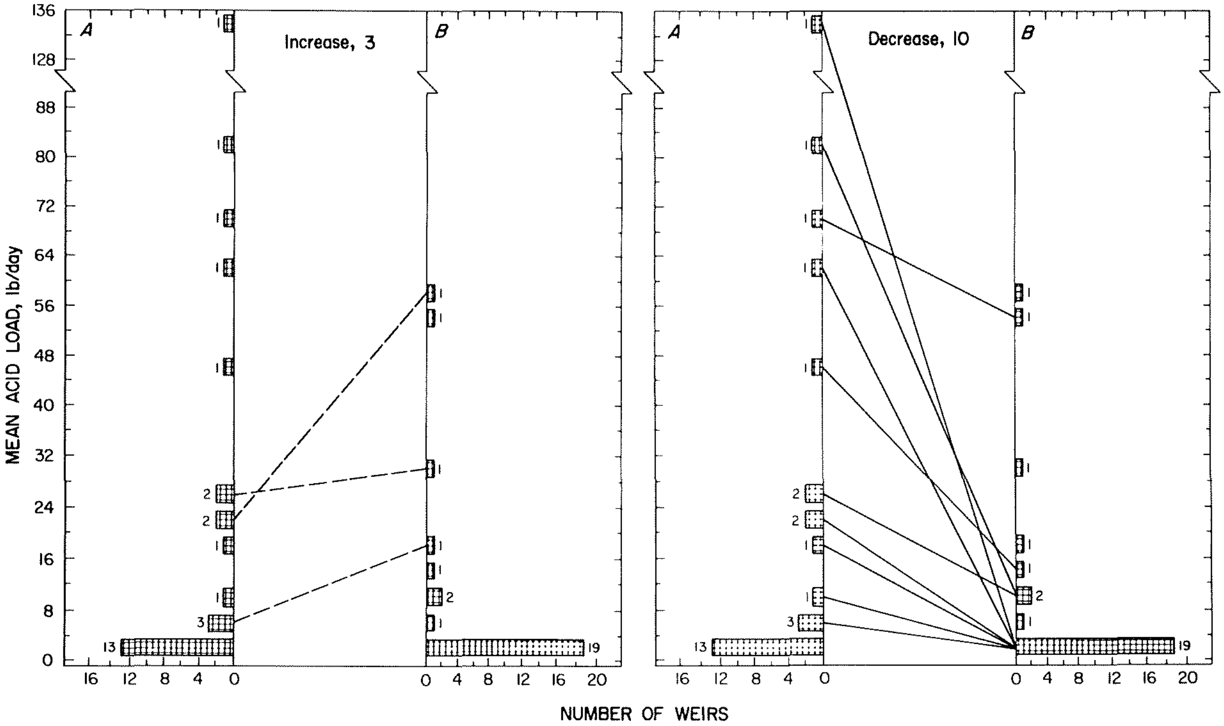

FIGURE 11. - Distributive rate of change for mean acid load from before sealing *(A)* to 10 years after seal completion *(B)*. Dashed lines show increase; solid lines show decrease. Of the 27 weir locations, 14 remained unchanged.

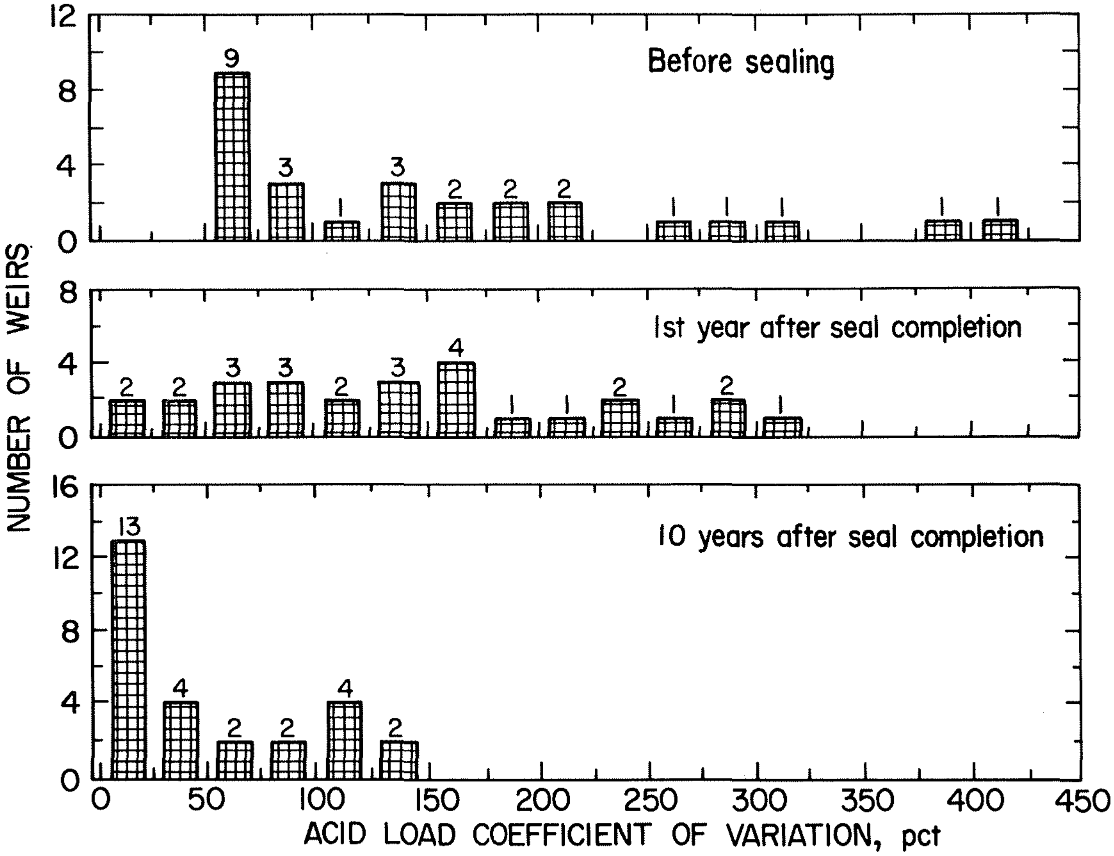

FIGURE 12. - Mean acid load coefficient of variation distribution for conditions before sealing, during the first year after seal completion, and 10 years after seal completion for 27 weir locations.

period. This impressive reduction in mean acid load variability is expressed in figure 13. Twenty-two weir locations (81 pct) realized a reduction in variability or scatter of acid load production, whereas only four (15 pct) increased over the 10-year period. The rate of change as indicated in figure 13 shows there has been an overall reduction in the percent coefficient of variation, with the greatest changes occurring at those locations showing decreases.

To determine if the variance changes were statistically significant, an F distribution test or F ratio value was used as a discriminating factor in the following hypothesis: that the variability of the acid load before sealing was equal to that of the acid load 1 year after sealing, against the alternative that they were different at the 2.5-pct significance level. The same hypothesis was used to test the variablity of the acid load before sealing to that of 10 years after sealing. Comparison of acid load variance before and after sealing for the 27 weir locations is shown in table 5. For 17 of the weir locations, the variances differed significantly from before to 1 year after sealing, with 11 (41 pct) showing a reduction and 6 (22 pct) an increase in acid load production. At two weir locations (7 pct), the acid load was reduced to zero 1 year after sealing. If effectiveness is expressed in terms of reduction in acid load variance, then 11 weir locations showed a significant reduction and 2 were reduced to zero, for a 48-pct effectiveness in the first year following sealing. At the 10-year interval, 13 weir locations (48 pct) were reduced to zero variance and 2 (7 pct) showed significant reductions, for a 55-pct effectiveness in acid load variance reduction.

TABLE 5. - Comparison of variance in acid load after sealing with variance before sealing

	Not significantly different	Significantly different[1]	No acid load
1 year after sealing:			
Number of weirs......	8	17	2
Percent.............	30	63	7
10 years after sealing:			
Number of weirs......	12	2	13
Percent.............	45	7	48

[1] 2.5-pct level of significance.

One recurring inconsistency that appeared in the data collected was the acid load variability for different entries in the same mine complex. When there was an inferred significant difference in acid load variance between two time intervals, and there were two or more entries for a given complex, there was an inconsistency in the quantity of acid load discharged from each entry. For example, data from the Hilliard Mine with four entries (weirs 66, 75, 76, and 79) showed that one entry decreased and two increased in acid load, while the fourth showed no significant difference between the two time intervals. Data from the West Emery complex, with three entries (weirs 41, 43, and 44), showed that one decreased and two increased in acid load. At the Lincoln Mine (weirs 57, 58, and 59), two decreased and one increased in acid load. At the Salzano Ross Mine, weir 33, three

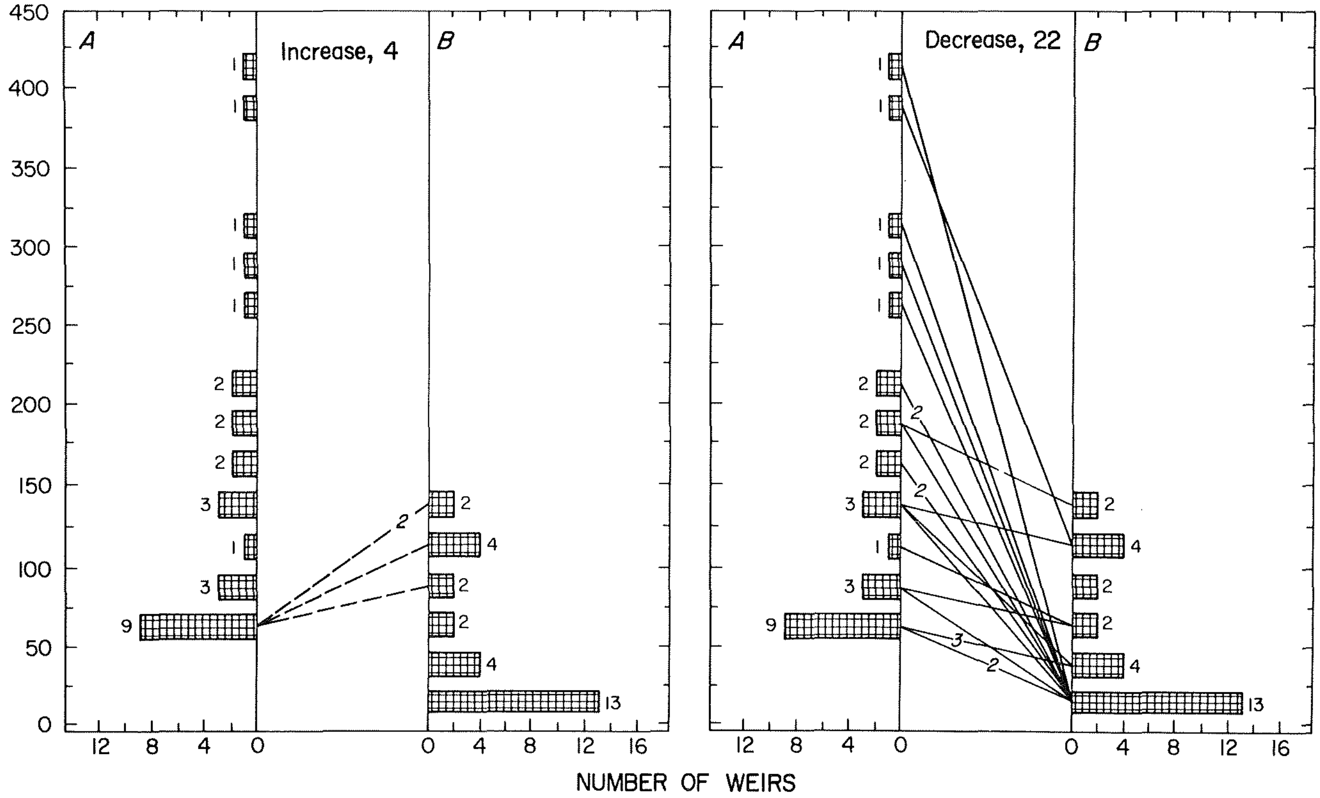

FIGURE 13. - Distributive rate of change for acid load coefficient of variation from before sealing (*A*) to 10 years after seal completion (*B*). Dashed lines show increase; solid lines show decrease. Of the 27 weir locations, 1 remained unchanged.

entries were monitored and all showed a decrease, while at weir 34, one entry increased in acid load. Differences of this type were also observed for the other parameters for these same mine complexes and may be due to the elevation of the mine entries with regard to structural positioning.

Summary

The following changes were observed in acid load production as a result of mine sealing: The total mean acid load was reduced by 62 pct over a 10-year period (table 4, fig. 10). The rate of change in total mean acid load in the 10 years implies that the acid load at 50 pct of the locations did not vary from presealing conditions by more than 2 lb/day. The greatest rate of change occurred at 10 locations that decreased in total mean acid load production (fig. 11). The total maximum acid load decreased by 86 pct, whereas the total minimum acid load increased by 365 pct (table 4). Sealing has resulted in an acid load production that was less variable than it was before seal completion (fig. 12). The percent change in coefficient of variation was greatest for those locations showing a decrease in acid load (fig. 13). Variance comparisons indicate there were more locations that showed significant reductions in acid load than there were with increases in acid load. There has been a suggested 55-pct effectiveness in acid load variance reduction over the 10 years. One characteristic that may be related to structural positioning is the inconsistency in parameter yields for a given mine complex with more than one entry.

TOTAL IRON LOAD

Table 6 shows the relative changes in total iron load resulting from mine seal construction. The total mean and minimum iron load increased during the first year following seal completion, and the total maximum iron load decreased during the same time interval. Summary tables of total iron load data for the three time intervals are in appendix A (tables A-7-A-9).

A comparison of total iron load before and 10 years after sealing reveals that the total mean and minimum iron loads increased 7 and 27 lb/day, respectively. The total maximum iron load decreased 313 lb/day from 389 to 76 lb/day.

TABLE 6. - Changes in total iron load

	Total mean	Total minimum	Total maximum
Quantity, lb/day:			
Before sealing...........	46	2	389
1st year after sealing...	56	4	188
10 years after sealing...	53	29	76
Quantity change from before sealing, lb/day:			
1st year after sealing...	+10	+2	-201
10 years after sealing...	+7	+27	-313
Percent change from before sealing:			
1st year after sealing...	+22	+100	-52
10 years after sealing...	+15	+1,350	-80

The increase in mean total iron load with regard to distribution by weir location is shown in figure 14. The number of weir locations that changed and the rates of change remained relatively constant over the 10-year period. Figure 15 shows that the total mean iron load increased at 8 weir locations, decreased at 8, and remained unchanged at 11, despite seal construction.

Mine sealing resulted in a reduction in the variability of total iron production. Prior to sealing, the variation in mean total iron load ranged from 50 to 275 pct per weir location, and 10 years later the variation was reduced to a maximum of 150 pct (fig. 16). Figure 17 shows this change in total iron load variability and indicates that 25 weir locations (93 pct) decreased, while 1 increased, and 1 remained unchanged.

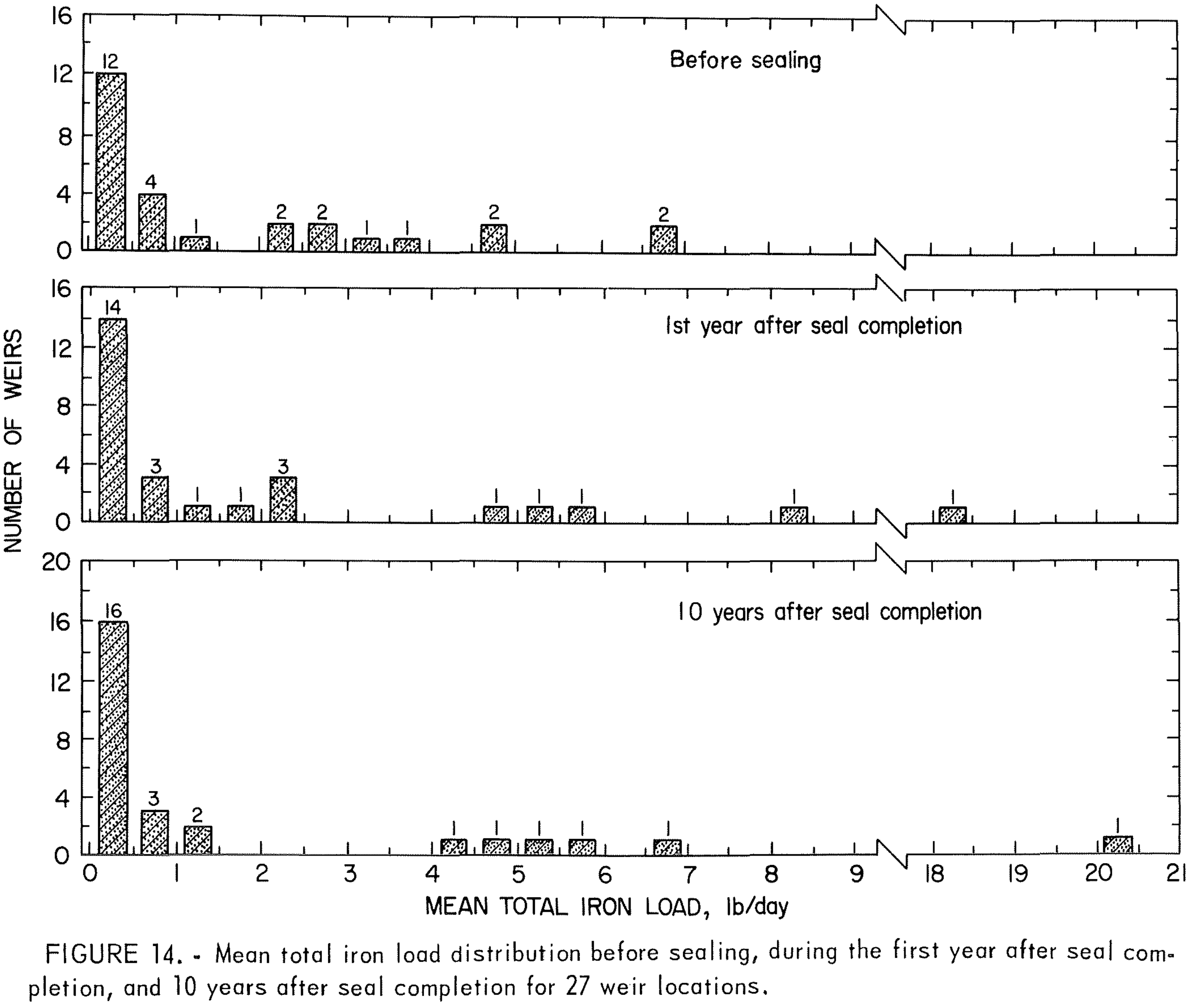

FIGURE 14. - Mean total iron load distribution before sealing, during the first year after seal completion, and 10 years after seal completion for 27 weir locations.

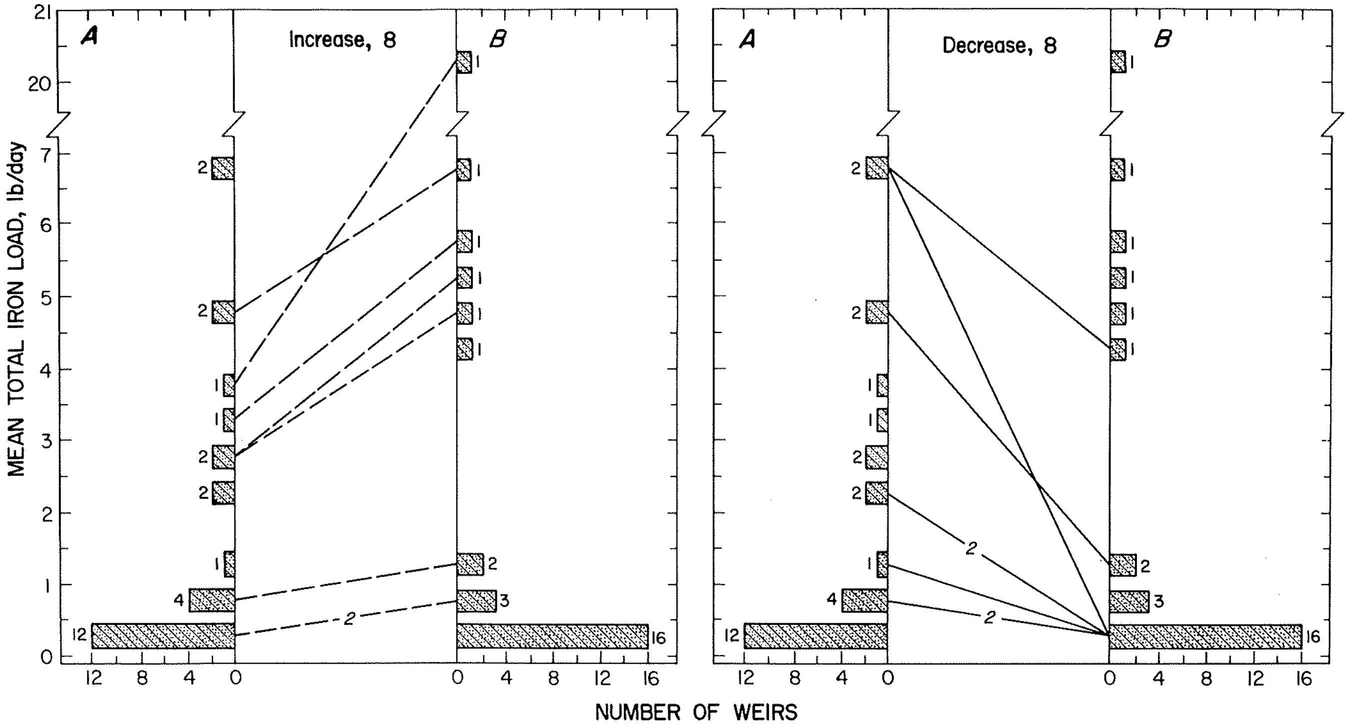

FIGURE 15. - Distributive rate of change for mean total iron load from before sealing *(A)* to 10 years after seal completion *(B)*. Dashed lines show increase; solid lines show decrease. Of the 27 weir locations, 11 remained unchanged.

Variance ratios of the total iron load from the conditions before sealing to those of 1 and 10 years after sealing show that after 1 year, 9 weir locations showed no significant difference, and 10 years later, the number of weirs indicating no significant difference increased to 14 (table 7). This suggests that the seals associated with these 14 weir locations have changed, with tendencies toward presealing conditions.

TABLE 7. - Comparison of variance in total iron load after sealing with variance before sealing

	Not significantly different	Significantly different[1]	No iron load
1 year after sealing:			
Number of weirs......	9	16	2
Percent.............	33	59	8
10 years after sealing:			
Number of weirs......	14	5	8
Percent.............	52	18	30

[1] 2.5-pct level of significance.

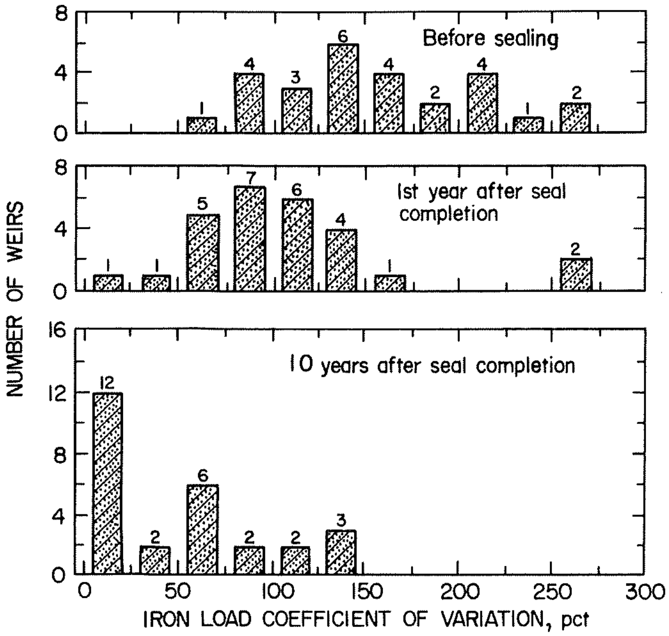

FIGURE 16. - Total iron load coefficient of variation for conditions before sealing, during the first year after seal completion, and 10 years after seal completion for 27 weir locations.

The number of weir locations that indicated a significant difference in total iron load at 1 year after sealing was 16, of which 4 increased (by 15, 6, and less than 0.5 lb/day), and 12 decreased, all with less than 2 lb/day. Ten years later, the number of weirs indicating significant differences dropped to five, with two locations increasing less than 1/2 lb/day and three locations increasing 6, 4, and less than 1 lb/day. Comparisons were not performed on eight weir locations that at the end of the 10-year interval had zero variances.

In summary, the effect of sealing on total iron load production is similar to the effect on mine water discharge. That is, the total mean and minimum iron loads increased and the total maximum decreased (table 6). There are about an equal number of weir locations having tendencies toward presealing conditions as there are those indicating reduced or unchanged total iron loads.

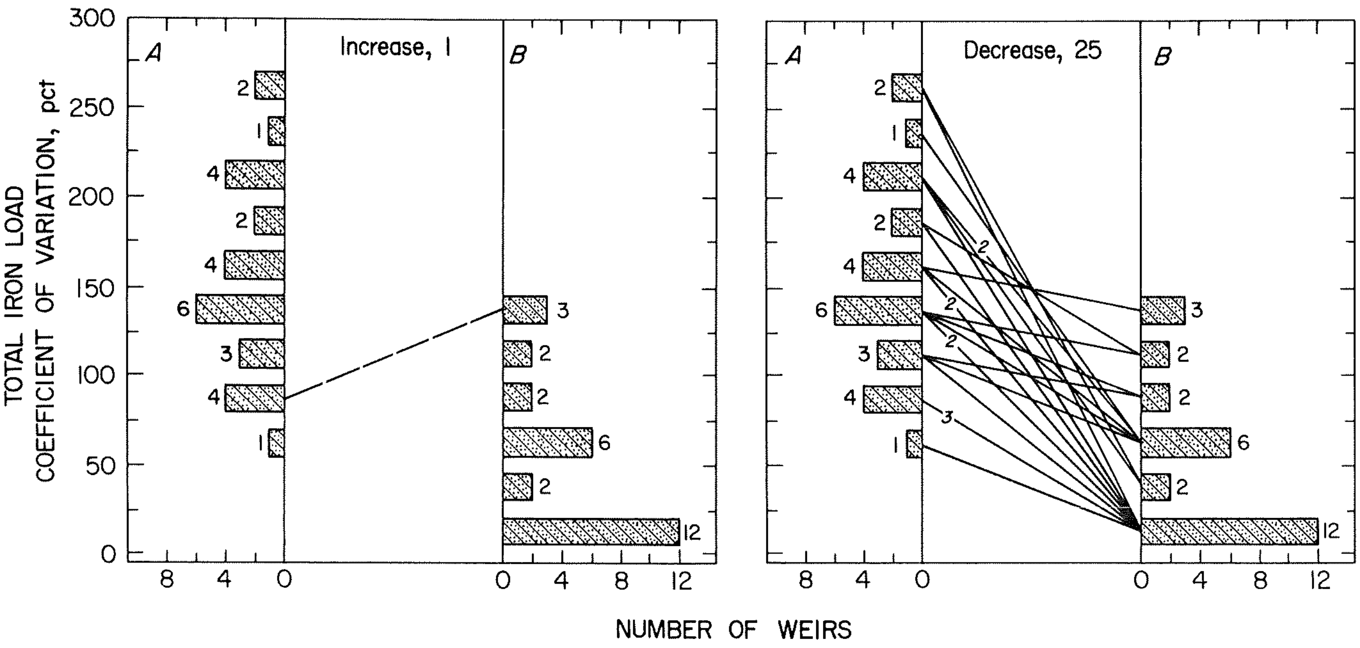

FIGURE 17. - Distributive rate of change for total iron load coefficient of variation from before sealing *(A)* to 10 years after seal completion *(B)*. Dashed line shows increase; solid lines show decrease. Of the 27 weir locations, 1 remained unchanged.

DISCUSSION AND RECOMMENDATIONS

The problems encountered during the field studies in the Moraine State Park area included the lack of mine maps showing the positions of mine entries and difficulties in the location of weirs, mine entries, and observation holes, due to caving, vegetative cover, and surface reclamation that followed deep mine sealing. Therefore, much more time was required than had been anticipated.

In order to avoid or minimize the problems encountered in evaluating mine sealing projects, future studies should concentrate on projects testing new mine seals that have been constructed in abandoned mine areas where the geologic and hydrologic parameters are well defined. Additional studies are not recommended in areas where seals have been constructed but data are incomplete or not available. Collection of data for short periods of time on a monthly basis, especially for larger areas such as Moraine State Park, is inadequate to establish trends. It is evident that more frequent sampling for a longer period of time (1 or more years) on a weekly basis is necessary to provide data that can be analyzed and used to evaluate the changes. This kind of detail was beyond the scope of this study; therefore, reasons for the observed changes in water quality cannot be conclusively determined.

As a result of mine sealing, certain long-term changes occurred in the mine pool and in water quality. Since extensive leakage and change in water quality were observed, it is assumed that deterioration of the seals or the areas around the seals has occurred. If this indeed has taken place, then one or more of the seals should be excavated to determine the reasons for leakage and the physical condition of the seal.

The degree to which the grout curtains served their purpose in limiting bedding or horizontal flow should be determined, including to what extent the size and distance between the holes contributed to forming a complete barrier to waterflow. Since flow rates increased, the effectiveness of these curtains should be studied.

Remote sensing studies should be used to aid in determining ground water movement related to lineaments and fracture traces. Information of this type will help in selecting the appropriate seal type, size, location, and cost with regard to water quality and load. It is recommended that an analysis of linear traces be used to further understand the hydrology of the problem areas and to provide a more systematic water discharge and water monitoring program. A remote sensing study in an area such as Moraine State Park should determine if certain seals were, in fact, constructed in areas of potential and realized high flow zones with regard to lineament and fracture traces.

CONCLUSIONS

The sample data collected illustrate measurable effects on water quality and quantity that are believed to be the direct result of mine sealing in the Moraine State Park area. These findings are the result of comparing the conditions of acid mine drainage before sealing to the conditions existing at the end of the 1st and 10th years following seal completion. The selection of 27 weir locations for evaluation was based on the existence of sufficient data for analysis. The remaining weir locations either were not located or were at or below lake level, or there were insufficient data on conditions either before or after sealing was completed. Since the conclusions largely depend on the significance placed on the number of samples collected during the study period and how well the samples represent the various areas of the park, the small number of samples collected 10 years after seal completion may not be representative of the overall park area. This may restrict certain conclusions.

The total mean water discharge, alkalinity, and total iron load increased over the 10-year period, whereas mean acid load decreased. Without exception, the total *minimum* water discharge, acid, alkalinity, and total iron load increased over the 10-year period. However, the total *maximum* water discharge, acid, alkalinity, and total iron load decreased. These changes in flow characteristics and water quality are believed to be related to the establishment of a mine pool created as a result of sealing. The suggested effectiveness in reducing acid load variance over the 10 years is approximately 55 pct. At the end of the 10-year interval, there appeared to be a tendency toward presealing conditions for mine water discharge at 6 weirs, for acid at 4 weirs, and for total iron load at 5 of the 27 weir locations. For a given mine complex with more than one entry, the parameter loads were not consistent. One of the more outstanding changes was in the distribution of the coefficient of variation for water discharge, acidity, and total iron load, which shows that sealing reduced the variability or scatter of each parameter load. At the end of the 10-year interval, the water discharge and water quality were more consistent than before seal construction.

The fact that waterflow and quality changed indicates that some factor pertaining to the seals, the areas surrounding the seals, or both, was changing with time. The grout curtains constructed at right angles through the center plugs were designed to divert waterflow around the seal area. This primarily assumes bedding plane flow and does not consider fracture permeability and flow around the curtain and the infiltration of air and water.

The suggested deterioration of the mine seals because of construction material, maintenance, and increased air or water content in the strata may be related to the acidity in the mine pool. Monthly monitoring of water discharge and parameter loads is not frequent enough to determine the details of the changes encountered.

Comparative values of water quality for those mines known to be inundated, or partly inundated, do not confirm that the development of a mine pool results in water quality improvement at the discharge points. For those mine entries associated with observation holes, each parameter--water discharge, acidity, and total iron load--can be shown to either increase, decrease, or vary at random.

Several mines were and remain the source of high water discharge. LANDSAT imagery made available after seal construction shows that there are several prominent lineaments that cross Lake Arthur and intersect these mine areas of high discharge. When the seals were constructed, ground water movement with regard to lineaments, discharge, and load was not considered.

Water samples of both the sealed entries and the mine pools indicated that, in general, the mine pool water was of better quality. Water samples from the inlet and outlet of Lake Arthur indicated that the water quality improved over the 10 years.

Mine seals do create varying size mine pools with water levels that fluctuate seasonally. The water level fluctuation alternately exposes sulfide minerals, allowing oxidation to continue. The oxygen is in part supplied by the infiltration of surface water containing dissolved oxygen. In addition, caving, piping, settlement, and ground movements create and aid natural joints, fractures, and lineations to increase permeability. A physical setting with increased permeability allows the infiltration of dissolved oxygen in water, and the direct infiltration of air in nonsaturated strata. Variation in atmospheric pressure also induces a change in the oxygen content of the overburden and mine pool area. Low mine pool water levels coincide with low precipitation, and it is during this yearly interval that oxidation is believed to be at maximum. As seasonal precipitation and infiltration increases, the mine pool level rises, and mine water discharge increases. The permeability of the seal restrains the rate of discharge and allows the pool level to rise, and water discharge remains a function of seasonal precipitation. However, mean water discharge has increased. The extent to which a given mine is inundated is related to permeability of the seal and strata, fracture, and lineation zones and to precipitation.

REFERENCES

1. Braley, S. A. An Evaluation of Mine Sealing. Mellon Inst., Pittsburgh, Pa., Spec. Rept. to Coal Ind. Advisory Comm. to Ohio River Valley Water Sanit. Comm., Res. Proj. 370-8, 1962, 33 pp.

2. Brown, M. B. (ed.). Stepwise Regression. Program P2R 13.2 in Biomedical Computer Program P-Series (BMDP-77); series ed. by W. J. Dixon. Dev. at Health Science Computing Facility, Univ. Calif., Los Angeles, Calif.; spons. by NIH Special Research Resources (grant RR-3), 1977, pp. 399-418.

3. Bucek, M. F., and J. L. Emel (HRB-Singer, Inc.). Evaluation of the Envivironment Effectiveness of Close Down Procedure--Eastern Underground Coal Mines. U.S. Environmental Protection Agency, Ind. Environ. Res. Lab., Cincinnati, Ohio, EPA-600/7-77-083, 1977, 140 pp.

4. Coal Mining. Substantial Progress Reported in Mine Seal Program. V. 15, February 1938, pp. 8-10.

5. Engineering News-Record. Mine Sealing Program To Reduce Acid Pollution in Stream. V. 16, January 1936, pp. 42-43.

6. Foreman, J. W. Evaluation of Pollution Abatement Procedures in Moraine State Park. Preprints, 3d Symp. on Coal Mine Drainage Research, Pittsburgh, Pa., May 19-20, 1970. Bituminous Coal Res., Inc., Monroeville, Pa., 1970, pp. 304-333.

7. _____. A Progress Report--Evaluation of Mine Drainage Abatement Projects in Western Pennsylvania. Preprints, 5th Symp. on Coal Mine Drainage Research, Louisville, Ky., Oct. 22-24, 1974. National Coal Assoc., Washington, D.C., 1974, pp. 128-132.

8. Foreman, J. W. (Gwin, Dobson, and Foreman, Inc., Consulting Engineers, Altoona, Pa.). Private communication, 1980; available upon request from Pittsburgh Research Center, Environ. Control, Bureau of Mines, Pittsburgh, Pa.

9. Foreman, J. W., and D. C. McLean. Evaluation of Pollution Abatement Procedures, Moraine State Park. U.S. Environmental Protection Agency, Environ. Prot. Technol. Ser., EPA-R2-73-140, January 1973, 71 pp.

10. Foreman, J. W., and E. G. Tarr. Moraine State Park Mine Drainage Project. Preprints, 2d Symp. on Coal Mine Drainage Research, Pittsburgh, Pa., May 14-15, 1968. Bituminous Coal Res. Inc., Monroeville, Pa., 1968, pp. 246-254.

11. Hill, R. D. Elkins Mine Drainage Pollution Control Demonstration Project. Preprints, 3d Symp. on Coal Mine Drainage Research, Pittsburgh, Pa., May 19-20, 1970. Bituminous Coal Res., Inc., Monroeville, Pa., 1970, pp. 283-303.

12. Leitch, R. D., and W. P. Yant. A Comparison of the Acidity of Waters From Some Active and Abandoned Coal Mines. BuMines RI 2895, 1928, 8 pp.

13. McNay, L. M. Surface Mine Reclamation, Moraine State Park, Pennsylvania. BuMines IC 8456, 1970, 28 pp.

14. Moebs, N. N., and S. Krickovic. Air-Sealing Coal Mines To Reduce Water Pollution. BuMines RI 7354, 1970, 33 pp.

15. Paterson, E. D., and J. A. Van Lieu. Coal Resources of Butler County, Pa. (Coal Resources of Western Pennsylvania). U.S. Geol. Survey Bull. 1143-C, 1971, 43 pp.

16. Scott, R. B. Evaluation of Bulkhead Seals. U.S. Environmental Protection Agency, Mine Drainage Pollut. Control Act., Rivesville, W. Va., October 1972, 29 pp.

17. Scott, R. B., and R. M. Hays. Inactive and Abandoned Underground Mines. U.S. Environmental Protection Agency, Off. Water and Hazard. Mater., Washington, D.C., EPA-440/9-75-007, 1975, 338 pp.

18. Sisler, J. D. Bituminous Coal Fields of Pennsylvania. Part II, Detailed Description of Coal Fields. Pa. Geol. Survey, 4th ser., Bull. M-6, 3d ed., 1961, pp. 78-94.

19. Tisdale, E. S., and W. E. Lyons. The Mine Sealing Program in the Ohio River Watershed. J. Am. Water Works Assoc., v. 26, 1934, pp. 1843-1852.

20. U.S. Code of Federal Regulations. Title 30--Mineral Resources. Chapter VII--Office of Surface Mining Reclamation and Enforcement, Department of the Interior; Subchapter K--Permanent Program Performance Standards; Parts 816-817--Surface and Underground Mining Activities. Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter O--Coal Mine Safety and Health; Part 75--Mandatory Safety Standards--Underground Coal Mines; Sec. 75.--1711--Sealing of Mines. July 1, 1981.

21. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environ. Data Service. Climatological Data, Annual Summary for Pennsylvania. V. 74-85, No. 13, 1969-80.

22. U.S. Geological Survey. Image Identification, EDIES, No. 853601449350. EROS Data Center, Sioux Falls, S. Dak., April 13, 1976.

APPENDIX A.--DATA FOR 27 WEIRS

TABLE A-1. - Mine water discharge at 27 weirs, before seal completion

Mine name	Weir	Entry[1]	Flow, gal/min			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer	18	1A	17.4	1.0	156.0	29.67	1.70	42
Shields	16	12	1.5	1.0	2.0	.51	.33	17
No name	20	16, 17	6.2	1.0	20.0	5.08	.82	22
Do	25	14	2.3	2.0	3.0	.57	.24	3
Fox	28	19A	5.4	1.0	13.0	4.72	.87	5
Do	31	19, 20, 21	12.7	1.0	100.0	14.08	1.11	51
Salzano Ross	33	23, 23A, 24	8.8	1.0	55.0	9.31	1.05	44
Do	34	25	10.2	1.0	50.0	10.72	1.05	26
N. Goubeaud	40	43, 44	10.5	1.0	50.0	13.00	1.23	17
W. Emery	41	54	2.9	1.0	12.0	2.44	.83	26
Do	44	53, 55	1.4	1.0	3.0	.66	.47	12
Do	43	57	4.4	1.0	15.0	3.41	.77	25
Fremont	45	59	2.7	1.0	10.0	2.09	.78	25
Do	46	60, 61	2.3	1.0	5.0	1.48	.66	8
Martzolf	51	71	2.4	1.0	6.0	1.78	.73	12
Do	53	73	22.6	2.0	200.0	47.29	2.08	17
Lindey	54	75	6.0	2.0	27.0	4.12	.68	51
Lincoln	57	76	5.9	1.0	18.0	5.56	.93	35
Do	58	77	9.2	2.0	18.0	4.35	.47	35
Do	59	78	7.9	2.0	20.0	4.81	.60	29
Kildoo	61	79	20.3	1.0	85.0	14.41	.71	47
Do	62	80	14.7	1.0	35.0	10.59	.72	41
Do	63	81	2.0	1.0	5.0	1.41	.70	11
Hilliard	66	82	12.2	1.0	100.0	24.30	1.99	16
Do	75	84	15.6	4.0	70.0	12.76	.81	51
Do	76	85	10.9	1.0	60.0	10.62	.97	31
Do	79	86	2.8	1.0	5.0	1.75	.62	10

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-2. - Mine water discharge at 27 weirs, during the first year after seal completion

Mine name	Weir	Entry[1]	Flow, gal/min			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer	18	1A	8.3	1.0	12.0	6.35	0.76	3
Shields	16	12	5.0	1.0	28.0	8.45	1.69	10
No name	20	16, 17	2.5	1.0	4.0	2.12	.84	2
Do	25	14	1.0	1.0	1.0	0	0	2
Fox	28	19A	20.8	2.0	94.0	28.70	1.37	11
Do	31	19, 20, 21	7.2	1.0	12.0	5.71	.79	5
Salzano Ross	33	23, 23A, 24	5.4	1.0	28.0	8.64	1.59	14
Do	34	25	39.5	1.0	236.0	67.37	1.70	13
N. Goubeaud	40	43, 44	16.2	1.0	30.0	10.47	.64	5
W. Emery	41	54	5.4	1.0	42.0	10.77	1.98	14
Do	44	53, 55	1.6	1.0	6.0	1.35	.84	15
Do	43	57	3.0	1.0	6.0	1.96	.65	14
Fremont	45	59	2.0	1.0	5.0	1.46	.78	7
Do	46	60, 61	3.0	1.0	9.0	2.77	.92	15
Martzolf	51	71	1.3	1.0	2.0	.50	.37	9
Do	53	73	6.4	2.0	12.0	3.31	.52	14
Lindey	54	75	7.0	2.0	28.0	7.9	1.12	10
Lincoln	57	76	5.1	3.0	8.0	1.95	.37	7
Do	58	77	20.0	3.0	60.0	19.03	.95	10
Do	59	78	3.6	1.0	6.0	1.87	.52	9
Kildoo	61	79	13.3	2.0	42.0	11.75	.88	17
Do	62	80	11.8	3.0	28.0	6.40	.54	13
Do	63	81	1.0	1.0	1.0	0	0	4
Hilliard	66	82	23.1	2.0	156.0	38.11	1.64	17
Do	75	84	7.0	1.0	28.0	10.54	1.52	11
Do	76	85	5.3	1.0	28.0	8.35	1.57	10
Do	79	86	10.7	1.0	60.0	17.70	1.78	11

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-3. - Mine water discharge at 27 weirs, 10 years after seal completion

Mine name	Weir	Entry[1]	Flow, gal/min			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer..................	18	1A	42.3	24.6	60.0	25.03	0.59	2
Shields................	16	12	4.7	2.4	7.0	3.25	.69	2
No name................	20	16, 17	18.4	3.3	33.4	21.28	1.16	2
Do..................	25	14	3.9	3.3	4.5	.84	.22	2
Fox....................	28	19A	.6	.2	1.0	.56	.93	3
Do..................	31	19, 20, 21	7.0	2.7	11.2	6.01	.86	2
Salzano Ross...........	33	23, 23A, 24	.4	.2	.5	.21	.53	2
Do..................	34	25	0	0	0	0	0	2
N. Goubeaud............	40	43, 44	1.4	.7	2.0	.91	.65	6
W. Emery...............	41	54	1.5	1.0	2.0	.71	.47	2
Do..................	44	53, 55	1.3	.6	2.0	.99	.76	2
Do..................	43	57	4.4	4.10	4.7	.42	.10	2
Fremont................	45	59	1.0	0	2.0	1.41	1.41	2
Do..................	46	60, 61	5.9	.8	11.0	7.21	1.22	2
Martzolf...............	51	71	.2	0	.4	.28	1.40	2
Do..................	53	73	4.4	1.7	7.0	3.74	.85	2
Lindey.................	54	75	6.1	5.8	6.4	.42	.07	2
Lincoln................	57	76	17.1	13.7	20.4	4.73	.28	2
Do..................	58	77	16.0	12.0	20.0	5.65	.35	2
Do..................	59	78	45.0	25.0	65.0	28.28	.63	2
Kildoo.................	61	79	18.5	2.0	35.0	23.33	1.26	2
Do..................	62	80	19.4	13.7	25.0	7.99	.41	2
Do..................	63	81	2.2	1.0	3.3	1.62	.74	2
Hilliard...............	66	82	1.8	1.2	2.3	.77	.43	2
Do..................	75	84	6.4	.7	12.0	7.99	1.25	2
Do..................	76	85	25.0	20.0	30.0	7.07	.28	2
Do..................	79	86	70.0	40.0	100.0	42.42	.61	2

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-4. - Acid load at 27 weirs, before seal completion

Mine name	Weir	Entry[1]	Acid load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer..................	18	1A	22.9	6.5	90.7	15.58	0.67	42
Shields................	16	12	.3	0	3.9	.99	3.09	17
No name................	20	16, 17	.1	0	1.9	.40	4.04	22
Do..................	25	14	.2	.1	.4	.15	.65	3
Fox....................	28	19A	.1	0	.4	.17	2.23	5
Do..................	31	19, 20, 21	26.1	1.1	68.0	19.08	.73	51
Salzano Ross...........	33	23, 23A, 24	132.8	0	465.0	89.58	.67	44
Do..................	34	25	.3	0	3.8	.84	2.62	26
N. Goubeaud............	40	43, 44	.1	0	1.0	.27	2.02	17
W. Emery...............	41	54	.9	0	4.9	1.41	1.64	26
Do..................	44	53, 55	1.0	0	5.0	1.38	1.46	12
Do..................	43	57	4.4	0	21.0	5.45	1.23	25
Fremont................	45	59	.6	0	4.1	1.12	1.76	25
Do..................	46	60, 61	1.2	0	5.8	2.04	1.65	8
Martzolf...............	51	71	.2	0	.5	.16	.71	12
Do..................	53	73	20.0	.3	117.0	27.67	1.38	17
Lindey.................	54	75	18.2	.1	50.6	11.46	.62	51
Lincoln................	57	76	26.9	1.3	280.0	49.21	1.83	35
Do..................	58	77	46.5	6.0	94.4	28.84	.62	35
Do..................	59	78	70.2	3.8	280.0	62.76	.89	29
Kildoo.................	61	79	80.3	1.6	235.0	49.05	.61	47
Do..................	62	80	60.3	1.3	151.0	47.87	.79	41
Do..................	63	81	1.1	0	2.2	.65	.57	11
Hilliard...............	66	82	11.1	0	130.0	31.82	2.86	16
Do..................	75	84	3.3	0	79.0	12.84	3.87	51
Do..................	76	85	4.0	.2	23.6	5.67	1.41	31
Do..................	79	86	7.0	.9	20.8	6.72	.95	10

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-5. - Acid load at 27 weirs, during the first year after seal completion

Mine name	Weir	Entry[1]	Acid load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer..................	18	1A	22.00	3.2	31.9	16.26	0.74	3
Shields................	16	12	.02	0	.2	.06	3.16	10
No name................	20	16, 17	0	0	0	0	0	2
Do..................	25	14	.20	0	.3	.21	1.41	2
Fox....................	28	19A	0	0	0	0	0	11
Do..................	31	19, 20, 21	4.70	0	15.8	6.64	1.40	5
Salzano Ross...........	33	23, 23A, 24	14.40	0	154.0	40.62	2.82	14
Do..................	34	25	1.30	0	11.3	3.30	2.45	13
N. Goubeaud............	40	43, 44	.30	0	1.0	.43	1.66	5
W. Emery...............	41	54	.10	0	.5	.14	1.70	14
Do..................	44	53, 55	2.10	0	13.1	3.85	1.81	15
Do..................	43	57	11.10	.1	25.1	8.63	.77	14
Fremont................	45	59	.01	0	.1	.03	2.64	7
Do..................	46	60, 61	.40	0	4.0	1.03	2.83	15
Martzolf...............	51	71	.03	0	.2	.07	2.12	9
Do..................	53	73	6.60	0	19.0	6.36	.96	14
Lindey.................	54	75	13.70	0	28.6	9.87	.71	10
Lincoln................	57	76	16.00	8.6	22.8	4.32	.27	7
Do..................	58	77	181.70	14.6	694.0	222.77	1.22	10
Do..................	59	78	19.50	2.7	46.9	14.85	.76	9
Kildoo.................	61	79	23.30	3.2	59.6	14.87	.63	17
Do..................	62	80	27.00	5.3	40.6	11.55	.42	13
Do..................	63	81	.70	0	1.9	.85	1.26	4
Hilliard...............	66	82	4.20	0	41.2	9.71	2.28	17
Do..................	75	84	12.80	.2	60.5	21.13	1.65	11
Do..................	76	85	8.20	.3	47.7	14.16	1.73	10
Do..................	79	86	10.00	2.2	40.1	11.16	1.13	11

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-6. - Acid load at 27 weirs, 10 years after seal completion

Mine name	Weir	Entry[1]	Acid load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer..................	18	1A	56.6	39.6	73.6	24.04	0.42	2
Shields................	16	12	0	0	0	0	0	2
No name................	20	16, 17	0	0	0	0	0	2
Do..................	25	14	.2	0	.3	.21	1.05	2
Fox....................	28	19A	.1	.1	.1	0	0	3
Do..................	31	19, 20, 21	29.3	10.7	47.8	26.23	.89	2
Salzano Ross...........	33	23, 23A, 24	3.4	2.4	4.3	1.34	.39	2
Do..................	34	25	0	0	0	0	0	2
N. Goubeaud............	40	43, 44	0	0	0	0	0	6
W. Emery...............	41	54	0	0	0	0	0	2
Do..................	44	53, 55	.15	.1	.2	.07	.47	2
Do..................	43	57	7.2	3.5	10.8	5.16	.71	2
Fremont................	45	59	0	0	0	0	0	2
Do..................	46	60, 61	2.9	0	2.9	0	0	2
Martzolf...............	51	71	.1	0	.1	0	0	2
Do..................	53	73	.2	0	.3	.21	1.05	2
Lindey.................	54	75	0	0	0	0	0	2
Lincoln................	57	76	9.0	1.0	17.0	11.31	1.25	2
Do..................	58	77	12.8	9.3	16.3	4.94	.38	2
Do..................	59	78	53.4	32.5	74.2	29.48	.55	2
Kildoo.................	61	79	10.1	.3	19.8	13.78	1.36	2
Do..................	62	80	0	0	0	0	0	2
Do..................	63	81	.2	0	.4	.28	1.4	2
Hilliard...............	66	82	0	0	.02	0	0	2
Do..................	75	84	1.5	.2	2.8	1.83	1.22	2
Do..................	76	85	0	0	0	0	0	2
Do..................	79	86	18.8	7.7	29.8	15.62	.83	2

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-7. - Total iron load at 27 weirs, before seal completion

Mine name	Weir	Entry[1]	Total iron load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer..................	18	1A	4.50	0.20	59.10	9.67	2.17	42
Shields................	16	12	.02	0	.20	.05	2.00	17
No name................	20	16, 17	.10	0	.40	.09	1.36	22
Do..................	25	14	.01	0	.01	.01	.86	3
Fox....................	28	19A	.03	0	.10	.03	1.16	5
Do..................	31	19, 20, 21	2.70	.10	24.50	3.45	1.29	51
Salzano Ross...........	33	23, 23A, 24	4.80	.10	59.00	9.11	1.90	44
Do..................	34	25	.20	.01	3.00	.57	2.64	26
N. Goubeaud............	40	43, 44	.60	.01	6.70	1.65	2.54	17
W. Emery...............	41	54	.40	0	2.80	.64	1.57	26
Do..................	44	53, 55	.40	.01	1.80	.60	1.61	12
Do..................	43	57	.90	.01	5.30	1.35	1.45	25
Fremont................	45	59	.40	0	3.80	.75	2.06	25
Do..................	46	60, 61	.30	.02	.60	.19	.78	8
Martzolf...............	51	71	.10	.02	.60	.16	1.14	12
Do..................	53	73	1.40	.20	6.00	1.85	1.36	17
Lindey.................	54	75	2.30	.30	11.00	2.51	1.11	51
Lincoln................	57	76	2.60	.10	2.47	4.77	1.84	35
Do..................	58	77	3.00	.40	13.50	2.56	.85	35
Do..................	59	78	3.80	.10	50.00	9.06	2.39	29
Kildoo.................	61	79	6.80	.01	46.40	8.53	1.25	47
Do..................	62	80	6.50	.10	46.40	9.43	1.44	41
Do..................	63	81	.10	.01	.10	.03	.71	11
Hilliard...............	66	82	.30	0	2.00	.55	1.69	16
Do..................	75	84	2.10	0	10.70	1.98	.95	51
Do..................	76	85	.50	.01	4.60	.82	1.54	31
Do..................	79	86	.80	0	5.20	1.58	2.00	10

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-8. - Total iron load at 27 weirs, during the first year after seal completion

Mine name	Weir	Entry[1]	Total iron load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer..................	18	1A	2.00	0.30	3.40	1.57	0.78	3
Shields................	16	12	.04	0	.10	.04	.93	10
No name................	20	16, 17	.01	0	.10	.01	1.41	2
Do..................	25	14	.20	.01	.30	.22	1.33	2
Fox....................	28	19A	.10	.02	.40	.13	.98	11
Do..................	31	19, 20, 21	1.30	.01	4.10	1.67	1.26	5
Salzano Ross...........	33	23, 23A, 24	4.90	.04	50.00	13.19	2.69	14
Do..................	34	25	.40	.02	1.40	.42	1.19	13
N. Goubeaud............	40	43, 44	.10	.01	.10	.04	.70	5
W. Emery...............	41	54	.10	0	.30	.07	1.12	14
Do..................	44	53, 55	.40	.04	.90	.22	.58	15
Do..................	43	57	2.20	.10	7.30	2.32	1.03	14
Fremont................	45	59	.10	0	.40	.13	1.04	7
Do..................	46	60, 61	.30	0	2.30	.78	2.54	15
Martzolf...............	51	71	.02	.01	.10	.01	.74	9
Do..................	53	73	.70	.02	2.80	.77	1.18	14
Lindey.................	54	75	8.10	.50	28.30	9.08	1.12	10
Lincoln................	57	76	2.30	1.40	2.80	.46	.20	7
Do..................	58	77	18.30	.80	43.80	14.11	.77	10
Do..................	59	78	1.70	.02	3.10	1.09	.65	9
Kildoo.................	61	79	5.20	.20	14.20	4.22	.81	17
Do..................	62	80	5.60	.30	14.20	3.97	.70	13
Do..................	63	81	.03	.02	.10	.01	.33	4
Hilliard...............	66	82	.30	.02	1.50	.41	1.61	17
Do..................	75	84	.70	.10	1.90	.58	.87	11
Do..................	76	85	.30	.10	.80	.24	.95	10
Do..................	79	86	.90	.20	3.70	1.16	1.29	11

[1] Entry locations are shown in figures 2 and 3 in the main text.

TABLE A-9. - Total iron load at 27 weirs, 10 years after seal completion

Mine name	Weir	Entry[1]	Total iron load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Wimer.......	18	1A	6.50	5.000	7.90	2.05	0.32	2
Shields.....	16	12	.10	0	.10	.07	.70	2
No name.....	20	16, 17	.50	.020	1.00	.69	1.38	2
Do........	25	14	.10	.100	.10	0	0	2
Fox.........	28	19A	.10	.010	.10	.06	.60	3
Do........	31	19, 20, 21	5.10	1.900	8.30	4.52	.89	2
Salzano Ross	33	23, 23A, 24	1.10	1.000	1.10	.07	.06	2
Do........	34	25	0	0	0	0	0	2
N. Goubeaud.	40	43, 44	.10	.030	.10	.04	.40	6
W. Emery....	41	54	.40	.200	.60	.28	.70	2
Do........	44	53, 55	.30	.200	.30	.07	.23	2
Do........	43	57	.10	.100	.10	0	0	2
Fremont.....	45	59	.10	0	.10	0	0	2
Do........	46	60, 61	.90	.010	1.70	1.19	1.32	2
Martzolf....	51	71	0	0	0	0	0	2
Do........	53	73	.30	.200	.30	.07	.23	2
Lindey......	54	75	.40	.100	.60	.35	.88	2
Lincoln.....	57	76	4.70	1.000	8.30	5.16	1.10	2
Do........	58	77	5.60	4.800	6.30	1.06	.19	2
Do........	59	78	20.20	13.000	27.30	10.11	.50	2
Kildoo......	61	79	4.10	.600	7.60	4.94	1.20	2
Do........	62	80	.20	.100	.30	.14	.70	2
Do........	63	81	.02	.020	.02	0	0	2
Hilliard....	66	82	.01	.004	.01	0	0	2
Do........	75	84	.04	.030	.04	0	0	2
Do........	76	85	1.20	.050	2.40	1.66	1.38	2
Do........	79	86	.90	.400	1.30	.63	.70	2

[1] Entry locations are shown in figures 2 and 3 in the main text.

APPENDIX B.--PARTIAL DATA FOR NINE WEIRS

TABLE B-1. - Mine water discharge at nine weirs, before seal completion

Mine name	Weir	Entry[1]	Flow, gal/min			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Alben......	19	5	5.5	1.0	10.0	2.19	0.39	26
Shields....	15	11	1.7	1.0	3.0	.82	.45	14
Do.......	17	13	1.7	1.0	2.0	.51	.30	6
Fox........	29	19	14.0	(2)	(2)	(2)	(2)	1
Goubeaud...	39	37, 38	2.3	1.0	5.0	1.34	.59	11
Isle.......	47	65, 66	5.5	1.0	20.0	3.90	.72	40
Martzolf...	49	68	6.7	3.0	15.0	3.80	.57	9
Do.......	50	69	3.3	1.0	8.0	3.20	.98	4
Do.......	52	72	2.0	1.0	6.0	1.54	.77	6

[1] Entry locations are shown in figures 2 and 3 in the main text.

[2] Insufficient data.

TABLE B-2. - Mine water discharge at eight of nine weirs, during the first year and 10 years after seal completion

Mine name	Weir	Entry[1]	Flow, gal/min			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
DURING 1ST YEAR AFTER SEAL COMPLETION[2]								
Fox........	29	19	2.6	1.0	9.0	3.57	1.37	5
Isle.......	47	65, 66	3.0	(3)	(3)	(3)	(3)	1
10 YEARS AFTER SEAL COMPLETION[4]								
Alben......	19	5	1.5	1.2	1.70	0.35	0.23	2
Shields....	15	11	1.2	.7	1.70	.70	.58	2
Do.......	17	13	8.0	4.2	11.80	5.37	.67	2
Fox........	29	19	.4	.2	.50	.21	.53	2
Goubeaud...	39	37, 38	1.8	.3	3.20	2.05	1.34	2
Martzolf...	50	69	NAp	Dry	10.00	NAp	NAp	1
Do.......	52	72	NAp	Dry	.18	NAp	NAp	1

NAp Not applicable.

[1] Entry locations are shown in figures 2 and 3 in the main text.

[2] There were no 1st-year data for 7 of the weirs.

[3] Insufficient data.

[4] Weir 47 (Isle Mine) was located at lake level; weir 49 (Martzolf Mine) was not located.

TABLE B-3. - Acid load at nine weirs, before seal completion

Mine name	Weir	Entry[1]	Acid load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Alben......	19	5	34.8	3.5	80.4	20.10	0.57	26
Shields....	15	11	2.5	.1	6.8	1.78	.72	14
Do.......	17	13	.2	0	.4	.15	.77	6
Fox........	29	19	49.7	(2)	(2)	(2)	(2)	1
Goubeaud...	39	37, 38	2.7	.3	13.0	3.74	1.37	11
Isle.......	47	65, 66	1.3	0	5.6	1.45	1.11	40
Martzolf...	49	68	1.7	.3	3.9	1.09	.63	9
Do.......	50	69	.2	.1	12.0	5.66	1.59	4
Do.......	52	72	.1	0	.2	.09	1.17	6

[1] Entry locations are shown in figures 2 and 3 in the main text.

[2] Insufficient data.

TABLE B-4. - Acid load at eight of nine weirs, during the first year and 10 years after seal completion

Mine name	Weir	Entry[1]	Acid load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
DURING 1ST YEAR AFTER SEAL COMPLETION[2]								
Fox............	29	19	2.1	0.9	4.7	1.5	0.73	5
Isle...........	47	65, 66	0	(3)	(3)	(3)	(3)	1
10 YEARS AFTER SEAL COMPLETION[4]								
Alben..........	19	5	0	0	0	NAp	NAp	2
Shields........	15	11	.5	.3	.6	0.21	0.42	2
Do...........	17	13	6.1	.3	11.8	8.13	1.33	2
Fox............	29	19	.6	.3	.9	.42	.70	2
Goubeaud.......	39	37, 38	.1	0	.1	.07	.70	2
Martzolf.......	50	69	NAp	Dry	0	NAp	NAp	1
Do...........	52	72	.1	Dry	.1	0	NAp	1

NAp Not applicable.

[1] Entry locations are shown in figures 2 and 3 in the main text.

[2] There were no 1st-year data for 7 of the weirs.

[3] Insufficient data.

[4] Weir 47 (Isle Mine) was located at lake level; weir 49 (Martzolf Mine) was not located.

TABLE B-5. - Total iron load at nine weirs, before seal completion

Mine name	Weir	Entry[1]	Total iron load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
Alben..........	19	5	2.60	0.30	12.00	2.34	0.90	26
Shields........	15	11	.03	.01	.10	.02	.79	14
Do...........	17	13	.01	.01	.03	.01	.60	6
Fox............	29	19	1.70	(2)	(2)	(2)	(2)	1
Goubeaud.......	39	37, 38	.30	.02	1.30	.04	1.56	11
Isle...........	47	65, 66	.70	.01	3.00	.67	.92	40
Martzolf.......	49	68	.70	.04	1.50	.45	.66	9
Do...........	50	69	.20	0	.50	.19	.87	4
Do...........	52	72	.20	.01	.30	.11	.74	6

[1] Entry locations are shown in figures 2 and 3 in the main text.

[2] Insufficient data.

TABLE B-6. - Total iron load at eight of nine weirs, during the first year and 10 years after seal completion

Mine name	Weir	Entry[1]	Total iron load, lb/day			Standard deviation	Coefficient of variation	Number of samples
			Mean	Minimum	Maximum			
DURING 1ST YEAR AFTER SEAL COMPLETION[2]								
Fox............	29	19	0.2	0.1	0.2	0.06	0.41	5
Isle...........	47	65, 66	.1	(3)	(3)	(3)	(3)	1
10 YEARS AFTER SEAL COMPLETION[4]								
Alben..........	19	5	0.10	0.040	0.10	0.04	0.40	2
Shields........	15	11	.01	.004	.01	.01	.40	2
Do...........	17	13	.10	.000	.10	.07	.07	2
Fox............	29	19	.20	.020	.30	.19	.95	2
Goubeaud.......	39	37, 38	.01	.004	.20	.13	1.30	2
Martzolf.......	50	69	NAp	Dry	.10	NAp	NAp	1
Do...........	52	72	NAp	Dry	0	NAp	NAp	1

NAp Not applicable.

[1] Entry locations are shown in figures 2 and 3 in the main text.

[2] There were no 1st-year data for 7 of the weirs.

[3] Insufficient data.

[4] Weir 47 (Isle Mine) was located at lake level; weir 49 (Martzolf Mine) was not located.

☆U.S. GOVERNMENT PRINTING OFFICE: 1983-605-015/25

INT.-BU.OF MINES,PGH.,PA. 26757