BuMines OFR 210-84

PB85-149292

A mining research contract report

JANUARY 1984

Final Report: Research on the Hydrology and Water Quality of Watersheds Subjected to Surface Mining

Contract Nos. J0166054 and J0166055

United States Department of Agriculture
Agricultural Research Service
and
The Ohio State University
Ohio Agricultural Research and
Development Center, Wooster, Ohio

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. BuMines OFR 210-84	2.	3. Recipient's Accession No. PB85 149292/AS

4. Title and Subtitle

Final Report: Research on the Hydrology and Water Quality of Watersheds Subjected to Surface Mining

5. Report Date Jan. 1984

6.

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8. Performing Organization Rept. No.

9. Performing Organization Name and Address

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10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) J0166054, J0166055
(G)

12. Sponsoring Organization Name and Address

Office of Assistant Director--Mining Research
Bureau of Mines
U.S. Department of the Interior
Washington, DC 20241

13. Type of Report & Period Covered
Contract research, 1/76--1/84

14.

15. Supplementary Notes

Approved for release November 2, 1984.

16. Abstract (Limit 200 words)

In 1976, an investigation was begun on the impact of surface mining and reclamation on the hydrology and water quality of surface and subsurface waters. The study was conducted in the Ohio coal surface mining region and considered three different coalbeds of Pennsylvanian age. The basic research unit at each site consisted of a watershed of less than 50 acres with an accompanying sediment pond and instrumentation for monitoring climatic variables. The watershed was instrumented to monitor ground water levels and surface water flow and to collect samples of both for water quality analyses. Each site was monitored throughout an approximate 5-year period that included a premine subperiod, a mining and reclamation subperiod, and a subperiod consisting of the initial years of the postreclamation condition. After regrading of spoil was complete at one of the sites, a number of 72.6-ft-long plots were instrumented on spoil and topsoiled areas. Four different slopes were used to study erosion processes and the effectiveness of reclamation treatments on the establishment of vegetative cover on a reclaimed surface. The treatments consisted of different topsoil and different mulching depths. Concurrent with the watershed and plot studies, an investigation was conducted on the economics of complying with reclamation laws in Ohio and the development or adaptation of surface and subsurface hydrology simulation models for conditions in the region under study.

17. Document Analysis a. Descriptors

Mining research
- Hydrology
- Water quality
- Ground Water
- Sediment quality

Runoff quality
Surface mining impacts
Watershed models
Ground water models

Hydrologic models
Reclaimed soils
Precipitation quality
Reclamation treatments

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group 08I

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited by NTIS.	Unclassified	35
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

FOREWORD

This joint report was prepared by the USDA-Agricultural Research Service, North Appalachian Experimental Watershed, Coshocton, Ohio and The Ohio State University-Ohio Agricultural Research and Development Center, Wooster, Ohio under USBM Contracts J0166055 (USDA-ARS) and J0166054 (OSU-OARDC). The contracts were initiated under the Mining Environmental Research Program. They were administered under the technical direction of the Denver Mining Research Center with Ms. Deborah P. Sherer acting as the Technical Project Officer. Ms. Gladys S. Barrera is the contract administrator for the Bureau of Mines.

This is a final report for the project. As such, it comprises an executive summary of the findings and accomplishments of all aspects of the investigation.

The contracts were awarded for conducting research as proposed in a document presented jointly by the USDA-ARS, North Appalachian Experimental Watershed and The Ohio State University-Ohio Agricultural Research and Development Center: A Research Proposal--Research on the Hydrology and Water Quality of Watersheds Subjected to Surface Mining in May 1975. The U. S. Geological Survey, the Soil Conservation Service, the Muskingum Watershed Conservancy District, the Utah State University, and three private mining companies are participants in the studies.

PREFACE

Those organizations and individuals contributing technical information to this report are as follows:

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ABSTRACT

Three watersheds of less than 50 Ac each were observed during premining conditions, during surface coal mining and reclamation, and after reclamation in different geologic settings in the coal region of Ohio. Surface and subsurface hydrologic and water quality parameters were monitored to determine the impacts that surface mining and reclamation had upon them.

A set of reclaimed soil and spoil plots on different slopes were studied for erosion-related effects and for various reclamation techniques.

An economic study of reclamation under the laws of Ohio indicated a cost/benefits ratio considerably greater than one, and showed a small net decrease in the regional economy because of the cost-increasing nature of reclamation requirements.

A ground-water model was modified for application to the specific geological and landscape conditions of Ohio and neighboring states' coal region. A new model for predicting surface runoff, infiltration, soil water recharge, and percolation was developed to interface with the ground-water model.

Watershed and plot experimental data indicated the following:

1. The three periods, premine, mining-reclamation, and postreclamation, were too short for many analytical purposes. The reclaimed watersheds were still adjusting to the disturbance, and hydrologic and water quality parameters were still changing at the end of observations at each site. The reported results are, therefore, those that can be most readily discerned. The postreclamation results apply to the early postreclamation period and may change as reclamation ages.

2. Mulched seedings on both plots and watersheds were the most successful treatments, both in terms of reestablishing ground cover and in terms of controlling erosion. Diversion terraces were used on two of the watersheds to control erosion while vegetation was becoming established. Both terrace systems repeatedly failed and masked the effects of the reclamation practice upon erosion control at those sites.

3. There was no difference in topsoil or spoil as a media for the reestablishment of vegetation (spoil and topsoil were both fertilized in accordance with soil tests).

4. Replaced topsoils contained more coarse fragments than the originals, but pH levels were about the same. The spoil that underlay the new topsoils, though coarser, exhibited average pH values similar to the original subsoil. At one of two sandstone sites, however, there was a wide range of spoil pH, some values being much lower than in the original subsoil. Both sandstone sites were marked by zones of toxic material on the surface after spreading of topsoil. No toxic material appeared after topsoil spreading at a limestone site.

5. Plot data showed runoff volume from spoil to be greater than that from reclaimed topsoil, but mulch or vegetation had the unexplainable effect of increasing runoff volume. However, both mulch and vegetation were effective in controlling erosion.

6. Mining and reclamation activities caused increased runoff and drastically increased erosion on the watersheds. After reclamation, runoff remained high, and, at the one site where erosion control was successful, sediment concentrations returned to the premine levels or below.

7. The underclay beneath the coal supported a perched water table that was destroyed during mining. This resulted in decreased dry-weather streamflow at the watershed outlet if a lower perched aquifer also drained to the outlet. At one site, the destroyed aquifer was the only source of dry-weather streamflow, so that type of flow ceased. After reclamation, the destroyed aquifers began to reestablish in the spoil, but were still under development at the end of observations. At that time, there was evidence that the new aquifers were beginning to contribute to dry-weather streamflow, but only slightly.

8. Chemical water quality was much influenced by whether the original overburden included limestone or sandstone in quantity. Generally, the sandstone sites experienced the poorest quality water as a result of mining. A few parameters at these sites exceeded the limits set by various regulatory agencies. Most of the parameters of significant environmental concern, such as chromium, cadmium, and mercury, were either not detected at all or were detected at low levels in a few samples. Sulfate concentration was higher after reclamation and was still increasing in surface water as the observations ceased.

9. Sulfates were also the primary problem parameter in ground-water quality. At all sites, the newly developing aquifers over the underclays from which the coal had been removed were comprised of calcium sulfate water instead of the original, predominantly calcium bicarbonate water. This may be the source of the increasing sulfate nature of streamflow. At two of the sites, by the end of observations, the sulfate water in the new aquifer had begun to contaminate the next perched aquifer below.

10. Sediment quality at the sandstone sites deteriorated more than at the limestone site prior to spreading topsoil.

11. Settling ponds were effective in trapping much of the larger sediment size fractions. The smaller size fractions that left the ponds were enriched with the metal parameters; nevertheless, many fewer metal materials were discharged from the ponds than entered them.

SUMMARY

In 1976, an investigation was begun of the impact of surface mining and reclamation upon the hydrology and water quality of surface and subsurface waters. The study was conducted in the Ohio coal surface mining region and considered three different coal beds of Pennsylvanian age. Two were overlaid by sandstone and shale; one was overlaid by limestone and shale.

The basic research unit at each site consisted of a watershed of less than 50 Ac with an accompanying sediment pond and instrumentation for monitoring climatic variables. The watershed was instrumented to monitor ground-water levels and surface-water flow and to collect samples of both for water quality analysis.

Observations were begun at each site prior to mining and were continued to the extent practicable throughout an approximately 5-year period that included a premine subperiod, a mining and reclamation subperiod, and a subperiod consisting of the initial years of the postreclamation condition.

After regrading of spoil was complete at one of the sites, a number of 72.6 ft-long plots were instrumented on spoil and topsoiled areas. Four different slopes were used to study erosion processes and the effectiveness of reclamation treatments on the establishment of vegetative cover on a reclaimed surface. The treatments consisted of different topsoil depths and different mulching depths.

Concurrent with the watershed and plot studies, were an investigation of the economics of complying with reclamation laws in Ohio and the development or adaptation of surface and subsurface hydrology simulation models for conditions in the region under study.

Results

Soils: The original topsoil-subsoil was replaced by topsoil-spoil. The replaced topsoil had more coarse fragments than the original, but on the average about the same pH. The spoil was much coarser than the original subsoil, but also had about the same average pH at each site. At one of the sandstone-shale sites, though, the pH range was much greater than in the original subsoil, and included some very low values. Toxic materials were found in a few places on the surface at the sandstone-shale sites after topsoil spreading.

Hydrologic: The subperiods were somewhat short for the purpose of definitively analyzing surface-water hydrology. However, the data indicated that direct storm runoff volume increased by three or four times after disturbance began on the watersheds. Peak flow rates increased by an order of magnitude and occurred sooner after a storm began than during the premine period. These effects were not appreciably modified by reclamation.

The plot data suggest that runoff volume from spoil is greater and at higher rates than from topsoil. Vegetation and mulching had the effect of reducing peak rates of flow, but of increasing runoff volume. No explanation was found for the increase in runoff volume.

Premine dry-weather streamflow was maintained by discharge from aquifers perched on the coal underclays. When coal was mined, the aquifers were

destroyed. Dry-weather streamflow thus decreased if a lower perched aquifer also contributed flow to the watershed outlet or stopped altogether if not.

New aquifers began reestablishing after reclamation, but the process was slow. They were developing over the underclay from which the coal had been removed and were also developing in areas of spoil material which overlay the premine land surface downslope from the original coal outcrop (Figure 3 of the main text). At the time observations ceased, there was evidence of contributions to dry-weather streamflow by the new aquifers at two of the sites, but in very small amounts compared to the premine period.

Sediment: As would be expected, sediment losses were most severe during the periods of active disturbance, reaching levels at the watershed outlets in the hundreds of thousands of milligrams per liter. However, minimal reclamation greatly reduced sediment concentrations. At the one watershed where reclamation and erosion control were most successful, postreclamation sediment concentrations were at levels equal to or below those of the premine condition (on the order of hundreds of milligrams per liter). Erosion control diversion terraces were established at two of the sites to enhance revegetation. In both cases, repeated failures in the diversions, their outlets, or both caused so much erosion that the effectiveness of the reclamation procedures upon erosion could not be quantitatively discerned.

Erosion plot data indicated that spoil produced more erosion than topsoil. Establishing vegetation on plots reduced bare-surface erosion by about 40%. Using mulch when establishing vegetated surfaces reduced erosion by 70%-90%, depending on mulch application rate, as compared to establishing vegetation without mulch.

Erosion plot data also indicated that the slope factor in the Universal Soil Loss Equation underpredicted soil loss for both topsoiled and spoil plots.

Surface-Water Chemical Quality: Water quality in chemical terms was strongly influenced by whether the overburden was characterized by limestone or sandstone. Water quality effects at the two sandstone sites were similar to each other.

Surface waters at the limestone site exhibited pH values from slightly below to well above 7.0. Those at the sandstone sites fell below 6.0 20% of the time.

Several water samples from the outlets of the sandstone sites exceeded the Office of Surface Mining regulatory levels of iron and manganese. Environmental Protection Agency National Interim Drinking Water Regulations for nitrate-N and for selenium were exceeded in several samples. None of the other eight regulated inorganic chemicals were exceeded in any samples.

Parameters not detected in any surface-water samples (including dry-weather streamflow as aquifer discharge) included arsenic, chromium, mercury, and sulfide. Parameters which were detected in less than half of all the water samples collected were antimony, cadmium, copper, lead, phenols, phosphorus, silver, and zinc.

Dissolved solids, calcium, magnesium, manganese, sodium, ammonium-N, strontium, bicarbonate, sulfate, chloride, and nitrate-N concentrations were about the same or somewhat lower after reclamation of the limestone site when compared to the premine period. These same parameter concentrations were notably higher after reclamation than before mining at the two sandstone sites.

At all sites, chemical water quality was still changing at the end of observations. Sulfate, in particular, was increasing.

Ground-Water Chemical Quality: Water quality in perched aquifers below the mined coals changed very little throughout the period of observation. An exception was at the limestone site where sulfate concentration rose slowly but steadily at two observation points, and was still rising at the end of observations. Another was at one of the sandstone sites where the underclay beneath the mined coal either pinched out or was disrupted during mining; sulfate concentration was also high.

Whereas premine waters in the aquifers immediately above the mined coal was primarily of the calcium bicarbonate type, water accumulating on top the postreclamation underclay in the zone in which the coal had been removed was of the calcium sulfate type. As described above, this newly-developing aquifer extended down through spoil material that, after reclamation, covered the premine land surface for a distance downslope from the original coal outcrop. Water in these zones, at the end of observations, was of the calcium bicarbonate type.

Dissolved iron and manganese concentrations exceeded Environmental Protection Agency Drinking Water Standards prior to mining in some samples and after reclamation in lower perched aquifers. In the redeveloping upper aquifer, these parameters, along with dissolved solids and sulfate, commonly exceeded the drinking water standards and were increased by about an order of magnitude from the premine levels in that aquifer.

Sediment Chemical Quality: pH of suspended sediment material remained constant throughout the study at the limestone site. pH significantly decreased at the sandstone sites during the periods of disturbance. However, reclamation included placing topsoil over the sandstone spoil, and this effectively sealed off the detrimental effects of the sandstone after that operation -- at least during the period of observation.

Settling of larger solids in the sediment ponds resulted in enrichment of the still-suspended solids with the various metal parameters. However, amounts of metals leaving the ponds were much less than those entering them.

In general, the results of this study indicate that maintaining water pH above 6.0 will result in sediment of acceptable quality.

Reclamation Procedures: Straw mulch rates of at least 1 t/Ac significantly increased plant growth during the vegetation establishment period, but topsoil had no effect upon plant growth or its maintenance in the first two years after reclamation. It should be noted that the latter observation is made in the context of fertilization of both spoil and topsoil in accordance with fertility/lime tests.

Hydrologic Simulation Models: An existing U. S. Geological Survey ground-water model was modified to simulate the perched-aquifer system common in southeastern Ohio. Modification also was made to account for spring discharge and for stream-aquifer interactions.

An entirely new model was developed to simulate surface runoff, infiltraion, root-zone soil water changes, and percolation to ground water.

Economics: Average 1979 costs of reclamation were about $4900 per Ac of disturbed land or about $2.25 per ton of coal removed -- 60% of which was accounted for by backfilling. Direct benefits of reclamation on the affected land were about $325 per Ac. Indirect benefits to adjoining lands were slight. Reclamation resulted in slight decreases in several aspects of the regional total economy, namely in total output, employment, and income.

I. INTRODUCTION

By the mid-1970's, surface mining and its after-effects had become an issue of national concern. Debate was in progress over a national law, later to be enacted as PL 95-87, Surface Mining Control and Reclamation Act of 1977. There was very little factual, quantitative data relating to the impact of surface mining and reclamation upon hydrology and water quality. In 1976 the Agricultural Research Service (ARS) of the U. S. Department of Agriculture, The Ohio State University-Ohio Agricultural Research and Development Center (OSU-OARDC), and the Ohio district of the U. S. Geological Survey (USGS) jointly undertook research designed to provide factual, quantitative knowledge about surface mine and reclamation impacts upon the quantities of interest. The Soil Conservation Service of the U. S. Department of Agriculture, Utah State University, the Muskingum Conservancy District, and three private mining companies also cooperated in the research investigation.

The investigation was concerned with studying relationships and documenting the impacts of mining and reclamation upon 1) the physical and chemical nature of soils and rock above the mined coal, 2) the occurrence and movement of water both on the land surface and as ground water, 3) the occurrence of erosion and the movement of sediment, 4) the chemistry of surface water, ground water, and sediment, and 5) the costs of monitoring these quantities and of reclaiming surface-mined areas for the purpose of minimizing adverse impacts.

The basic research concept was to monitor quantities of interest and conduct experiments beginning at selected sites before mining began, continuing through the period of mining and reclamation disturbance, and also continuing on into the period after reclamation was finished. The research was conducted without interference in the operations and plans of the mining companies on whose lands the sites were located.

Numerous reports resulted from this project. The appendix is a complete list of those published in various journals or available through universities (theses) or through NTIS (U. S. Bureau of Mines reports).

This report summarizes and gives the highlights of the research findings. Details of project design, operation, and results may be found in the above-mentioned reports. The titles of the reports as given in the appendix relate well to the topics discussed herein, so number referencing is not used in this report, except to publications not produced by this study. Numbered references are given in the list of references.

To aid the reader in referring to specific watershed site data and analyses, some explanation of the reporting sequence is in order. The data and analyses for the premine period at two of the sites (designated Watersheds C06 and M09 as explained below) and for the first year for Watershed J11 are given in the report whose title contains the phrase, Phase 1. Mining and reclamation (disturbed period) data are given for the former two watersheds in separate publications whose titles contain the phrase, Phase 2. Postreclamation data for those watersheds are in the Phase 3 reports. Data for all three phases at Watershed J11 are contained in the single report whose title refers to that watershed.

II. EXPERIMENTAL CONDITION

A. The Physical Setting

Three experimental sites were chosen in east central Ohio, each one being representative of soils and geology found in conjunction with a different mineable coal bed. The primary experimental unit was a natural drainage basin (watershed) under 50 Ac in size. Figure 1 shows their locations. Each was designated according to the county in which it was located and according to the regionally-used number of the coal bed that crops out in the watershed.

Eighteen plots, for studying reclamation treatments and erosion, were established after regrading of spoil near Watershed C06. Each was 72.6 ft long. Four slopes, 9%, 16%, 23%, and 30% were used. Three topsoil depths, three mulching rates (including zero in both cases), and vegetated and fallow conditions were tested.

Watersheds C06 and J11 were established over stratigraphy characterized by sandstone and shale above the coal bed to be mined, while Watershed M09 stratigraphy contained limestone and shale over the coal.

Watershed C06 was wooded prior to mining; Watershed M09 was a pastured area; and Watershed J11 was a mixture of pasture and woods.

The Numbers 6, 9, and 11 coal beds are more formally designated, respectively, as the Middle Kittanning No. 6 coal bed of the Allegheny Formation, the Meigs Creek (Sewickley) No. 9 coal bed of the Monongahela Formation, and Waynesburg No. 11 coal bed of the Monongahela Formation. They are all Pennsylvanian age. Each of these coal beds, as well as others located above, between, and below them in the stratigraphic column, is founded on a clay or clayey layer, called an underclay, that impedes the downward movement of water.

Of particular significance to this study is the fact that each underclay supported a zone of saturation, called for convenience a perched aquifer or water table, that had a water table located in the rock overlying each coal bed. In general, the perched water tables did not reach as high as the next overlying clay bed, hence the use of the term, perched. Figure 2 is a cross section representative of southeastern Ohio hydrogeologic conditions. These perched aquifers were significant to the study because they supported dry-weather stream flow (baseflow) in each of the study watersheds.

The outlets of Watersheds C06 and M09 were located so that baseflow from each was supported by two perched aquifers, the top one on the clay underlying the coal to be mined, and the lower one on the next lower coal and clay bed in the stratigraphic column at the site. Baseflow at the Watershed J11 outlet, however, was supported only by the perched aquifer in which the No. 11 coal was located.

B. Mining and Reclamation Operations

Removal of timber and/or stripping and stockpiling of topsoil began the period of disturbance on each watershed. The contour-area method of surface mining was used at Watersheds C06 and M09. The entire coal bed was removed in each case. The clay beds appeared not to have been pierced at either site. The haulback

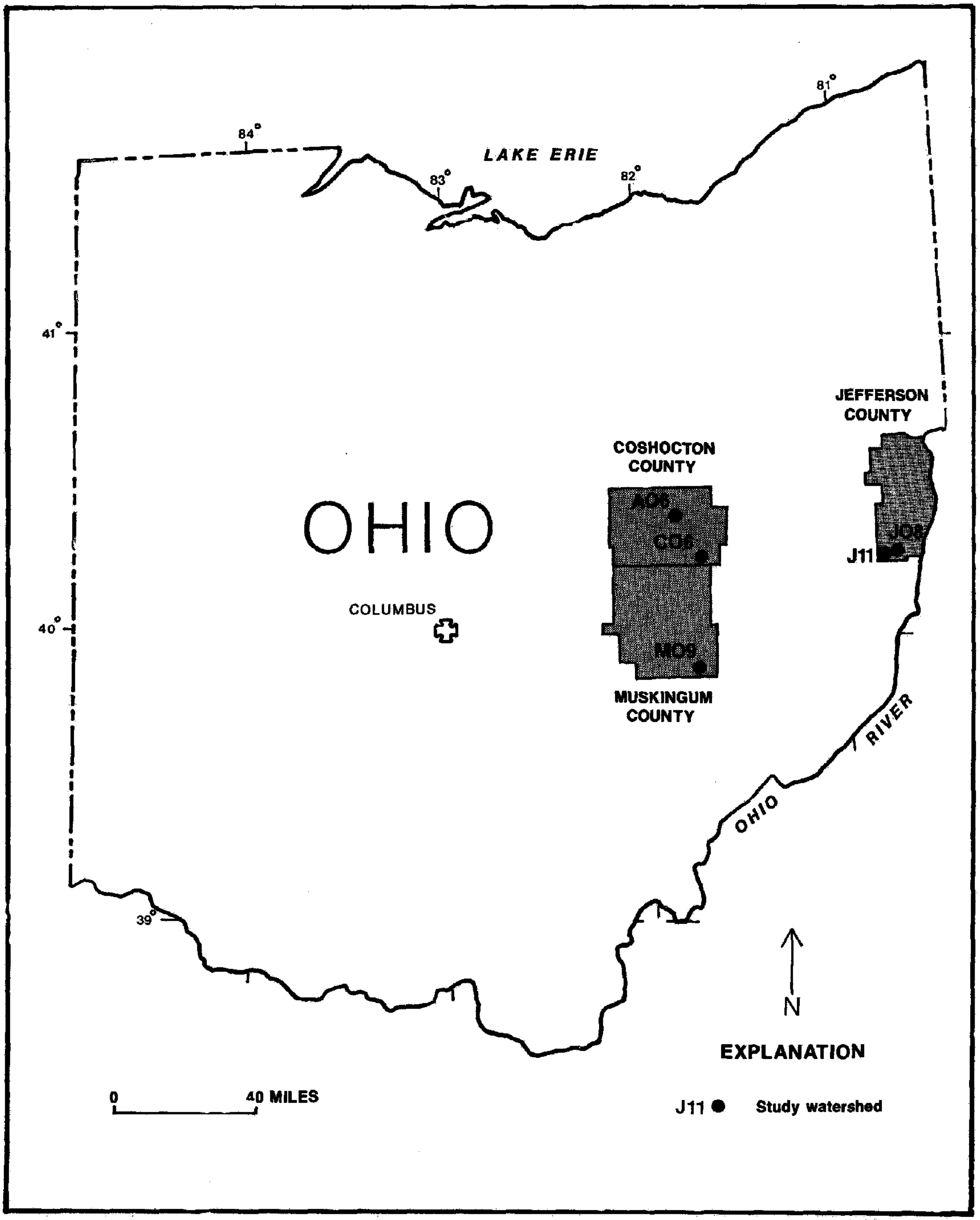

FIGURE 1. - Location of study watersheds.

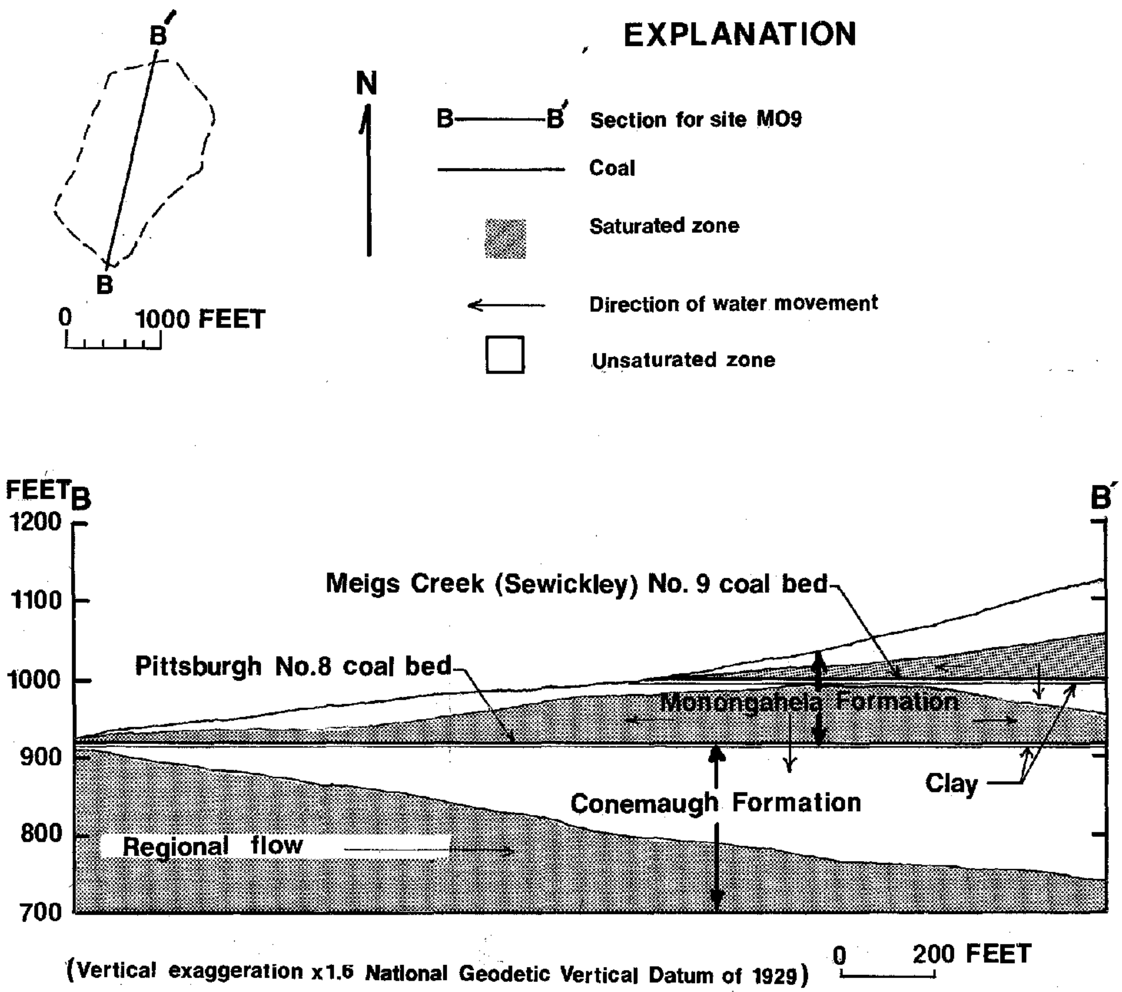

FIGURE 2. - Cross section for Watershed M09 illustrating premining ground-water occurrence and flow.

method was used at Watershed J11, and, at this site, surface mining terminated in a high wall along the eastern boundary. Some of the coal under the high wall was removed by auger. The shaley clay underlying the coal at Watershed J11 either pinched out or was punctured by the mining in the vicinity of the high wall.

Removal of the overburden necessitated piling spoil (broken and pulverized overburden rock) in windrows. These windrows altered drainage patterns, and their net effect at each site was evidenced in a continuously changing watershed geometry and size. Each watershed was greatly reduced in size as mining progressed. Reclamation began as mining ceased in an area and initially consisted of regrading the spoil back to an approximation of the original watershed contours. As this process proceeded, the watershed expanded in size. The effect of this contraction and expansion in area as well as the changing surface conditions and drainage patterns could not be fully monitored during the experiment for both practical and financial reasons.

At the completion of the regrading process, from five months to two years after initial disturbance, a watershed exhibited its nominal postmine geometry -- nominal in the sense that settling and compaction were yet to occur, and temporary erosion control measures might, for a time, alter the surface configuration. Figure 3 is a typical cross section of a regraded site. It shows that in general, regraded topography may be expected to exhibit lower high points and that hill slopes may be less steep than prior to mining. It also shows that regrading generally spreads spoil far downslope from the level of the coal bed removed in the mining operation. This graded spoil on top of the premine land surface below the level of the coal outcrop has hydrologic significance, as will be seen.

Continuing reclamation activities consisted of respreading topsoil, fertilizing, liming as needed, and seeding. At each site, the reclaimed surface was protected with erosion control measures. The successful erosion control measure applied by the mine operator at Watershed M09 consisted of using a disk-like tool to crimp a straw mulch into the seeded surface. At the other sites, the operators constructed diversion terraces.

The diversions were apparently successful at Watershed C06 in that the slopes between terraces became well vegetated and showed little visual evidence of erosion. The terrace channels, too, were well vegetated and neither eroded nor filled with sediment. However, the single terrace outlet to which nearly all terraces drained suffered severe erosion. The mine operator had also constructed two small detention dams across the main watershed drainageway below the terrace outlet. These dams overtopped on occasion, and severe erosion also occurred in the main drainageway.

At Watershed J11, the terraces themselves failed, as did the single outlet at that site.

Because of fluctuating demand for coal, mining schedules varied from those originally estimated by the mining companies. Watersheds C06 and M09 were mined on schedules that were roughly in phase with each other. The mining and reclamation period at these two watersheds was about doubled in length (from a planned one year to two years) by a mine workers' strike. Watershed J11 was mined approximately two years after the other two were reclaimed. The premine observation periods on Watersheds C06 and M09 were each less than a year in length, while

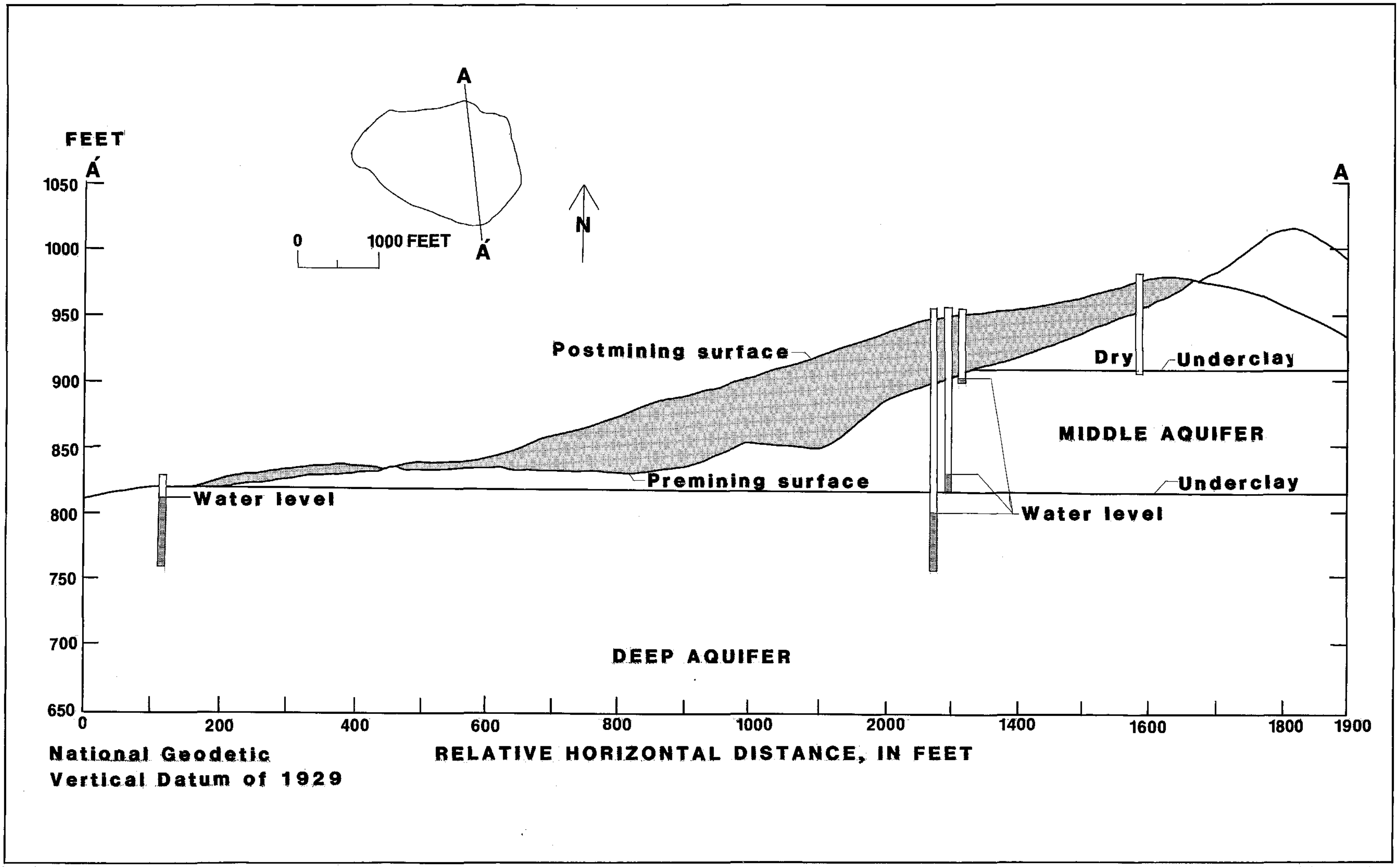

FIGURE 3. - Geologic and hydrogeologic cross section showing changes resulting from surface mining and reclamation at Watershed C06.

that for Watershed J11 was about three years in length. The fully reclaimed condition was observed for a period of about two years at Watershed M09. Control of erosion at Watershed C06 was not acheived until after observations ceased at that site. Watershed J11 underwent two reclamaion attempts, about a year apart, after mining, and final reclamation was not completed until after observations ceased at that watershed. The second reclamation effort resulted in about a 40% increase in the size of the watershed and a drastic change in drainage pattern.

C. Research Tasks, Observations, and Instrumentation

Physical and chemical characteristics of soils and overburden rock were established for both the premine and postreclamation conditions at each site. Premine vegetation was also surveyed.

Each watershed outlet was equipped to record depth of flow vs time and to obtain samples of the flowing water. These samples were refrigerated on site or otherwise preserved for laboratory testing for concentrations of sediment and numerous chemical and other properties. Each watershed outlet was located downstream from the lowest point of regrading along the stream channel, and was maintained throughout the study.

Ground-water observation wells were installed prior to mining, destroyed during mining, and reinstalled after regrading. Some wells at each site were outside the disturbed areas and survived throughout the observation period. The wells were installed in clusters, each well in a cluster penetrating to a different perched aquifer. Casing was installed where necessary to prevent a higher aquifer from influencing observations in a lower aquifer. During premine well installation, a continuous rock core was taken at each site to a depth that reached into the third aquifer. These cores were taken to the laboratory for physical and chemical analyses that led to characterizing the stratigraphy at each site.

Sedimentation ponds were constructed below each watershed outlet prior to mining. The Watershed C06 and M09 ponds were instrumented with water level recorders and with equipment to measure and sample discharge.

A "weather station" was installed near each watershed for the purpose of monitoring precipitation, temperature, and other weather-related variables.

The plots were instrumented with runoff measuring devices and proportional flow samplers developed especially to handle the expected high sediment loads and the large rock sizes from the bare spoil plots.

Economic studies were made of the administrative and legal costs of compliance with Ohio reclamation regulations, of the costs of the physical phases of Ohio surface mine reclamation, of the extent of indirect benefits of reclamation, and of the economic impacts of reclamation regulations on output, employment, and income of major industries in Ohio's coal mining region.

An existing ground-water model was modified for application in the perched-water-table conditions of southeastern Ohio, and a new comprehensive hydrologic model was constructed for the purpose of simulating the land phase of the hydrologic cycle -- overland flow, infiltration, root-zone soil-water storage changes, and percolation.

D. Climatic Experience

The most notable and potentially significant characteristic of the climate during the study period was the increasingly larger annual precipitation received during the period 1976 through 1980. Long-term precipitation records were available near Watersheds C06 and M09. Examination of these records and comparison with those of the years of observation, showed the study period to start off with slightly below average precipitation, followed by increasing amounts from year to year. The years 1979 and 1980 saw precipitation at near record levels.

E. Conditions of the Experiment

Each site was observed over about a five-year period. The premine period was short at two of the sites, the period of observation during active disturbance of each site was short or interrupted by the strike, and only one site was observed in the final reclaimed condition for as much as two years. Such short periods and other conditions prohibited the use of statistical techniques to distinguish the more subtle impacts of mining and reclamation upon the quantities of interest. Some impacts, however, were quite apparent, and these are the ones addressed in this report.

After a severe disturbance like surface mining and reclamation, a landscape begins another period of slower and less dramatic change as it seeks a sort of balance with nature. In a reclaimed landscape, further consolidation and compaction may occur in both soils and spoil. The latter may have been partially dried during the period of disturbance and may rewet to some near-equilibrium water content, a process that requires time. The broken and crumbled "fresh" rock of the spoil will initially weather more rapidly than the old faces of the original rock, releasing greater quantities of soluble material to the water occupying and flowing in the spoil. The full extent of the impact of this process may require many years before it can be assessed.

This investigation, because of its brevity and the nature of the several phenomena under observation, could only address the immediate and most apparent impacts of surface mining and reclamation. Several more years may have to pass before the true extent of such a parameter as ground-water chemical quality can be evaluated.

III. RESULTS OF WATERSHED AND PLOT OBSERVATIONS

A. Physical Changes

Replacement of the overburden with spoil and the regrading of same over the original watershed surface downslope from the coal outcrop was discussed in connection with Figure 3.

Virtually all aspects of the reclaimed watersheds' geometries above the extent of disturbance were profoundly changed. Watersheds C06 and M09 experienced reductions in area by about 15%. Watershed J11, prior to final reclamation at the time observations ceased, had increased by about 10% in area compared to its original geometry. The total relief within each watershed decreased -- up to 37% at Watershed M09. Surface drainage patterns after reclamation bore no resemblence to those extant prior to mining or during mining.

Premining soils were stripped, stockpiled, and respread following regrading of the spoils. Topsoils generally contained greater amounts of coarse material that were mixed in during both the stripping and respreading periods. At Watershed J11, on an original sandstone-shale stratigraphy, both coarse materials and toxic materials were particularly noticeable in the respread topsoil compared to the other two sites. The other sandstone-shale site (Watershed C06) exhibited some toxic topsoil areas, while Watershed M09 on limestone-shale appeared to have none.

Soils at the two sandstone-shale sites were classified as belonging to the Fairpoint soil series. Those at the limestone-shale site were classified as Morristown. Topsoil pH at all three sites was not greatly different, on the average, than in the original soils.

Postreclamation "subsoil" consisted of spoil materials and were therefore quite coarse. Subsoil (spoil) pH was not greatly different after mining than before, on the average. At Watershed J11, though, the range in spoil pH was much greater than at any other site. With a range of 3.5 to 8.2, it was also greater than prior to mining. Premining subsoil pH in the sandstone areas generally ranged from about 4.5 to about 5.0, and at the limestone site from 4.5 to 7.0.

Postreclamation vegetation at each site consisted of grasses and legumes. Good cover was established at Watersheds C06 and M09, and there was little visual evidence of surface erosion at these sites. Good vegetative cover was not established after either of the two reclamation periods at Watershed J11 prior to the end of observations. The land areas between diversions and the diversion channels showed evidence of erosion.

B. Hydrology

At Watershed J11 the effect of mining upon surface runoff was expressed as increased direct storm runoff (total runoff minus baseflow), by a three to four times faster response, and by about an order of magnitude increase in peak flow rates. The premine period at the other two sites was too short and contained too few events of high enough magnitude to allow well-founded conclusions. However, comparisons using the data that were collected were not inconsistent with the conclusion reached with Watershed J11 data.

Results from the plots established near Watershed C06 indicated that spoil produces somewhat more runoff and greater peak flow rates than does topsoil. However, no apparent relationship could be established for the hydrologic variables as a function of degree of slope of the plots.

No reason could be found for the observation that vegetating and/or mulching a plot resulted in reduction of peak flow rates, but in an increase in runoff volume.

Destruction of the overburden on the mined coal involved dewatering of the aquifer perched on the underclay at that level. Destruction of this body of ground water removed a source of dry-weather stream flow (baseflow). Dry-weather stream flow thus decreased at Watersheds C06 and M09, and a lower perched aquifer became the sole source of baseflow. At Watershed J11, the aquifer above the No. 11 coal was the only source of baseflow, and baseflow ceased entirely at that site shortly after mining began.

Ground-water levels in the aquifer perched over the mined-coal underclays recovered only slowly at all sites. The upper postreclamation aquifers were observed to be redeveloping not only over the mined-coal underclays, but also within the spoil on top the original land surface downslope from the underclay outcrops at all sites (Figure 3).

Ground-water levels were still rising at the end of observations, but at no site had they risen to the point where hydrologic analyses could detect that the aquifers were again contributing baseflow. However, as noted in a later discussion of surface-water chemistry, increases in sulfate concentration were observed in the baseflow at Watersheds C06 and M09. It is also noted later that the aquifers redeveloping above the mined-coal underclays were of the calcium sulfate type, whereas, the premine aquifers at and below that level were predominantly of the calcium bicarbonate type. Water accumulating in the spoil above the original land surface was of the calcium bicarbonate type, also. The water type of the aquifers below the mined coal did not change on a large scale after mining, so these observations indicate that the redeveloping aquifer over the underclay was indeed contributing to baseflow at the two mentioned sites.

At Watershed J11, the underclay was either punctured or nonexistent in the vicinity of the high wall left at the end of mining. Wells located in both the redeveloping upper aquifer and in the lower aquifer indicated that in this area the two aquifers had merged.

C. Sediment

During the premine period, average watershed sediment concentrations ranged from 500 to 700 mg/l with maxima reaching as high as about 6000 mg/l.

The periods of most severe sediment concentrations for the sites were when active mining was occurring in areas hydraulically connected to the outlet weir. Periods of active reclamation work on the watersheds were also critical in terms of high sediment concentration and loads. During these periods of active disturbance, average sediment concentrations were on the order of 10^4 mg/l and maxima were on the order of 10^5 mg/l.

Initial reclamation noticeably reduced sediment concentrations. Repairs of the diversion outlet at Watershed C06 and of the diversions and outlet at

Watershed J11 were reflected in immediate declines of sediment concentrations, but averages and maxima stayed relatively high because failure reoccurred soon after repair at each watershed.

As noted earlier, straw crimped into the soil surface effected successful erosion control during vegetation establishment at Watershed M09. Mining period sediment concentrations at this watershed rose as high as or higher than at the other two, but postreclamation concentrations dropped down to levels even lower than during the premine period.

The trap efficiency of the Watershed C06 sediment pond ranged from 66% to 98%. At Watershed M09, the range was much greater, being from 13% to 74%. At the latter site, trap efficiency increased with increasing load to about one ton per event, after which level it plateaued at about 70%.

Data from the plots indicated that, as expected, sediment losses generally increased with slope for both topsoiled and nontopsoiled plots. Soil losses were generally greater from spoil than from topsoil plots.

The practice of mulching to aid in the establishment of vegetation reduced soil loss by 70% for a 1 t/Ac application rate and by 90% for a 2 t/Ac rate when compared to vegetated but nonmulched plots. When considering all vegetated plots, mulched or nonmulched, the data show about a 40% reduction in soil loss compared to plots with bare topsoil surfaces.

Plot data were also used to evaluate whether the Universal Soil Loss Equation (USLE) can be applied to reclaimed soils. Soil tests yielded a soil erodibility (K factor) value that was about the same for topsoil and spoil. Testing with plot data (which showed much variability) showed that the slope had a lesser effect on sediment yield from this reclaimed soil than was predicted by the USLE slope factor.

D. Surface-Water Chemical Quality

Water chemical quality was strongly influenced by the type of rock in the overburden at a site. Watersheds C06 and J11, being on sandstone-shale, were similar to each other in water quality experience, but different from Watershed M09 which was on limestone-shale.

The pH of the water samples collected from Watershed M09 was in almost all cases 7.0 or greater. This pH is high enough to precipitate many metals which generally contribute to poor water quality, i.e. iron and manganese. This is in contrast to Watersheds C06 and J11 where 20% of the water samples collected during the active mining and reclamation period were below the lower Office of Surface Mining (OSM) regulation level of 6.0. Several water samples collected at the outlets of Watersheds C06 and J11 also exceeded the OSM regulatory level for iron (7 mg/l) and manganese (4 mg/l). These high values are rather striking as they represent water soluble iron and manganese concentrations and not total concentrations. The high iron and manganese concentrations were found in water samples with the lowest pH values. However, the majority of samples (80%) collected during the active mining and reclamation period and almost 100% of the remainder of the samples collected during this study had pH values greater than 6.0. Above this level, very little correlation between parameter concentrations and pH was observed.

Water quality evaluated in terms of the Environmental Protection Agency (EPA) National Interim Drinking Water Regulations met water criteria for maximum contaminant levels for 8 of the 10 inorganic chemicals regulated (arsenic, barium, cadmium, chromium, fluoride, lead, mercury, and silver). Six and two samples at Watersheds M09 and J11, respectively, exceeded the EPA regulation level for nitrate-N of 10 mg/l. This was primarily due to application of nitrogen fertilizer on the surface of the watersheds during the reclamation process. Four samples at Watershed M09 also slightly exceeded the EPA regulation level for selenium (10 μg/l).

Several parameters of potential importance which were assayed in the water samples were not detected at any of the mine sites. These parameters include arsenic, chromium, mercury, and sulfide. Other parameters which were detected in less than half of all the water samples collected at Watersheds C06, M09, or J11 were antimony, cadmium, copper, lead, phenols, phosphorus, silver, and zinc.

Dissolved solids, calcium, magnesium, manganese, sodium, ammonium-N, strontium, bicarbonate, sulfate, chloride, and nitrate-N concentrations either did not change or decreased in runoff from Watershed M09 in the postreclamaion period compared to the premine period. At Watershed C06, concentrations of these parameters were significantly higher after reclamation than before mining. Watershed J11 concentrations were also higher during the partially reclaimed period, but the increase was not so pronounced as at Watershed C06.

Generally, differences in concentration between premine and postreclamation periods were greater in baseflow samples than in samples taken during storm runoff periods. At the end of observations, baseflow chemical parameter concentrations were still changing. Sulfate, the most important parameter observed, was still increasing.

The monitoring of precipitation chemical quality showed that concentrations of ammonium-N, copper, and zinc were often higher in precipitation than in surface runoff. Significant amounts of the dissolved aluminum, barium, iron, nitrate-N, and sodium in surface-water samples also could be attributed to precipitation.

Data from Watershed M09 suggest that a reclamation practice which controls sediment loss and maintains the pH of the surface water above 6.0, would result in acceptable water quality.

E. Ground-Water Chemical Quality

Premine ground waters in the aquifers from which coal was removed at Watershed C06 and M09 were predominantly of the calcium bicarbonate type. At Watershed J11, two types of water were present -- calcium bicarbonate and calcium sulfate. Lower perched aquifers at all three sites contained calcium bicarbonate and sodium bicarbonate types.

As the aquifers redeveloped after mining, observations indicated that water accumulating in zones where coal had been removed was of the calcium sulfate type, while that accumulating within spoil that had been regraded over the premine land surface downslope from the coal outcrop was of the calcium bicarbonate type.

Water type in lower aquifers did not change with two notable exceptions. In the vicinity of the location of the apparent disruption of the shaley clay bed at Watershed J11, postreclamtion water type in the next lower aquifer became calcium sulfate type, like that in the redeveloping aquifer above. From the time of the reinstallation of wells after reclamation at Watershed M09 to the end of monitoring, water quality at two observation wells in the aquifer immediately below the mined coal steadily increased in sulfate.

EPA-recommended limits for drinking water for concentrations of dissolved solids, iron, manganese, and sulfate were commonly exceeded in water in the redeveloping aquifers within mine spoils. Concentrations of these parameters generally increased by about an order of magnitude from the premine aquifer to the postreclamation aquifer.

The concentrations of some parameters in the lower aquifers exceeded drinking water standards both before mining and after reclamation, e.g., dissolved iron and dissolved manganese. In the lower aquifer at Watershed J11, several parameters, including hardness, noncarbonate hardness, calcium, magnesium, sulfate, manganese, dissolved solids, and chloride exhibited increased concentrations after reclamation, generally by a factor of about two.

F. Sediment Chemical Quality

Suspended sediment chemistry was also very much influenced by the type of overburden material at the three mine sites. The average concentrations, during each mining period, of the 17 parameters monitored were very similar for Watersheds C06 and J11.

At Watershed M09, the dominant cation, in terms of concentration both during the active mining and reclamation period and the reclaimed period, was calcium. The pH of the suspended sediment material at Watershed M09 remained constant throughout the study. At Watersheds C06 and J11, a significant decrease in pH of the suspended sediment material was observed during the mining and reclamation period compared to the premine period. Those parameters which become more soluble as the pH decreases, such as aluminum, iron, manganese, and sulfate, were observed to have increased in concentration. However, after reclamation the replaced topsoil essentially sealed the sandstone spoil from erosion, and sediment chemical quality was found to be similar to that observed during the premine period.

The sediment ponds at Watersheds C06 and M09 allowed much of the heavier sediment material to settle out. As a result, the sediment material which remained in suspension and which was transported into the stream water below the mine site was found to be enriched in concentration of the various metal parameters monitored. However, even though this sediment material may have been enriched in concentration, the amount of metal which was transported out of the sediment pond was much less than the amount which entered the pond.

The same observation may be made for sediment chemical quality as was made for water chemical quality. Data from Watershed M09 suggest that a reclamation practice which maintains the pH of the surface water above 6.0, would result in acceptable sediment quality.

G. Reclamation Procedures

Straw mulch rates of at least 1 t/Ac applied at the time of seeding significantly increased plant growth and vegetative cover in the vegetation establishment period.

Topsoil depths of 0 in, 6 in, and 12 in had no significant effect on vegetative cover or dry-matter yields. When fertilized and limed according to soil test dictates, any of these rooting media will suffice, at least during the vegetation establishment period and the following two years.

IV. HYDROLOGIC MODELING RESULTS

A. Ground-Water Model

A quasi three-dimensional ground-water flow model (Trescott, 1; Trescott and Larson, 2) was modified to properly simulate ground-water conditions similar to those found in southeastern Ohio where perched aquifers lie one above another and discharge to the surface via springs and seeps. Perched water tables required that the method of calculating the vertical flow rate be changed. A hydraulic-head-dependent spring discharge function and a head-dependent stream-aquifer interchange function were added, also. Modifications were made to allow recharge from precipitation to any layer as well as recharge by leakage through an overlying clay bed supporting a higher perched water table. This model is available as U. S. Geological Survey Water Resources Investigations Open-File Report 82-4019 (No. 19 in the Appendix).

B. Comprehensive Land-Phase Hydrologic Model

An entirely new model was developed to simulate runoff, infiltration, root-zone soil water storage changes, and percolation. The model concept considers the watershed land surface to be comprised of polygonal elements. Each element is the top surface of a vertical prism extending down through soil and rock to the first water table. Infiltration at the upper prism surface separates the available water at the surface into that which runs off and that which recharges soil water storage or contributes to percolation. A kinematic approach is used to simulate the flow of surface water to and down the stream channel. A one-dimensional, porous media flow equation is used to simulate soil water storage changes in the root zone and the movement of percolating water above the water table. This model will later be released as an NTIS report.

Originally, the comprehensive model was to be linked with the ground-water model. Experience showed the time scales between near surface hydrologic activity and ground-water activity to be so different that inclusion of the ground-water model in the comprehensive model was not practical. Simulations were, therefore, run using two separate models. The comprehensive model, described above, was used to simulate surface runoff and percolation. The ground-water model was used to simulate aquifer flow and discharge.

V. ECONOMIC RESULTS

Costs of obtaining permits under Ohio law in 1977 ranged from $100 to $500 per Ac or from 2.2 to 3.5 cents per ton of coal, depending on acreage in a permit.

Average costs of reclamation in 1979 were $4900 per Ac of disturbed area ($2.25 per ton of coal provided). Backfilling accounted for more than 60% of these costs.

Direct benefits of reclamaton were $325 per Ac of reclaimed surface-mined land, with indirect benefits to the value of neighboring land being slight.

Considering the southeastern Ohio region's total economy, reclamation regulations resulted in regional decreases in total output, employment, and income of 0.24%, 0.16%, and 0.23%, respectively. These decreases occurred because reclamation requirements are cost-increasing. Thus, overall production for the region is lowered.

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